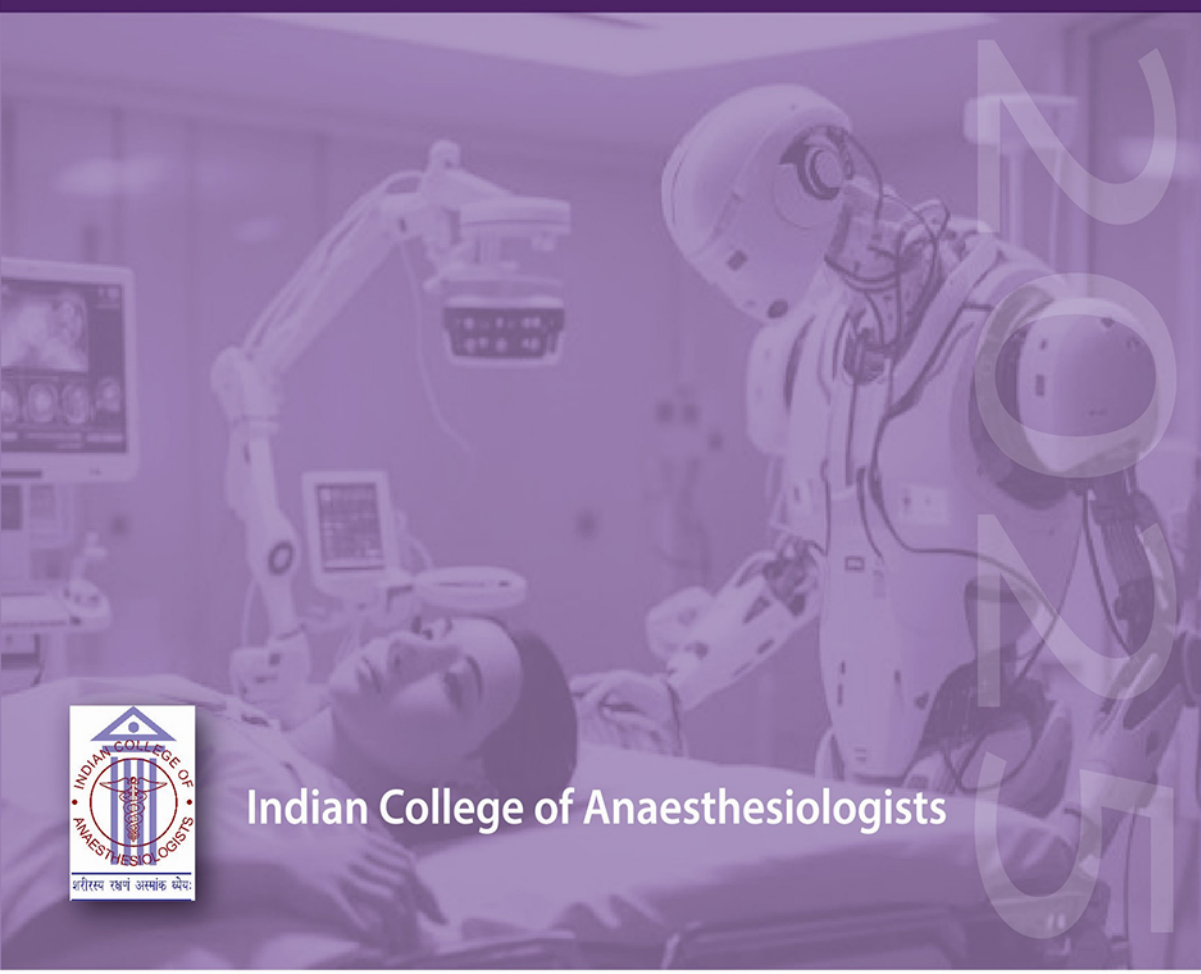
website www.jaypeebrothers.com, for detailed information on anesthesia books, visit our website www.jaypeebrothers.com

Yearbook *of* Anesthesiology 14



Indian College of Anaesthesiologists

Editors
Mukul Chandra Kapoor
Gaurav Kakkar

JAYPEE

Contents

1. **Interventional Radiology Suite Within a Freestanding Ambulatory Surgery Center: Anesthetic and Quality Assurance Considerations 1**
   Kara M Barnett, Joanna Serafin, Natalie B Simon, Suken H Shah
   - Interventional Radiology Procedures Performed in the Ambulatory Surgery Center *3*
   - Interventional Radiology Suite Design in the Ambulatory Surgery Center *4*
   - Patient Selection Considerations *7*
   - Anesthesia Care for Interventional Radiology in the Ambulatory Surgery Center *9*
   - Scheduling and Efficiency Considerations *11*
   - Postoperative Care *12*
   - Quality Improvement Initiatives and Tracking *13*
2. **Patients with Obesity and Obstructive Sleep Apnea in the Ambulatory Surgery Center 17**
   Kelly Lebak
   - Obesity *17*
   - Obstructive Sleep Apnea *21*
3. **Risk Assessment in Emergency/Urgent Surgery 27**
   Pradeep A Dongare, Kishori Biradar
   - Definitions *28*
   - Need for Risk Assessment *29*
   - Preoperative Evaluation—Estimating Perioperative Risk *30*
   - Evolution of Risk Assessment Tools *31*
   - American Society of Anesthesiologists *32*
   - Scoring Systems Adapted for Emergency Surgeries *32*
   - Scoring Systems Developed for Emergency Surgeries *32*
   - Limitations of Scoring Systems *37*
   - Role of Artificial Intelligence in Risk Prediction *37*
4. **Upcoming Role of Artificial Intelligence in Airway Management 40**
   Reeta Singh, Susheela Taxak
   - What is Artificial Intelligence? *41*
   - Use of AI in Airway Assessment and Management *41*
   - Use of AI in Predicting a Difficult Airway *42*
   - Predictive Machine Learning Model Using Clinical Assessment for Difficult Airways *43*
   - AI Used in Analysis of Radiological Images, Face Scans, and Speech for Airway Assessment *43*
   - Role of AI in Fiberoptic Visualizing Devices Used in Intubation *47*
   - Robotics in Airway Management *48*
   - Challenges, Limitations, and the Future of AI in Airway Management *48*

5. Maternal Cardiac Arrest 54
Michael J Furdyna, Michaela K Farber
- Epidemiology *55*
- Management of Maternal Cardiac Arrest *55*
- Causes of Maternal Cardiac Arrest and Specific Management *59*
- Postarrest Care *66*
- Prevention and Preparation *66*

6. Anesthetic Management of Tracheoesophageal Fistula 70
Anju Gupta, Manjula Sarkar, Nishkarsh Gupta
- Diagnosis and Pathophysiology *73*
- Embryology *73*
- Preoperative Evaluation *75*
- Preoperative Preparation and Optimization *75*
- Surgical Technique *76*
- Anesthetic Management *77*
- Postoperative Analgesia *82*
- Postoperative Complications *82*
- Anesthesia for Thoracoscopic Tracheoesophageal Fistula/Esophageal Atresia Repair *82*

7. Nonoperating Room Anesthesia in Pediatrics 88
Ranju Singh, Pooja Singh
- Patient Selection and Preoperative Assessment for Nonoperating Room Anesthesia Procedures *90*
- Equipment and Resource Considerations for Nonoperating Room Anesthesia *92*
- Anesthesia Techniques and Pharmacological Considerations for Pediatric Procedures *93*
- Monitoring *96*
- Considerations for Specific Pediatric Nonoperating Room Anesthesia Procedures *97*
- Collaboration and Communication: Multidisciplinary Approach in Nonoperating Room Anesthesia *99*
- Managing Emergencies and Complications in Nonoperating Room Anesthesia *99*
- Postanesthesia Care and Discharge Planning for Nonoperating Room Pediatric Patients *100*

8. Pediatric Thoracic Anesthesia 104
Monica Hervias Sanz, Francisco Javier Escriba Alapont
- Pediatric Airway, Respiratory Physiology, and Ventilation *105*
- One-Lung Ventilation *106*
- Analgesic Techniques for Thoracic Surgery *120*

9. Analgesia in Thoracic Surgery 123
Himani V Bhatt, John Choi, Ali N Shariat
- Neuraxial Techniques in Cardiac and Thoracic Surgery *124*
- Chest Wall Anatomy *125*
- Techniques *125*

- Superficial and Deep Parasternal Intercostal Plane Blocks *129*
- Clinical Implications *130*

10. Anesthesia for Pulmonary Endarterectomy 136
Palesa Motshabi Chakane, Muhammad Farooq, Palesa Mogane
- Diagnosis *137*
- Risk Prediction *138*
- Perioperative Management *138*

11. Anesthetic Considerations and Management of Traumatic Brain Injury..... 144
V Bhadri Narayan
- Consequences of Traumatic Brain Injury *145*
- Pathophysiology *145*
- Classification *146*
- Pathophysiology of Traumatic Brain Injury *147*
- Management *150*
- Intraoperative Considerations *153*

12. Remifentanil: An Update 156
Gaurav Kakkar
- Chemical and Pharmacological Properties *157*
- Mechanism of Action *158*
- Clinical Applications *161*
- Intensive Care *161*
- Administration and Dosage *162*
- Remifentanil in Special Populations *163*
- Contraindications *165*
- Strategies for Mitigation, Monitoring, and Management *166*
- Research and Future Directions *166*

13. Anesthesia for Geriatric Cancer Patients..... 169
Uma Hariharan, Rajiv Chawla, Shagun Bhatia Shah
- Anatomical and Physiological Changes in the Elderly *170*
- Geriatric Pharmacology *170*
- Perioperative Concerns in the Geriatric Population *174*
- Preoperative Assessment and Risk Stratification in Geriatric Oncological Patients *176*
- Nutritional Assessment *177*
- Perioperative Management *178*
- Pain Relief and Postoperative Care in Geriatric Oncological Patients *179*
- Geriatric Oncology in India *181*

14. Perioperative POCUS..... 185
Massimiliano Meineri
- Focused Cardiac Ultrasound *186*
- Focused Intraoperative Transesophageal Echocardiography *187*
- Lung Ultrasound *188*
- Diaphragmatic Ultrasound *189*
- Airway Ultrasound *189*

- Gastric Ultrasound *189*
- Training *190*
- Certification and Quality Control *190*

15. Fluid Stewardship in the Critically Ill 194
Nishant Kumar, Anshu Gupta, Maitree Pandey

- Fluid Stewardship *195*
- Fluid Stewardship Team *199*

16. Noninvasive Ventilation in Critical Care 204
Matthew Camilleri, Giles Coverdale, Mathew Patteril

- Noninvasive Ventilation Equipment *205*
- Physiological Effects of Noninvasive Ventilation *206*
- Noninvasive Ventilation to Prevent Intubation *207*
- Noninvasive Ventilation and High-flow Nasal Oxygen Prevent Desaturation During Intubation *211*
- Noninvasive Ventilation following Tracheal Extubation *211*

17. Point-of-care Ultrasound in Critical Care 215
Vijayalaxmi Bellana, Nageswar Bandla

- Ultrasound Physics *215*
- Knobology *219*
- Sonoanatomy *219*
- Vascular Access *220*
- Lung Ultrasound *223*
- Cardiac Ultrasound *226*
- Assessment of Volume Status *227*

18. Current Concepts in the Management of Septic Shock 243
Ramprasad Matsa

- Pathophysiologic Principles *244*
- Treatment and Control of Infective Process *244*
- Shock Resuscitation *245*
- Modulation of Host Response *250*

19. Perioperative ECMO Support: A Primer for Anesthetists 256
Ujwal Dhundi, Praveen Kumar G, Vivek Kakar

- Extracorporeal Membrane Oxygenation Fundamentals *257*
- Perioperative Management of ECMO Patients *264*

20. High-altitude Medicine: Anesthesiology and Critical Care Challenges 276
Shagun Bhatia Shah, Rajiv Chawla, Uma Hariharan

- Classification of Altitude Regions *277*
- Physics at High Altitude *277*
- Acclimatization *279*
- High-altitude Pathophysiology *279*
- Pregnancy and Altitude *280*
- High-altitude Illness *280*
- Anesthetic Challenges *284*
- Recent Advances *290*

21. Epidemiology and Management of Burnout among Anesthesiologists 293
Marycarmen Flores, Ricardo Lopez-Betancourt, Anoushka M Afonso
- Physician Burnout *294*
- Burnout among Anesthesiologists *294*
- Coronavirus Disease-2019 Effects on Burnout among Anesthesiologists *296*
- Interventions for Burnout *296*

22. Mentoring Anesthesiologists 301
Mukul Chandra Kapoor
- Attributes of a Mentor *302*
- Need for Mentorship *302*
- Benefits of Mentorship *303*
- Mentoring Needs Change with Time *306*
- The Mentorship Journey *306*
- Phases of a Mentoring Program *307*
- Selection Process for Mentorship Program *307*
- Monitoring of the Program *309*
- Barriers to Successful Mentoring *309*
- Mentorship Malpractice *310*

23. Safety in Anesthesia—Global Perspective 312
Carolina Haylock-Loor
- Anesthesiology, Anesthesiologists, and Safe Anesthesia *313*
- Standardized Protocols and Guidelines *315*
- Well-trained and Resilient Workforce *316*
- Essential Equipment and Medications *317*
- Safety Culture *318*

24. Role of Anesthesiologist in Perioperative Patient Safety 322
Shashi Kiran, Neha Aeron, Kate Boothroyd
- To Err is Human *324*
- Patient Safety—A Shared Responsibility! *324*
- Continuous Education and Professional Development *327*
- Patient Communication and Consent *327*
- Patient Protection Events *327*
- Child and Adult Safeguarding *328*
- Teamwork *328*
- Patient Transfers *328*
- Medication Errors *329*
- Airway Complications *330*
- Healthcare-associated Infections *330*
- Hand Hygiene *330*

Index 335

CHAPTER

19

Perioperative ECMO Support: A Primer for Anesthetists

Ujwal Dhundi, Praveen Kumar G, Vivek Kakar

ABSTRACT

Following decades of technological innovation and clinical improvements in critical care practice, extracorporeal membrane oxygenation (ECMO) is not only saving the lives of patients with refractory respiratory and/or cardiac failure but also allowing our surgical (and interventional) colleagues to spread their wings and take on cases that were previously deemed either technically impractical or clinically very high risk.

The critical care physicians in tertiary ECMO centers have already taken the lead in developing their ECMO programs; its increasing use de novo in the operating rooms (ORs) necessitates that the anesthesiologists involved in these cases also become familiar with ECMO. ECMO is a complex therapy with steep learning curves and multiple potential complications. Therefore, hospitals should implement formal training programs for ECMO specialists and regular mechanisms of maintaining skills in each area where they will be used.

Keywords: Extracorporeal membrane oxygenation; Perioperative ECMO; ECMO for anesthetists

KEY POINTS

- Extracorporeal membrane oxygenation (ECMO) is being used for an increasing number of indications in operating rooms (Ors), for complex procedures, and procedures on high-risk patients.
- Patients already on ECMO in critical care may also need elective or emergent procedures in OR/catheterization laboratory (Cath Lab).
- Anesthesiologists must become familiar with ECMO, seek formal training, and lead the perioperative planning and management of patients undergoing these procedures.
- ECMO is a complex and resource-intensive therapy, and close multidisciplinary coordination is essential at every stage to limit complications and achieve the best outcomes.

INTRODUCTION

Extracorporeal membrane oxygenation has existed for over 50 years, but its use in the adult population has risen sharply over the past two decades. In addition to the traditional indications such as acute and acute-on-chronic cardiac and or respiratory failure, there is an ever-growing list of other scenarios where its use has been reported, including complex or high-risk procedures in the OR and Cath Lab. Several centers

JAYPEE BROTHERS

initiate ECMO in the OR, and patients already established on ECMO may also need to visit the OR for planned or emergent procedures. Therefore, the modern anesthetist must be well-versed with the fundamental principles of ECMO, familiar with the equipment, and trained in timely and effective troubleshooting. In addition, they must also be familiar with the nuances of perioperative management of ECMO patients.

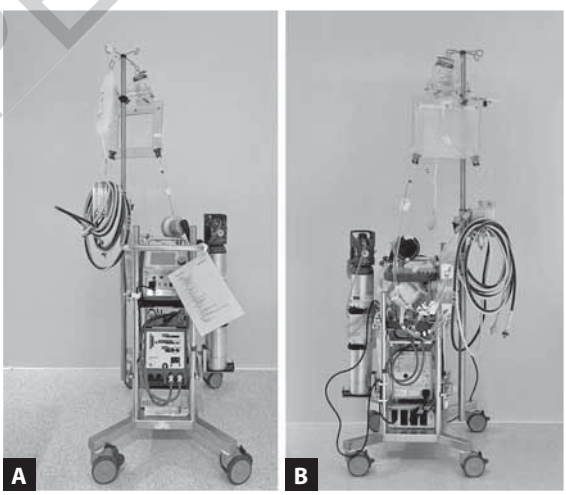
EXTRACORPOREAL MEMBRANE OXYGENATION FUNDAMENTALS

What is ECMO?

Extracorporeal Membrane Oxygenation, or extracorporeal life support (ECLS), is a life-saving therapy that can support patients with advanced respiratory failure or cardiogenic shock, refractory to conventional medical management. It is similar to the traditional cardiopulmonary bypass machine used by cardiothoracic surgeons in the OR for decades. Still, technological advancements have allowed it to be packaged into a miniaturized and yet sophisticated form **(Figs. 1A and B)**, and the advancements in various fields of medicine have allowed it to be safely used at the bedside for longer durations.[1]

Brief History

Development of ECMO began once significant technical and clinical advancements were made in the field of cardiopulmonary bypass.[2] ECMO use in adults was first reported in a polytrauma patient in 1971,[3] and even after a United States National Institute of Health (NIH) funded randomized controlled trial that followed failed to show any benefit[4] enthusiasm for demonstrating the perceived benefits of this therapy continued with further studies.[5] The clinical practices and technology available then differed significantly from today, e.g., mechanical ventilation, anticoagulation, etc. Over the past five decades, the technology and the materials used for ECMO have continually evolved. The cannulae are coated with biologically inert substances that resist activation of the coagulation and inflammation pathway; centrifugal pumps



Figs. 1A and B: Modern extracorporeal membrane oxygenation (ECMO) machine.

JAYPEE BROTHERS

that are magnetically levitated and less traumatic to blood cells; and integrated multi-parameter monitoring despite a more compact physical form factor have made ECMO much safer.[6] Clinical care of ECMO patients has also improved over the same period with safer ventilatory management,[7,8] safer anticoagulation protocols with the availability of point-of-care testing,[9] and an overall improvement in critical care standards.[10] Ultrasound-guided percutaneous cannulation, better anticoagulation protocols, more accessible ECMO training, the ability to safely rehabilitate patients, and the possibility of bridging select patient groups to destination devices or therapies have also contributed to better outcomes.

The CESAR (Conventional ventilation or ECMO for Severe Adult Respiratory failure) trial that pitched venovenous ECMO (VV ECMO) against the prevalent standard of care for patients with acute respiratory distress syndrome (ARDS) recruited 90 patients in each arm across the participating centers in the United Kingdom (UK) and demonstrated a 16% absolute risk reduction in mortality for patients referred to an ECMO center.[11] Its findings were immediately validated by observational data published during the flu pandemic.[12] Even though the EOLIA trial published in 2019[13] could not reproduce the results of the CESAR trial, this has not dulled the enthusiasm for VV ECMO, as evidenced by the number of ECMO centers and annual ECMO runs that have grown significantly since 2009.[14] While the excitement for VV ECMO has also increased the use of venoarterial ECMO (VA ECMO) for patients with cardiogenic shock, several recent trials have failed to show significant benefits over standard medical therapy.[15,16] VA ECMO has also been used to resuscitate patients with cardiac arrest refractory to conventional cardiopulmonary resuscitation, also referred to as extracorporeal cardiopulmonary resuscitation (ECPR). A small trial from Minnesota showed significantly improved outcomes in patients with refractory ventricular fibrillation (VF).[17] However, several other trials since then have yet to show any benefit.[18,19] Regardless, the updated American Heart Association (AHA) guidelines suggest considering ECPR in centers with access to VA ECMO and the capability to initiate it rapidly in patients with refractory cardiac arrest.[20]

ECMO Modalities

Broadly, there are two main types of ECMO: VV ECMO and VA ECMO. As the name suggests, VV ECMO draws blood out of the patients' venous system, usually the vena cava, and returns it to the venous system. It is used in patients with respiratory failure resulting in refractory hypoxia and or hypercapnic acidosis despite maximum medical therapy. VA ECMO also draws blood out of patients' venous system but returns it to the patients' arterial system, usually the aorta. VA ECMO supports patients with cardiogenic shock refractory to maximum medical therapy, although it can also support patients with combined cardiorespiratory failure. The indications for using VV ECMO and VA ECMO are shown in **Box 1 and Table 1**, respectively.

ECMO Cannulation and Configurations

Each ECMO type can achieve its goal using various cannulation strategies to access the venous and/or arterial system, also known as ECMO configurations. ECMO cannulae come in multiple sizes from different manufacturers, with various coatings to make them biologically inert, relatively, and most cannulae are wire-reinforced. The cannula used to draw the blood out of a patient is called an "access", "drainage", or

JAYPEE BROTHERS

"venous" cannula. These are usually long and wide (we use 38 cm and 55 cm lengths, up to 29 Fr in diameter), with several side holes along the length near the tip for adequate drainage. The cannula that is used to return blood to the patient is called a "return" or "arterial" cannula, and these are much shorter and thinner (we use 15 cm and 23 cm lengths, up to 21 Fr), with only a few holes at the tip of the cannula.

Venovenous ECMO can be accomplished using the following configurations:

- *Femoral-jugular VV ECMO:* The access cannula is placed in the inferior vena cava via one of the femoral veins, with the tip close to the right atrium. The return cannula is placed in the superior vena cava, accessed via one of the jugular veins.
- *Femorofemoral VV ECMO:* The access and return cannula are placed in the inferior vena cava, with the access cannula tip lower than the return cannula's tip.

BOX 1: Indications for use of venovenous extracorporeal membrane oxygenation (VV ECMO) in the operating room (OR).

Extremely difficult or impossible management of airway and ventilation:
- Tracheoesophageal fistula[21]
- Resection of airway masses
- Tracheobronchial resections
- Severe airway trauma or airway disruption
- Risk of airway obstruction[22–25]
- Large bronchopleural fistula[26]
- Complete or near complete airway occlusion with foreign body aspiration[27]
- Airway compression due to intrinsic/extrinsic compressive lesions like mediastinal masses[28]
- Severe tracheomalacia[29]

Management of the patient with underlying parenchymal lung disease:
- Complex lung resection[30]
- Peri-lung transplant surgery[31]

TABLE 1: Indications for use of venoarterial extracorporeal membrane oxygenation (VA ECMO) in the operating room (OR).

Specialty	***Procedure***	***Specific consideration***
Airway and thoracic surgery	• Major carinal resection • Complex lung resection • Risk of airway obstruction • Major tracheobronchial tree disruption in trauma[24,32]	For hemodynamic and gas exchange support during the major vessel resection or compression and risk of airway obstruction
Abdominal surgery	Resection of pheochromocytoma with refractory cardiogenic shock or malignant arrhythmia[33]	
Obstetrics	• Peripartum cardiomyopathy • Acquired cardiomyopathy • Amniotic fluid embolism • Pregnancy with pulmonary hypertension[34–36]	Insert sheaths in groins preemptively

Contd...

JAYPEE BROTHERS

Contd...

Specialty	Procedure	Specific consideration
Interventional cardiology	• TAVR • MitraClip • Ventricular tachycardia ablation[37–40]	Initiate ECMO preprocedure or insert the sheaths in the groin for rapid initiation if needed intraprocedure
Miscellaneous	• Massive pulmonary embolism • ECPR • Organ donation[41–44]	• Intraoperative resuscitation • Salvage ECMO for unstable brain dead donors, and ECMO-assisted DCD donation
Anesthetic emergencies	Malignant hyperthermia[45] Local anesthetic systemic toxicity[46] Takotsubo cardiomyopathy[47] Anaphylaxis[48] Fat embolism[49]	

(DCD: donor after circulatory death; ECPR: extracorporeal cardiopulmonary resuscitation; TAVR: transcatheter aortic valve replacement)

In both above configurations, the tips of the access and return cannula must be at least 10–15 cm apart to avoid draining the well-oxygenated blood returning to the patient's circulation back into the machine. This creates an inefficient gas exchange mechanism called recirculation, which is clinically observed by seeing both the access and return blood of similar, bright red (well-oxygenated) color. This issue is only relevant to patients on VV ECMO.

- *Jugular-bicaval VV ECMO:* Some companies have devised specially designed cannulae with access and return lumens built into a single cannula. The cannula is placed via the jugular vein (most often right), and the tip is positioned under fluoroscopy and transesophageal echocardiography (TEE) into the inferior vena cava. The return opening must be placed in the right atrium facing the tricuspid valve. The proposed benefit of this strategy is to allow better mobilization by using a single cannulation site, avoiding the lower limbs, especially in patients where rehabilitation may be the key to their overall outcomes, e.g., patients awaiting a lung transplant. Several centers routinely and safely ambulate their patients with femoral cannulations.[50]

Venoarterial ECMO can be accomplished using the following configurations:

- *Peripheral VA ECMO:* The access cannula is placed in the inferior vena cava via one of the femoral veins, and the tip is usually positioned near the right atrium. However, there is some evidence in support of advancing the tip into the superior vena cava.[51] The return cannula is placed in the descending aorta and accessed via one of the common femoral arteries. This predisposes the limb with the arterial cannulation to limb ischemia by restricting the forward flow of blood. The insertion of another smaller cannula must mitigate this problem, called the "distal perfusion cannula" (DPC) into the superficial femoral artery or the popliteal artery, toward the foot ("anterograde") or in one of the foot arteries,

JAYPEE BROTHERS

dorsalis pedis or posterior tibial, toward the heart. This cannula is fed from the oxygenated blood being returned to the patient. The flow of blood retrogradely in the aorta against the failing heart increases the left ventricular afterload. It predisposes these patients to left ventricular distension and pulmonary edema, which has been repeatedly shown to result in poor outcomes.[52] This problem can be mitigated by preemptively using a left ventricle (LV) off-loading strategy.

- However, the jury is still out on the best option [we used an intra-aortic balloon pump (IABP) for all our patients].[53] Although VA ECMO can support gas exchange, in some patients with combined cardiopulmonary failure, where the heart has started to recover but the lungs are still poorly functioning; there is the risk of poorly oxygenated blood being pumped by the recovering or recovered heart into the coronaries, upper limbs, and the brain. In contrast, the well-oxygenated blood is being supplied to the rest of the body by VA ECMO. This is also known as the Harlequin syndrome, the North–South syndrome, or differential hypoxia. Patients with peripheral VA ECMO must always have a right radial arterial line (the brachiocephalic trunk is the first vessel coming off the aorta) and cerebral oximetry in place to facilitate timely detection of this physiology. The use of the axillary artery has been reported to avoid the complications reported with femoral cannulations.[54]
- *Central VA ECMO:* Patients who develop refractory cardiogenic shock with their chest open, most often the postcardiotomy patients, failing to come off the cardiopulmonary bypass, are often continued on the operative cannulation strategy involving the biatrial access and ascending aorta return cannula, with the cannula then connected to an ECMO machine as opposed to the cardiopulmonary bypass machine. In these cases, the chest is usually left open in anticipation of myocardial recovery, allowing ECMO to be removed and the chest to be closed in a few days. However, the use of central VA ECMO for more extended periods has also been reported, with the chest closed and cannulae tunneled out either superiorly or inferiorly.[55] Increasingly, many centers are moving toward peripheral VA ECMO cannulation, even for postcardiotomy cardiogenic shock.[56]

There is good evidence of better outcomes with percutaneous cannulation compared to surgical cutdown.[57] However, in cases with severe peripheral vascular disease or small-caliber vessels, it may be advisable to get a vascular surgeon involved and consider a surgical cutdown with the placement of a cannula using a synthetic graft.[58] Whether the cannulation is achieved percutaneously, using an ultrasound-guided, Seldinger-based technique, or a surgical cutdown, it does not affect the classification of ECMO type or configuration. There has been an attempt to standardize the terminology used for types and configurations of ECMO, incorporating a choice of cannula size and site. Still, it has not become standard practice yet. A detailed discussion on this subject is beyond the scope of this chapter; the reference has been included for further reading.[59]

ECMO Circuit and Basic Physiology

All ECMO circuits have similar components and basic designs. Blood is drawn out of a patient's venous system via an access cannula, with the help of a pump, circulated the circuit through an oxygenator (or the "membrane lung") before returning to the patient's venous or arterial system. A schematic diagram of a basic ECMO circuit is shown in **Figure 2**. The pump used in most machines is centrifugal, often magnetically

JAYPEE BROTHERS

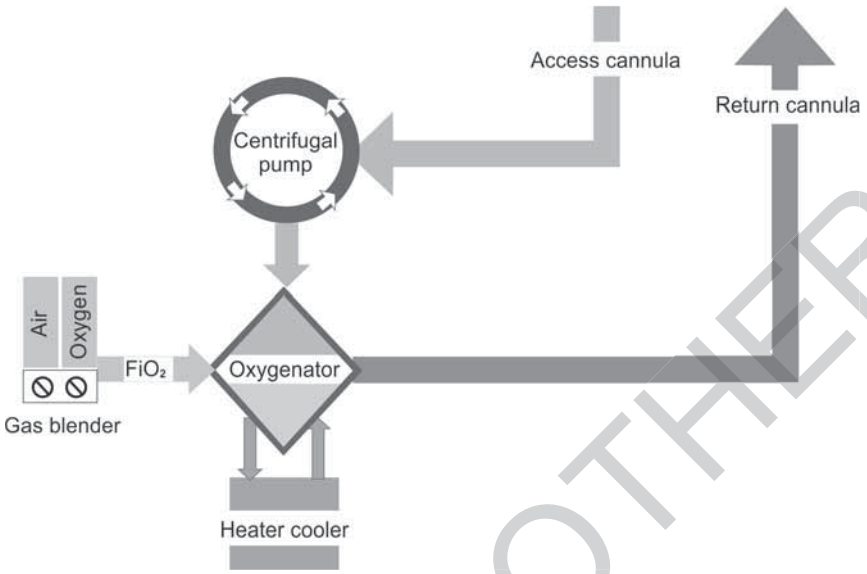


Fig. 2: Schematic diagram of a basic extracorporeal membrane oxygenation (ECMO) circuit. (FiO_2: fraction of inspired oxygen)

levitated, and hence much less traumatic to the blood cells than a roller pump used in cardiopulmonary bypass machines and some of the older ECMO machines. The oxygenator is the critical component and the basis of ECMO therapy. It is made up of tightly packed hollow fibers, most often made of polymethylpentene (PMP) that is gas permeable and participates in gas exchange and temperature regulation of the blood flowing through it, determined by the oxygen content of the gas (sweep gas) it receives from the device called the blender, and the temperature of the water that it receives from a device called the heater–cooler.

- Oxygenation depends on the blood flow rate through the oxygenator, the blood's hemoglobin content, and the sweep gas's oxygen fraction. Decarboxylation depends on the partial pressure of the carbon dioxide in the blood coming into the oxygenator and the sweep gas flow rate.[60]
- The centrifugal pump in the ECMO circuit provides hemodynamic support to the patient when the blood is returned to the aorta. The difference is that it is nonpulsatile; in the case of peripheral VA ECMO, it is retrograde, i.e., toward the heart.[61]

The oxygenator is also called the membrane lung, but compared to the native lung, which has a surface area of up to 140 m^2, the membrane lung's surface area is only up to 2 m^2.

Indications and Patient Selection

Extracorporeal membrane oxygenation is not a cure, but it helps keep patients alive, who are otherwise almost certainly looking at death, which allows time for spontaneous recovery or for procedures that may aid recovery. The indications for ECMO have continued to expand in recent years, but it is advisable to think of ECMO indication in any case using the following framework:

JAYPEE BROTHERS

- *Bridge to recovery:* ECMO in patients where there is a reasonable expectation of full or sufficient recovery that will allow separation from ECMO, e.g., bacterial or viral pneumonia leading to ARDS, viral myocarditis, or toxic exposure leading to cardiogenic shock, ECMO for patients who develop refractory cardiac arrest due to STEMI (ST-elevation myocardial infarction) but after complete revascularization (also known as ECPR), etc.
- *Bridge to definitive treatment:* ECMO may also be used in patients who can recover fully or enough to be separated from ECMO, but that may require one of the following:
  - Therapeutic procedures, e.g., valve replacement (open or percutaneous), coronary revascularization, or treatment of complications of myocardial infarction.
  - Lung and or heart transplant in patients with advanced lung and or heart disease that have already undergone necessary multidisciplinary discussion and workup and are ideally already active on the transplant list.
  - Ventricular assist device(s), either as a destination therapy or as a bridge to heart transplant.
- *Bridge to decision:* Often, the clinical situation is not as black and white as the above two scenarios, and trained clinical judgment of the multidisciplinary team may decide to proceed with ECMO even though it is not clear if recovery is possible and although no transplant workup has been done, no obvious contraindication is apparent at the time.
- *Periprocedural ECMO:* Given the increasing ease and comfort of various teams in tertiary hospitals with ECMO therapy, it is also starting to be used to facilitate an expanding set of procedures that may have previously been turned down due to prohibitive risk, e.g., transcatheter aortic valve replacement (TAVR), complex percutaneous coronary intervention (PCI), ventricular tachycardia (VT) ablation, etc. It is also used to make it easier to perform some surgical procedures, e.g., major airway tumors or trauma.

Contraindications

Patients who refuse to accept ECMO therapy and are unlikely to benefit based on the above framework should not be offered ECMO. Published reports are increasingly challenging several of the criteria previously considered absolute contraindications based on age, weight, access restrictions, suitability for anticoagulation, or willingness to accept a blood transfusion, so it largely depends on individual centers' experience and policy.

Anticoagulation

Anticoagulation is essential to prevent thromboembolic complications of ECMO therapy and is the current standard of care.[62] Patients on VA ECMO are at a greater risk of arterial thromboembolism, while VV ECMO patients have a greater incidence of venous thromboembolis.[63] Patients typically receive a 50–100 U/kg bolus dose of unfractionated heparin (UFH) at the time of cannulation, followed by an infusion targeting activated clotting time (ACT), active partial thromboplastin time (aPTT), or anti-factor Xa. Targets are higher for patients on VA ECMO (aPTT 60–80 s) than VV ECMO (40–60 s). There are several reports of patients on ECMO, specifically

JAYPEE BROTHERS

VV ECMO, where anticoagulation has had to be held for extended periods for a variety of reasons (major bleeding, neurotrauma), and patients have suffered no harm.[64] For patients with heparin-induced thrombocytopenia, argatroban or bivalirudin may be used.[65]

Weaning from ECMO

Patients are weaned off ECMO support when the underlying condition is reversed, and other organ systems also function well. This involves progressive weaning of the sweep gas flow rate and oxygen content in patients on VV ECMO[66] and weaning the blood flow rate in patients on VA ECMO.[67]

PERIOPERATIVE MANAGEMENT OF ECMO PATIENTS

As discussed, an anesthetist may interface with ECMO in procedural areas in several ways:

- ECMO initiation
- Procedures on ECMO patients
- ECMO decannulation

ECMO Initiation

Even if the patient is being cannulated for a few hours to facilitate a procedure, the same level of attention to detail, bearing in mind the following:

- Even though ECMO cannulation is an extension of the traditional Seldinger technique-based vascular access, and the expertise has been reported across several specialties, including cardiothoracic and vascular surgery, anesthesia and critical care, interventional cardiology, interventional radiology, and emergency physicians, the hospitals must specify the training and onboarding route to ECMO cannulation competency in their policy.
- The ECMO configuration will largely depend on the proposed procedure. For example, a femorofemoral VV ECMO will be more suitable for major thoracic and upper airway surgeries.
- Cannulation must be ultrasound, echocardiography, or fluoroscopy-guided; hence, these competencies must be part of the training program.
- Percutaneous cannulation should be the default approach unless otherwise indicated, e.g., severe peripheral vascular disease.
- Cannula sizes must be able to support the anticipated need based on patient size, underlying heart and or lung function, and likely complications of the planned procedure. Current recommendations for desired ECMO flow for patients receiving VV ECMO and VA ECMO are based on the fact that their underlying heart and or lungs are completely failing, and ECMO must sufficiently replace those functions, as opposed to ECMO initiation for high-risk procedures in otherwise stable patients. Most manufacturers provide a datasheet with information on flows and pressure drops across their selection of ECMO cannula, which follows the Hagen–Poiseuille Law.
- The cannulae must be adequately secured with appropriately resilient suture material at the insertion site and several anchor points along their length and covered with transparent dressings.

JAYPEE BROTHERS

- The possibility of limb ischemia must be anticipated and addressed at the outset in patients receiving peripheral VA ECMO. Patients may tolerate short procedures requiring only a small-caliber arterial cannula (15 Fr). If a bigger arterial cannula is required or if the patient has severe peripheral vascular disease, the insertion of a DPC may be necessary to prevent limb ischemia. Regardless of the selected approach, throughout the procedure, color, warmth, Doppler signals, and near-infrared spectroscopy (NIRS) should be closely monitored for the adequacy of limb perfusion.
- Occasionally, patients undergoing coronary or structural interventions in the Cath Lab or undergoing major surgeries in the OR will suddenly decompensate, e.g., coronary dissection, refractory VT/VF, pulmonary embolism, etc. Hospitals should have a policy on escalation of such cases appropriately to their "Shock Teams" and set criteria for determining candidacy for mechanical circulatory support (MCS).
- ECMO in patients with refractory cardiac arrest poses several unique challenges, a discussion that is outside the scope of this chapter.

Procedures on ECMO Patients

Preoperative Assessment and Planning

Standard preoperative assessment and planning applies as much to these patients, with perhaps more attention to detail. The perioperative plan must be collaboratively developed and shared with the entire team, which includes the proceduralist, anesthetist, critical care physician, perfusionist, and OR nurses. The team and plan will depend on whether the patient is receiving ECMO in the OR, e.g., high-risk TAVR, or is already on ECMO in intensive care unit (ICU) and needs to undergo a procedure in the OR, e.g., laparotomy for bowel ischemia.

The following should be established:

- Roles and responsibilities
- The ECMO plan includes the cannulation, configuration, estimated flow requirements, anticoagulation, relevant intraoperative considerations, and a postoperative plan for ECMO decannulation. It should be clear if ECMO will be needed from the outset or if it will be used only in the event of complications.
- Management of non-ECMO support in the perioperative period
- Goals of care and limits of escalation, which may include a review of the patient's comorbidities, baseline functional status, the severity of the current condition for which several outcome prediction scores may be used, and the patient's current or previously expressed wishes. It should also discuss the action plan if the patient deteriorates before the proposed procedure. Would they be an ECMO candidate as a bridge to the procedure?

Intraoperative Care

- *Patient transfer:* Elective patients will present themselves to the OR. Still, the ECMO patients in the ICU must be transferred to the OR with appropriate staff and support according to the hospital policy, which should also include pre- and post-transfer safety checklists.
- *Anesthesia and analgesia:* Patients with VV ECMO may have very low minute ventilation, either due to underlying lung disease, e.g., severe ARDS, or due to

JAYPEE BROTHERS

lack of ventilation for extended periods during major thoracic procedures, and patients on VA ECMO will have a significant proportion of blood flow bypass the lung. The efficacy of inhalational anesthesia and its titration may be challenging; hence, total intravenous anesthesia is prudent for patients undergoing ECMO procedures. ECMO adds 800–1,500 mL to the volume of distribution. The highly lipid-soluble and protein-bound drugs also have more significant sequestration in the ECMO circuit and often require higher doses, e.g., propofol, fentanyl, midazolam, dexmedetomidine, etc.[68-72] Neuromuscular blockers may have reduced clearance due to organ dysfunction, common in patients with ECMO.

- *Antibiotics:* Cephalosporins are the commonly used antibiotics for surgical prophylaxis, and their clearance is minimally affected by ECMO. They can be used in the usual doses for critically ill patients. Vancomycin has similar pharmacokinetics, but its clearance may be decreased in these patients, and the dosing interval should be adjusted. It is more prudent to have therapeutic drug monitoring in this situation.[73-76]
- *ECMO management:* The ECMO-specific management for both VA and VV ECMO patients is summarized in **Table 2**. Changes to ECMO blood flows significantly impact hemodynamics and biventricular function, so any adjustment to pharmacological support should coordinate with the changes to the ECMO settings. Likewise, changes to ECMO sweep gas flow rate, and fraction of inspired oxygen (FiO_2) can rapidly impact gas exchange, so such changes must be coordinated with any changes to the mechanical ventilation settings.

TABLE 2: Balancing extracorporeal membrane oxygenation (ECMO) versus non-ECMO support in operating room (OR).

	VA ECMO	***VV ECMO***
Hemodynamics	• ECMO blood flow (EBF) directly influences the hemodynamic parameters (MAP, CVP, PAP) • EBF requirements will be higher in patients with cardiogenic shock and or higher body mass compared to those undergoing elective procedures in OR • Flows should be titrated to MAP and perfusion endpoints, e.g., lactate, MvO_2, etc., and appropriate targets must be reviewed by the team on a case-by-case basis	• ECMO Blood Flow (EBF) has no impact on the hemodynamics of a patient on VV ECMO • Patients with end-stage lung disease or severe ARDS may have varying degrees of pulmonary hypertension, which may be sensitive to hypoxia, hypercapnia, and or acidosis. Worsening pH will impact the biventricular function and systemic hemodynamics • VV ECMO flows should target to 60% of the patient's cardiac output to maintain adequate oxygenation • For patients who require extracorporeal CO_2 removal, lower ECMO flows can be tolerated

Contd...

JAYPEE BROTHERS

Contd...

	VA ECMO	*VV ECMO*
Gas exchange	• ECMO sweep gas adjustments can help with gas exchange • Sweep gas FiO_2 will influence the oxygenation, while the sweep gas flow rate will influence the carbon dioxide clearance • Patients with recovering or only moderately impaired LV but a diseased lung will be at risk of Harlequin syndrome, which should be monitored using ABGs from the right radial arterial line and cerebral NIRS monitoring, and the ventilator may also need to be optimized as needed	• Every ECMO setting influences the gas exchange • Sweep gas FiO_2 and EBF will influence the oxygenation, while the sweep gas flow rate will influence the carbon dioxide clearance • EBF that is at least two-thirds of the patient's native cardiac output will ensure oxygen saturation in 90 s (%) • Patients with normal lungs undergoing elective procedures will contribute significantly to gas exchange, so any changes with ECMO settings may amplify the impact on gas exchange, therefore the anesthetist and perfusionist must jointly review ABGs and agree on any changes to the ventilator and or ECMO
	All patients should receive protective lung ventilation with plateau pressure ≤25 cmH_2O, driving pressure ≤15 cmH_2O, tidal volumes ≤6 mL/kg predicted IBW, and individually titrated PEEP	

(ABG: arterial blood gases; ARDS: acute respiratory distress syndrome; CVP: central venous pressure; FiO_2: fraction of inspired oxygen; IBW: ideal body weight; LV: left ventricle; MAP: mean arterial blood pressure; MvO_2: mixed venous oxygen saturation; NIRS: near-infrared spectroscopy; PAP: pulmonary artery pressure; PEEP: positive end-expiratory pressure; VA ECMO: venoarterial ECMO; VV ECMO: venovenous ECMO)

The teams managing the patient and ECMO must maintain good, closed-loop communication throughout the procedure.

- *Anticoagulation:* As discussed, anticoagulation may be safely withheld in many ECMO patients for extended periods, provided a reasonable ECMO flow rate is maintained, especially in VA ECMO [greater than 3–3.5 LPM (liter per minute)]. Discussion of the need for withholding anticoagulation should be a part of the preoperative planning, and the potential thromboembolic risk versus risk of bleeding during the surgery should be considered. In patients with heparin-induced thrombocytopenia, the thromboembolic risk is much higher in the absence of anticoagulation. Still, the bleeding risk is also much higher if the decision is made to continue anticoagulation with direct thrombin inhibitors during the surgery. Likewise, patients with existing thrombi, e.g., in the inferior vena cava or the ventricles, may require careful discussion of the risks involved. Therefore, decisions on anticoagulation must be made on a case-by-case basis. Where the decision has been made to withhold anticoagulation, heparin may be

JAYPEE BROTHERS

stopped 6 hours before the scheduled procedure. It is usually sufficient to prevent direct thrombin inhibitors for 6 hours before the surgery but may require longer if there is significant hepatic and or renal dysfunction. Anticoagulation is best monitored intraoperatively using ACT, complemented by frequent viscoelastic assessment [thromboelastography (TEG), rotational thromboelastometry (ROTEM)].

- *ECMO-specific monitoring:* Standard monitoring per the latest guidelines must be used in all ECMO patients, which should be sufficient for all patients on VV ECMO. For patients on VA ECMO, you also need to consider the following.
  - *Right radial arterial line:* The earliest evidence of Harlequin syndrome will be evident from a significant drop in partial pressure of oxygen (pO_2) in the right subclavian (therefore, the right radial). This is more likely in patients with reasonably functioning LVs undergoing major thoracic procedures on VA ECMO.
  - *NIRS:* A pair should always be applied to the forehead and calves. The forehead reading helps detect Harlequin SYNDROME or another sudden global cerebral event in time. The readings from the pads applied to calves can be used to monitor leg perfusion in patients with VA ECMO, both on the side of arterial cannulation and the contralateral side where an IABP or Impella may have been inserted.
  - Based on mechanical ventilator settings, the end-tidal CO_2 monitor may read lower than expected, as pulmonary blood flow is reduced and most gas exchange occurs at the oxygenator.
  - *Cardiac output monitoring:* A Swan–Ganz catheter is routinely used in patients on VA ECMO to monitor hemodynamics and biventricular function, titration of therapy continuously, and during ECMO weaning. Pulmonary artery catheter (PAC) insertion in VA ECMO patients may be challenging as much of the blood is diverted toward ECMO. Thermodilution measurements are not validated in ECMO, primarily if the thermal filament lies across the tricuspid valve as the injectate is unreliably distributed between the pulmonary artery and the ECMO cannula.[77]
  - Fick's estimate of cardiac output is also inaccurate, as gas exchange occurs both at the oxygenator and the lungs. Thermodilution and Fick's method can render an error of as high as 3 LPM if the ECMO flows are high.[78]
  - Mixed venous oxygen saturation from PACs may be a valuable target for monitoring.

ECMO Troubleshooting

To ensure a consistent and systematic approach to all troubleshooting scenarios. Even though perfusionists will be at hand to help navigate any ECMO emergencies, all ECMO specialists should have access to troubleshooting protocols and undergo periodic refresher training for individual technical skills in a simulated team environment (role allocation, team dynamics, communications). **Table 3** gives a summary of standard alarms and recommended actions.

ECMO Decannulation

The strategy for decannulation will depend on the ECMO modality and indication. For patients receiving ECMO in the OR for high-risk surgeries, the decision on the

JAYPEE BROTHERS

timing of decannulation should be a part of the preoperative plan. This may include decannulation by the surgeon or proceduralist at the end of the procedure or transfer to the ICU on ECMO for observation. Patients may sometimes be extubated before

TABLE 3: Basic extracorporeal oxygenation (ECMO) troubleshooting.

Alarm/scenario	*Possible causes*	*Management*
Low venous pressure, or access line chattering/ chugging	• Hypovolemia • Access cannula malposition • Access cannula kink • High intrathoracic pressure, e.g., tension pneumothorax, repeated coughing and straining, etc. • Cardiac tamponade • Flows too high relative to cannula size	• Reduce EBF until line chugging or chattering stops • Confirm and address the etiology, e.g., reposition the cannula, fluid bolus, insert bigger cannula, etc.
High pre-membrane pressure	Clots in the oxygenator or at the oxygenator inlet	• Inspect the oxygenator for clots • Check for signs of intravascular hemolysis (platelets, PF-Hb) • Check oxygenator function (pre-/post-oxygenator ABGs) • Cut in a new oxygenator
High post-membrane Pressure	• Return line kink • High systemic arterial pressures (in VA ECMO)	• Remove any kink in the return line • Reduce ECMO flows or control elevated systemic arterial pressure (VA ECMO)
Gas failure	• Oxygen tank empty • Gas tubing disconnected	• Replace the oxygen tank or connect to the wall supply • Reconnect the gas tubing
Pump failure	• Mechanical failure • Power failure	• Check power supply connection • Use the hand-crank to maintain the EBF • Cut in a new pump or switch to the backup ECMO machine
Air bubble detected	Air entrainment in the circuit, e.g., open line ports (CVC, PAC, CRRT, etc.), cracked circuit tubing, damaged ECMO membrane, etc.	• Visually inspect the entire circuit for evidence of air • Use the machine-specific steps for de-airing the circuit • If a large volume of air is entrained, cut in a new oxygenator or switch to the backup machine

(CVC: central venous catheter; CRRT: continuous renal replacement therapy; PAC: pulmonary artery catheter; PF-Hb: plasma-free hemoglobin)

JAYPEE BROTHERS

ECMO is gradually weaned off, e.g., major airway repair. Patients on VV ECMO can be safely decannulated by critical care physicians at the bedside with purse-string sutures for hemostasis followed by close observation for 24 hours. Although patients with peripheral VA ECMO are conventionally decannulated in the OR and undergo an open repair of the cannulated artery, anecdotal use of newer percutaneous closure devices suggests that they are probably superior to manual pressure,[79] even surgical decannulation. Still, enough data is not available to make a firm recommendation.

Since the decannulation of VA ECMO occurs in the OR and involves a transition of care from ICU to anesthesia, the OR teams must be familiar with the process of weaning and potential challenges. A patient's weaning readiness must be determined collectively by the ICU and other members of the shock team (heart failure, interventional cardiology, cardiac surgery). Patients are weaned by progressively reducing ECMO blood flow rate while closely monitoring the invasive systemic and pulmonary hemodynamics [central venous pressure (CVP), pulmonary artery pressure (PAP), cardiac output], perfusion indices (mixed venous saturation, lactate), and echocardiographic indices [right ventricle (RV) and LV ejection fraction (EF), left ventricular outflow tract (LVOT), velocity time integral (VTI)], and adjusting the pharmacological support to optimize these parameters. The challenges often arise from the fact that the ECMO blood flow rate cannot be lowered below or maintained below a certain level for long periods without increasing thromboembolic risk, and any delays between deemed decannulation readiness and subsequent transfer to OR for decannulation increase the likelihood of failure. Patients with VA ECMO are older and more fragile than VV ECMO patients; they will often have multi-organ failure in various stages of recovery, and several patients will need to come off on at least moderate support with multiple agents so expectations must be aligned between the critical care and OR team.

CONCLUSION

The rapidly evolving technology, standardized, evidence-based guidelines, and growing clinical expertise with ECMO and its various indications within critical care are also encouraging its use perioperatively to facilitate an increasing number of procedures that would have been declined previously on the grounds of the complexity of the procedure or the fragility of the patient. Even if patients receive ECMO only for a few hours in a procedural area, several challenges and complications may still occur, requiring attention to detail throughout. All OR staff who attend to ECMO patients must have a similar level of training and experience with all aspects of ECMO care, supported by simulation and practical refresher sessions completed at least twice a year. At the dawn of an era where ECMO is continually redefining what is feasible surgically, and it is likely to become an integral part of the OR skillset, anesthetists should prepare themselves adequately to embrace that future.

REFERENCES

1. Kakar V, North A, Bajwa G, Raposo N, Kumar PG. Long Runs and Higher Incidence of Bleeding Complications in COVID-19 Patients Requiring Venovenous Extracorporeal Membrane Oxygenation: A Case Series from the United Arab Emirates. Indian J Crit Care Med Peer-Rev Off Publ Indian Soc Crit Care Med. 2021;25(12):1452-8.
2. Hessel EA 2nd. A Brief History of Cardiopulmonary Bypass. Semin Cardiothorac Vasc Anesth. 2014;18(2):87-100.

JAYPEE BROTHERS

3. Hill JD, O'Brien TG, Murray JJ, Dontigny L, Bramson ML, Osborn JJ, et al. Prolonged extracorporeal oxygenation for acute post-traumatic respiratory failure (shock-lung syndrome). Use of the Bramson membrane lung. N Engl J Med. 1972;286(12):629-34.
4. Zapol WM, Snider MT, Hill JD, Fallat RJ, Bartlett RH, Edmunds LH, et al. Extracorporeal membrane oxygenation in severe acute respiratory failure. A randomized prospective study. JAMA. 1979;242(20):2193-6.
5. Morris AH, Wallace CJ, Menlove RL, Clemmer TP, Orme JF, Weaver LK, et al. Randomized clinical trial of pressure-controlled inverse ratio ventilation and extracorporeal CO_2 removal for adult respiratory distress syndrome. Am J Respir Crit Care Med. 1994;149(2 Pt 1):295-305.
6. Betit P. Technical Advances in the Field of ECMO. Respir Care. 2018;63(9):1162-73.
7. Brower RG, Lanken PN, MacIntyre N, Matthay MA, Morris A, Ancukiewicz M, et al. National Heart, Lung, and Blood Institute ARDS Clinical Trials Network. Higher versus lower positive end-expiratory pressures in patients with the acute respiratory distress syndrome. N Engl J Med. 2004 Jul;351(4):327-36.
8. Amato MBP, Meade MO, Slutsky AS, Brochard L, Costa ELV, Schoenfeld DA, et al. Driving Pressure and Survival in the Acute Respiratory Distress Syndrome. N Engl J Med. 2015;372(8):747-55.
9. Rajsic S, Breitkopf R, Jadzic D, Popovic Krneta M, Tauber H, Treml B. Anticoagulation Strategies during Extracorporeal Membrane Oxygenation: A Narrative Review. J Clin Med. 2022;11(17):5147.
10. Vincent JL. Critical care--where have we been and where are we going? Crit Care. 2013;17Suppl 1(Suppl 1):S2.
11. Peek GJ, Mugford M, Tiruvoipati R, Wilson A, Allen E, Thalanany MM, et al. Efficacy and economic assessment of conventional ventilatory support versus extracorporeal membrane oxygenation for severe adult respiratory failure (CESAR): a multicentre randomised controlled trial. The Lancet. 2009;374(9698):1351-63.
12. Australia and New Zealand Extracorporeal Membrane Oxygenation (ANZ ECMO) Influenza Investigators; Davies A, Jones D, Bailey M, Beca J, Bellomo R, Blackwell N, et al. Extracorporeal Membrane Oxygenation for 2009 Influenza A(H1N1) Acute Respiratory Distress Syndrome. JAMA. 2009;302(17):1888-95.
13. Combes A, Hajage D, Capellier G, Demoule A, Lavoué S, Guervilly C, et al.; EOLIA Trial Group, REVA, and ECMONet. Extracorporeal Membrane Oxygenation for Severe Acute Respiratory Distress Syndrome. N Engl J Med. 2018;378(21):1965-75.
14. Extracorporeal Life Support Organization. ELSO Annual Report 2023. Available from https://www.elso.org/aboutus/annualreport/annualreport2023.aspx [Last accessed July, 2024].
15. Ostadal P, Rokyta R, Karasek J, Kruger A, Vondrakova D, Janotka M, et al. ECMO-CS Investigators. Extracorporeal Membrane Oxygenation in the Therapy of Cardiogenic Shock: Results of the ECMO-CS Randomized Clinical Trial. Circulation. 2023;147(6):454-64.
16. Banning AS, Sabaté M, Orban M, Gracey J, López-Sobrino T, Massberg S, et al. Venoarterial extracorporeal membrane oxygenation or standard care in patients with cardiogenic shock complicating acute myocardial infarction: the multicentre, randomised EURO SHOCK trial. EuroIntervention. 2023;19(6):482-92.
17. Yannopoulos D, Bartos J, Raveendran G, Walser E, Connett J, Murray TA, et al. Advanced reperfusion strategies for patients with out-of-hospital cardiac arrest and refractory ventricular fibrillation (ARREST): a phase 2, single centre, open-label, randomised controlled trial. Lancet. 2020;396(10265):1807-16.
18. Belohlavek J, Smalcova J, Rob D, Franek O, Smid O, Pokorna M, et al.; Prague OHCA Study Group. Effect of Intra-arrest Transport, Extracorporeal Cardiopulmonary

JAYPEE BROTHERS

Resuscitation, and Immediate Invasive Assessment and Treatment on Functional Neurologic Outcome in Refractory Out-of-Hospital Cardiac Arrest: A Randomized Clinical Trial. JAMA. 2022;327(8):737-47.
19. Suverein MM, Delnoij TSR, Lorusso R, Brandon Bravo Bruinsma GJ, Otterspoor L, Elzo Kraemer CV, et al. Early Extracorporeal CPR for Refractory Out-of-Hospital Cardiac Arrest. N Engl J Med. 2023;388(4):299-309.
20. Richardson ASC, Tonna JE, Nanjayya V, Nixon P, Abrams DC, Raman L, et al. Extracorporeal Cardiopulmonary Resuscitation in Adults. Interim Guideline Consensus Statement From the Extracorporeal Life Support Organization. ASAIO J. 2021;67(3):221-8.
21. Van Drumpt AS, Kroon HM, Grüne F, van Thiel R, Spaander MCW, Wijnhoven BPL, et al. Surgery for a large tracheoesophageal fistula using extracorporeal membrane oxygenation. J Thorac Dis. 2017;9(9):E735-8.
22. Zhou R, Liu B, Lin K, Wang R, Qin Z, Liao R, et al. ECMO support for right main bronchial disruption in multiple trauma patient with brain injury—a case report and literature review. Perfusion. 2015;30(5):403-6.
23. Lang G, Ghanim B, Hötzenecker K, Klikovits T, Matilla JR, Aigner C, et al. Extracorporeal membrane oxygenation support for complex tracheo-bronchial procedures†. Eur J Cardiothorac Surg. 2015;47(2):250-6.
24. Kim JJ, Moon SW, Kim YH, Choi SY, Jeong SC. Flexible bronchoscopic excision of a tracheal mass under extracorporeal membrane oxygenation. J Thorac Dis. 2015;7(3):E54-57.
25. Lei J, Su K, Li XF, Zhou YA, Han Y, Huang LJ, et al. Ecmo-assisted carinal resection and reconstruction after left pneumonectomy. J Cardiothorac Surg. 2010;5(1):89.
26. Odish MF, Yang J, Cheng G, Yi C, Golts E, Madani M, et al. Treatment of Bronchopleural and Alveolopleural Fistulas in Acute Respiratory Distress Syndrome With Extracorporeal Membrane Oxygenation, a Case Series and Literature Review. Crit Care Explor. 2021;3(5):e0393.
27. Park AH, Tunkel DE, Park E, Barnhart D, Liu E, Lee J, et al. Management of complicated airway foreign body aspiration using extracorporeal membrane oxygenation (ECMO). Int J Pediatr Otorhinolaryngol. 2014;78(12):2319-21.
28. Ramanathan K, Leow L, Mithiran H. ECMO and adult mediastinal masses. Indian J Thorac Cardiovasc Surg. 2021;37(S2):338-43.
29. Carlson SF, Smith NJ, Joyce LD, Joyce DL, Rossi PJ. Acquired tracheomalacia due to aortic aneurysm managed with venopulmonary extracorporeal membrane oxygenation for perioperative support. J Vasc Surg Cases Innov Tech. 2021;7(4):737-40.
30. Suk P, Šrámek V, Čundrle I Jr. Extracor gery. Membranes (Basel). 2021;11(6):416.
31. Mason DP, Thuita L, Nowicki ER, Murthy SC, Pettersson GB, Blackstone EH. Should lung transplantation be performed for patients on mechanical respiratory support? The US experience. J Thorac Cardiovasc Surg. 2010;139(3):765-773.e1.
32. Rinieri P, Peillon C, Bessou JP, Veber B, Falcoz PE, Melki J, et al. National review of use of extracorporeal membrane oxygenation as respiratory support in thoracic surgery excluding lung transplantation. Eur J Cardiothorac Surg. 2015;47(1):87-94.
33. Dang Van S, Hamy A, Hubert N, Fouquet O. Cardiogenic shock induced by a voluminous phaeochromocytoma rescued by concomitant extracorporeal life support and open left adrenalectomy. Eur J Cardiothorac Surg. 2016;50(4):782-3.
34. Tincrès F, Conil JM, Crognier L, Rouget A, Georges B, Ruiz S. Veno-arterial extracorporeal membrane oxygenation in a case of amniotic fluid embolism with coexisting hemorrhagic shock: lessons learned. Int J Obstet Anesth. 2018;33:99-100.
35. Mikami T, Kamiunten H. Emergent caesarean section under mechanical circulatory support for acute severe peripartum cardiomyopathy. J Cardiol Cases. 2018;17(6):200-3.

JAYPEE BROTHERS

36. Vitulo P, Beretta M, Martucci G, Hernandez Baravoglia CM, Romano G, Bertani A, et al. Challenge of Pregnancy in Patients With Pre-Capillary Pulmonary Hypertension: Veno-Arterial Extracorporeal Membrane Oxygenation as an Innovative Support for Delivery. J Cardiothorac Vasc Anesth. 2017;31(6):2152-5.
37. Staudacher DL, Bode C, Wengenmayer T. Severe mitral regurgitation requiring ECMO therapy treated by interventional valve reconstruction using the MitraClip. Catheter Cardiovasc Interv. 2015;85(1):170-5.
38. Mizote I, Schirmer J, Schäfer U. A case of successful Mitraclip implantation in a patient having a large coaptation gap under extracorporeal membrane oxygenation (ECMO). Catheter Cardiovasc Interv. 2018;91(4):827-30.
39. Drews T, Pasic M, Buz S, Dreysse S, Klein C, Kukucka M, et al. Elective use of femoro-femoral cardiopulmonary bypass during transcatheter aortic valve implantation. Eur J Cardiothorac Surg. 2015;47(1):24-30.
40. Baratto F, Pappalardo F, Oloriz T, Bisceglia C, Vergara P, Silberbauer J, et al. Extracorporeal Membrane Oxygenation for Hemodynamic Support of Ventricular Tachycardia Ablation. Circ Arrhythm Electrophysiol. 2016;9(12):e004492.
41. Tarzia V, Bortolussi G, Bianco R, Buratto E, Bejko J, Carrozzini M, et al. Extracorporeal life support in cardiogenic shock: Impact of acute versus chronic etiology on outcome. J Thorac Cardiovasc Surg. 2015;150(2):333-40.
42. Hollenberg SM. Cardiogenic shock. Crit Care Clin. 2001;17(2):391-410.
43. Yeh CF, Wang CH, Tsai PR, Wu CK, Lin YH, Chen YS. Use of Extracorporeal Membrane Oxygenation to Rescue Patients With Refractory Ventricular Arrhythmia in Acute Myocardial Infarction. Medicine (Baltimore). 2015;94(30):e1241.
44. Hsieh CE, Lin HC, Tsui YC, Lin PY, Lin KH, Chang YY, et al. Extracorporeal Membrane Oxygenation Support in Potential Organ Donors for Brain Death Determination. Transplant Proc. 2011;43(7):2495-8.
45. Skerritt C, Carton E. Veno-venous extracorporeal membrane oxygenation in the management of malignant hyperthermia. Br J Anaesth. 2019;122(6):e82-3.
46. Bacon B, Silverton N, Katz M, Heath E, Bull DA, Harig J, et al. Local Anesthetic Systemic Toxicity Induced Cardiac Arrest After Topicalization for Transesophageal Echocardiography and Subsequent Treatment With Extracorporeal Cardiopulmonary Resuscitation. J Cardiothorac Vasc Anesth. 2019;33(1):162-5.
47. Esnault P, Née L, Signouret T, Jaussaud N, Kerbaul F. Reverse Takotsubo cardiomyopathy after iatrogenic epinephrine injection requiring percutaneous extracorporeal membrane oxygenation. Can J Anesth. 2014;61(12):1093-7.
48. Carelli M, Seco M, Forrest P, Wilson MK, Vallely MP, Ramponi F. Extracorporeal membrane oxygenation support in refractory perioperative anaphylactic shock to rocuronium: a report of two cases. Perfusion. 2019;34(8):717-20.
49. Valchanov K, Ercole A, Fowles J, Parmar J, Gopalan D. Veno-Venous Extracorporeal Membrane Oxygenation for Fat Embolism. J Med Cases. 2014;5(9):488-90.
50. Keshavamurthy S, Bazan V, Tribble TA, Baz MA, Zwischenberger JB. Ambulatory extracorporeal membrane oxygenation (ECMO) as a bridge to lung transplantation. Indian J Thorac Cardiovasc Surg. 2021;37(Suppl 3):366-79.
51. Cove ME. Disrupting differential hypoxia in peripheral veno-arterial extracorporeal membrane oxygenation. Crit Care. 2015;19(1):280.
52. Rajagopal K. Left Ventricular Distension in Veno-arterial Extracorporeal Membrane Oxygenation: From Mechanics to Therapies. ASAIO J. 2019;65(1):1-10.
53. Lüsebrink E, Binzenhöfer L, Kellnar A, Müller C, Scherer C, Schrage B, et al. Venting during venoarterial extracorporeal membrane oxygenation. Clin Res Cardiol. 2023;112(4):464-505.

JAYPEE BROTHERS

54. Pisani A, Braham W, Brega C, Lajmi M, Provenchere S, Danial P, et al. Right axillary artery cannulation for venoarterial extracorporeal membrane oxygenation: a retrospective single centre observational study. Eur J Cardiothorac Surg. 2021;59(3):601-9.
55. Downey P, Ragalie W, Gudzenko V, Ardehali A. Ambulatory central veno-arterial extracorporeal membrane oxygenation in lung transplant candidates. J Heart Lung Transplant. 2019;38(12):1317–9.
56. Ohira S, Malekan R, Goldberg JB, Lansman SL, Spielvogel D, Kai M, et al. Axillary artery cannulation for veno-arterial extracorporeal membrane oxygenation support in cardiogenic shock. JTCVS Tech. 2021;5:62-71.
57. Danial P, Hajage D, Nguyen LS, Mastroianni C, Demondion P, Schmidt M, et al. Percutaneous versus surgical femoro-femoral veno-arterial ECMO: a propensity score matched study. Intensive Care Med. 2018;44(12):2153-61.
58. Calderon D, El-Banayosy A, Koerner MM, Reed AB, Aziz F. Modified T-Graft for Extracorporeal Membrane Oxygenation in a Patient with Small-Caliber Femoral Arteries. Tex Heart Inst J. 2015;42(6):537-9.
59. Broman LM, Taccone FS, Lorusso R, Malfertheiner MV, Pappalardo F, Di Nardo M, et al. The ELSO Maastricht Treaty for ECLS Nomenclature: abbreviations for cannulation configuration in extracorporeal life support - a position paper of the Extracorporeal Life Support Organization. Crit Care. 2019;23(1):36.
60. Bartlett RH. Physiology of Gas Exchange During ECMO for Respiratory Failure. J Intensive Care Med. 2017;32(4):243-8.
61. Fresiello L, Hermens JAJ, Pladet L, Meuwese CL, Donker DW. The physiology of venoarterial extracorporeal membrane oxygenation—a comprehensive clinical perspective. Perfusion. 2024;39(1_suppl):5S-12S.
62. McMichael ABV, Ryerson LM, Ratano D, Fan E, Faraoni D, Annich GM. 2021 ELSO Adult and Pediatric Anticoagulation Guidelines. ASAIO J. 2022;68(3):303-10.
63. Olson SR, Murphree CR, Zonies D, Meyer AD, Mccarty OJT, Deloughery TG, et al. Thrombosis and Bleeding in Extracorporeal Membrane Oxygenation (ECMO) Without Anticoagulation: A Systematic Review. ASAIO J. 2021;67(3):290-6.
64. Kurihara C, Walter JM, Karim A, Thakkar S, Saine M, Odell DD, et al. Feasibility of Venovenous Extracorporeal Membrane Oxygenation Without Systemic Anticoagulation. Ann Thorac Surg. 2020;110(4):1209-15.
65. Šoltés J, Skribuckij M, Říha H, Lipš M, Michálek P, Balík M, et al. Update on Anticoagulation Strategies in Patients with ECMO—A Narrative Review. J Clin Med. 2023;12(18):6067.
66. Vasques F, Romitti F, Gattinoni L, Camporota L. How I wean patients from veno-venous extra-corporeal membrane oxygenation. Crit Care. 2019;23(1):316.
67. Fried JA, Masoumi A, Takeda K, Brodie D. How I approach weaning from venoarterial ECMO. Crit Care. 2020;24(1):307.
68. Shekar K, Fraser JF, Smith MT, Roberts JA. Pharmacokinetic changes in patients receiving extracorporeal membrane oxygenation. J Crit Care. 2012;27(6):741.e9-18.
69. Shekar K, Roberts JA, Ghassabian S, Mullany DV, Ziegenfuss M, Smith MT, et al. Sedation during extracorporeal membrane oxygenation-why more is less. Anaesth Intensive Care. 2012;40(6):1067-9.
70. Shekar K, Roberts JA, Mcdonald CI, Fisquet S, Barnett AG, Mullany DV, et al. Sequestration of drugs in the circuit may lead to therapeutic failure during extracorporeal membrane oxygenation. Crit Care. 2012;16(5):R194.
71. Shekar K, Roberts JA, Mullany DV, Corley A, Fisquet S, Bull TN, et al. Increased sedation requirements in patients receiving extracorporeal membrane oxygenation for respiratory and cardiorespiratory failure. Anaesth Intensive Care. 2012;40(4):648-55.
72. Nigoghossian CD, Dzierba AL, Etheridge J, Roberts R, Muir J, Brodie D, et al. Effect of Extracorporeal Membrane Oxygenation Use on Sedative Requirements in Patients with Severe Acute Respiratory Distress Syndrome. Pharmacotherapy. 2016;36(6):607-16.

JAYPEE BROTHERS

73. Shekar K, Fraser JF, Taccone FS, Welch S, Wallis SC, Mullany DV, et anl.; ASAP ECMO Study Ivestigators. The combined effects of extracorporeal membrane oxygenation and renal replacement therapy on meropenem pharmacokinetics: a matched cohort study. Crit Care. 2014;18(6):565.
74. Donadello K, Antonucci E, Cristallini S, Roberts JA, Beumier M, Scolletta S, et al. β-Lactam pharmacokinetics during extracorporeal membrane oxygenation therapy: a case-control study. Int J Antimicrob Agents. 2015;45(3):278-82.
75. Cheng V, Abdul-Aziz MH, Burrows F, Buscher H, Cho YJ, Corley A, et al. ASAP ECMO Investigators. Population Pharmacokinetics of Vancomycin in Critically Ill Adult Patients Receiving Extracorporeal Membrane Oxygenation (an ASAP ECMO Study). Antimicrob Agents Chemother. 2022;66(1):e0137721.
76. Mulla H, Pooboni S. Population pharmacokinetics of vancomycin in patients receiving extracorporeal membrane oxygenation. Br J Clin Pharmacol. 2005;60(3):265-75.
77. Su Y, Liu K, Zheng JL, Li X, Zhu DM, Zhang Y, et al. Hemodynamic monitoring in patients with venoarterial extracorporeal membrane oxygenation. Ann Transl Med. 2020;8(12):792.
78. Ortoleva JP, Alfadhel A, Dalia AA. Invasive Hemodynamic and Physiologic Considerations in Patients Undergoing Extracorporeal Membrane Oxygenation. J Cardiothorac Vasc Anesth. 2021;35(9):2549-51.
79. Scherer C, Stremmel C, Lüsebrink E, Stocker TJ, Stark K, Schönegger C, et al. Manual Compression versus Suture-Mediated Closure Device Technique for VA-ECMO Decannulation. J Interv Cardiol. 2022;2022:9915247.

JAYPEE BROTHERS

for detailed information on anesthesia books, visit our **website www.jaypeebrothers.com,** for detailed information on anesthe

Yearbook *of* Anesthesiology 14

The *Yearbook of Anesthesiology* remains the most popular and sought-after update book for Anesthesiologists and students of Anesthesiology and Critical Care. The book's reader base has risen steadily with each succeeding edition. This 14th edition significantly focuses on contemporary anesthesia, apart from emerging technologies and new challenges. All Anesthesiology Professionals and Trainees will find the book a valuable introduction to the diverse applications of technology in health.

Like the previous editions, this edition has been scripted by international and national experts in Anesthesiology and Critical Care. It is suitable as a textbook for postgraduate training in the clinical aspects of Anesthesiology and Critical Care. Recent advances in the field have been amply covered. The book attempts to cover topics from all subspecialties of anesthesiology. It also tries to cover some futuristic areas and discusses the challenges likely to be faced by the profession of anesthesiology and critical care in the coming times.

Printed in India

Available at all medical bookstores or buy online at www.ejaypee.com

JAYPEE BROTHERS
Medical Publishers (P) Ltd.
EMCA House, 23/23-B, Ansari Road, Daryaganj, New Delhi - 110 002, INDIA
www.jaypeebrothers.com

Join us on facebook.com/JaypeeMedicalPublishers
Follow us on instagram.com/JaypeeMedicalPublishers

Shelving Recommendation
ANESTHESIA

ISBN 978-93-5696-626-0