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Ultrasound in Extracorporeal Membrane Oxygenation: An ELSO State-of-the-Art Review

Ghislaine Douflé,*† Erika R. O'Neil,‡§ Susana Abreu,¶ Nada Ali Aljassim,‖ Matteo Di Nardo,# Nchafatso G. Obonyo,**††‡‡ Valentina Pinzon,§§ Susanna Price,¶¶‖‖ Kollengode Ramanathan,##*** and Martin Balik†††

Ultrasound has become indispensable in the management of patients supported with extracorporeal membrane oxygenation (ECMO), enabling rapid diagnosis, procedural guidance, physiologic monitoring, and informed decision-making across the entire ECMO continuum. This review, conducted under the auspices of the Extracorporeal Life Support Organization (ELSO), provides evidence-based recommendations for the use of ultrasound in adult, pediatric, and neonatal ECMO patients. An international, multidisciplinary panel of experts with dual expertise in ECMO and ultrasound, representing all ELSO chapters, convened to define the scope and structure of the review. A comprehensive literature review identified 133 relevant publications informing recommendations. The review addresses training and competency requirements, choice of ultrasound modalities, and the role of ultrasound before ECMO initiation, during cannulation, throughout ECMO support, for troubleshooting complications, and during ECMO weaning and post-decannulation care. Pre-ECMO ultrasound is emphasized for assessment of cardiopulmonary function, vascular anatomy, and identification of contraindications or reversible conditions. Real-time ultrasound guidance is recommended for cannulation to reduce complications and confirm optimal cannula positioning. During ECMO, echocardiography and extracardiac ultrasound are central to monitoring cardiac function, cannula position, ventricular loading conditions, pulmonary pathology, neurological complications, and vascular integrity. Ultrasound-based strategies for diagnosing hypoxemia, recirculation, tamponade, ventricular distension, and limb ischemia are detailed. Finally, ultrasound plays a critical role in assessing readiness for ECMO liberation and identifying post-ECMO complications. This review highlights the pervasive role of ultrasound as a core competency in ECMO care and provides a practical framework to support safe, effective, and standardized ultrasound use across diverse ECMO programs worldwide. *ASAIO Journal* 2026; 72:85–98

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From the *Interdepartmental Division of Critical Care Medicine of the University of Toronto, Toronto, Ontario, Canada; †Department of Anesthesia and Pain Management, Toronto General Hospital, Toronto, Ontario, Canada; ‡United States Air Force, Department of Pediatrics, Brooke Army Medical Center, San Antonio, Texas; §Uniformed Services University of the Health Sciences, Bethesda, Maryland; ¶Pediatric Cardiology Department, Hospital de Santa Marta, Unidade Local de Saude São Jose, Lisboa, Portugal; ‖Pediatric Cardiovascular Unit, King Fahad Medical City, Riyadh, Saudi Arabia; #Pediatric Intensive Care Unit, Bambino Gesù Children's Hospital, IRCCS, Rome, Italy; **Critical Care Research Group and Institute for Molecular Biosciences, The University of Queensland, Brisbane, Queensland, Australia; ††Initiative to Develop African Research Leaders (IDeAL), KEMRI-Wellcome Trust Research Programme, Kilifi, Kilifi County, Kenya; ‡‡Wellcome Trust Centre for Global Health Research, Imperial College London, London, United Kingdom; §§Clínic Somer, Critical Care Medicine, Rionegro, Antioquia, Colombia; ¶¶Departments of Cardiology and Intensive Care, Royal Brompton & Harefield NHS Foundation Trust, London, United Kingdom; ‖‖National Heart & Lung Institute, Imperial College London, London, United Kingdom; ##Yong Loo Lin School of Medicine, National University of Singapore, National University Health System, Singapore; ***Cardiothoracic Intensive Care Unit, Department of Cardiac, Thoracic and Vascular Surgery, National University Heart Centre, National University Health System, Singapore; and †††Department of Anesthesiology and Intensive Care, 1st Faculty of Medicine, Charles University and General University Hospital in Prague, Czechia, EU.

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Reviewers: Nadia Aissaoui (Service de Médecine intensive-réanimation, Hôpital Cochin, Assistance Publique-Hôpitaux de Paris (AP-HP). Centre & Université Paris Cité, Paris, France), Stephanie Cha (Department of Anesthesiology & Critical Care Medicine, Johns Hopkins University School of Medicine, Baltimore, MD), Aparna Hoskote (Cardiorespiratory and Critical Care Division, Great Ormond Street Hospital for, Children National Health Service Foundation Trust, London, UK).

Correspondence: Ghislaine Douflé, Interdepartmental Division of Critical Care Medicine of the University of Toronto, Toronto, Ontario, Canada. Email: ghislaine.doufle@utoronto.ca; Erika R. O'Neil, United States Air Force, Department of Pediatrics, Brooke Army Medical Center, San Antonio, TX. Email: erika.oneil.md@gmail.com.

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Background

Ultrasound has become an integral part of critical care medicine, allowing the diagnosis of life-threatening conditions, aiding in urgent decision-making, and guiding invasive procedures. The utility of ultrasound during the management of extracorporeal membrane oxygenation (ECMO) is manifold including assessment of ECMO candidacy, pericannulation, patient monitoring while on ECMO, troubleshooting, and weaning from ECMO.

A group of international experts with experience in both ECMO and ultrasound were selected to represent all chapters of the Extracorporeal Life Support Organization (ELSO). These experts convened virtually multiple times to develop the structure and sections of this review on ultrasound use in ECMO. All authors then performed a literature search to include the most relevant publications, and ultimately 133 articles were included. The following review aim to provide evidence-based, detailed, and standardized guidance on the use of ultrasound in ECMO patients.

Training for Ultrasound in ECMO

Position statements on the organization of ECMO programs state that selected team members should be proficient in vascular and cardiac ultrasound (echocardiography) for insertion, maintenance, and weaning of ECMO.[1,2] However, since ECMO programs vary widely in terms of team members' background specialty, ultrasound training and proficiency differ from one center to the other. While in some centers, intensivists caring for the patients perform and interpret ultrasound independently using point-of-care ultrasound (POCUS), other centers rely on consulting imaging teams. Strictly speaking, POCUS encompasses a wide range of techniques performed by the treating physicians (rather than by consulting services) and can be performed within a wide range of applications from basic to advanced.[3–5] For ECMO cannulation guidance, the ability to swiftly alternate between views, awareness of the different procedural steps, and potential artifacts generated by the wires and cannulas are paramount to prevent complications. While some parameters may be assessed by individuals with basic ultrasound training, most echocardiographic parameters on ECMO require advanced training. Importantly, a minimum number of examinations performed to ensure proficiency does not guarantee competence, especially when performed without appropriate supervision; one should perform within the scope of practice delineated by their training and institutional policies.[6,7] Finally, recording and archiving of images is essential given the rapid changes that may occur on ECMO support and for ongoing education and quality assurance.[8] We therefore recommend that all ECMO centers have institutional policies that cover aspects of clinical competency, training, and record-keeping of ultrasound imaging which can be applied in the ECMO setting.

Choice of Ultrasound Modality

Both transthoracic and transesophageal echocardiography (TTE and TEE) can be performed on patients requiring ECMO. Transesophageal echocardiography in ECMO patients is proven to be safe and provides better visualization of cardiac chambers, guidewires, and cannulas.[9,10] When echogenicity is limited, contrast-enhanced ultrasound (CEUS) can improve both structural and functional assessment of both ventricles and its use is safe in ECMO patients even if contrast injection may trigger the bubble detector alarm. Transient inactivation or reset of the bubble alarm may be warranted in such a situation.[11]

Role of Ultrasound Before ECMO Initiation

A cardiopulmonary ultrasonographic examination is recommended before ECMO initiation to guide the choice of optimal configuration and exclude contraindications (*e.g.,* aortic dissection, aortic regurgitation, severe atheromatous aortic disease) or conditions for which ECMO is not indicated (*e.g.,* large pleural effusion, tensioned pneumothorax, tamponade).[12] The comprehensiveness of the pre-ECMO ultrasound will be dictated by the patient's condition but should include an assessment of biventricular morphology and function, valvular function, and vascular anatomy (Table 1).

Cardiogenic Shock in Adult and Pediatric Patients

Left ventricular (LV) systolic function quantification using the modified Simpson's method (or visual assessment if poor endocardial definition) and quantification of stroke volume (SV) and cardiac index identify potential venoarterial ECMO (VA ECMO) candidates.[13] Right ventricular (RV) dysfunction can be diagnosed by the presence of RV dilation, paradoxical septal motion with leftward shift of the septum, reduced RV longitudinal systolic function with M-Mode (tricuspid plane systolic excursion [TAPSE]) or tissue Doppler (RV S′), and decreased fractional area change (FAC).[14] Pulmonary artery pressure (PAP) can be estimated using tricuspid or pulmonary regurgitation velocity. Patients with congenital heart disease (CHD) in cardiogenic shock (CS) should be evaluated with echocardiography, but measurements are unique to this population and beyond the scope of this review. In neonates and pediatric patients, the RV can be assessed using TAPSE, RV *S*′, and FAC. For both TAPSE and RV *S*′, normal reference values are available.[15–20]

Valvular assessment is essential before initiation of VA ECMO as severe aortic regurgitation (AR) is generally a contraindication to VA ECMO and devices such as intra-aortic balloon pump (IABP) and microaxial pump (Impella), as they may worsen the AR. However, in patients in CS secondary to severe AR, left atrial venoarterial ECMO can be an option as a bridge to valvular surgery.[21,22]

Diagnosis of pathologies requiring additional surgical intervention, such as ventricular septal defect or papillary muscle rupture should also be made.

For patients in cardiac arrest undergoing ECMO during cardiopulmonary resuscitation (ECPR), ultrasound enables exclusion of reversible cardiac and noncardiac causes of arrest such as severe hypovolemia, tamponade, or pneumothorax. It may also aid in identifying electrical rhythm changes and the area of maximal compression during CPR.

Respiratory Failure in Adult and Pediatric Patients

Left-sided valvular pathology and severe ventricular dysfunction should also be excluded before venovenous (VV)

Table 1. Ultrasound Assessment Before ECMO Initiation

Parameters to Assess	Specific Conditions to Rule Out to Inform Indication and Choice of Configuration
LV size and function **LV diameter and thickness** **LVEF** (Simpson's, 3D), **LVOT VTI**, Tissue Doppler mitral annulus systolic velocity, LV strain **Cardiac index** Diastolic function (*E/A*, *E/e*', LA volume, TR velocity) **Wall motion abnormalities**	**Severe LV dysfunction**, including diastolic dysfunction (VV ECMO) **Papillary muscle rupture, interventricular septal rupture, free wall rupture** (may require additional interventions)* (VA ECMO)
RV size and function **RV size, RV end-diastolic area/LV end-diastolic are**a **RV wall thickness** **TAPSE, tricuspid** S' **velocity** **RV FAC**, RV free wall longitudinal strain **TR velocity and RVSP estimation** (if TR jet not available or massive TR: PA acceleration time or pulmonary regurgitation can be used to estimate RVSP) PA acceleration time, biphasic PA forward flow McConnell sign RV/PA coupling (e.g.,TAPSE/RVSP, RV FAC/RVSP, or TAPSE/TR velocity)	**Proximal PE and signs of chronic pulmonary hypertension** (RV hypertrophy, PA pressures >60 mm Hg, pericardial effusion) for VV ECMO
	Neonatal and pediatric Congenital heart disease; congenital aortic and mitral stenosis, coarctation, aortic arch interruption, coronary anomalies, and obstructive total anomalous pulmonary venous return
Ventricular interdependence **Paradoxical septal motion** Eccentricity index	
Valvular pathology **Left and right-sided valvular pathology (regurgitation and stenosis)**	**Significant mitral and aortic pathology** (VV ECMO) **Tricuspid and pulmonary stenosis** (VV ECMO) **Severe aortic regurgitation** (VA ECMO)
Superior and inferior vena cava morphology, size, respiratory variation, and thrombosis **For neonatal and pediatric: inferior vena cava-to-right atria continuity, left superior vena cava with a bridging vein, presence of patent duct**	
Atrial anatomy and size Prominent Eustachian valve, Chiari network Dilated coronary sinus, persistent left superior vena cava Atrial septal defect, patent foramen ovale (CFD and bubbles with agitated saline) Presence of pacemaker wires	
Intracardiac thrombi (right and left)	
Aorta	**Aortic dissection, significant atheroma, and calcifications (VA ECMO)**
Pericardial effusion	**Cardiac tamponade**
Lung ultrasound: B-lines, lung consolidation, pleural line pattern (fragmented, irregular, or thickened), pleural effusion	**Tension pneumothorax, significant pleural effusion**
Vascular ultrasound: vessel size and anatomy	**Occlusive thrombus and stenosis on vascular ultrasound**

Adapted from Douflé *et al*.[12] Key parameters appear in bold.

*These conditions are not contraindications to ECMO but need to be diagnosed as they may require additional interventions.

CFD, color flow Doppler; *E/a*, early transmitral velocity/atrial transmitral velocity; *E/e*', early transmitral velocity/tissue Doppler velocity at the mitral annulus; ECMO, extracorporeal membrane oxygenation; LA, left atrium; LV, left ventricle; LVEF, left ventricular ejection fraction; LVOT VTI, left ventricular outflow tract velocity-time integral; PA, pulmonary artery; PE, pulmonary embolism; RA, right atrium, RV, right ventricle; RV FAC, right ventricular fractional area of change; RVSP, right ventricular systolic pressure; TAPSE, tricuspid annular plane systolic excursion; TR, tricuspid regurgitation; VV ECMO, venovenous ECMO; VA ECMO, venoarterial ECMO.

ECMO initiation. Hypotension can develop secondary to severe hypoxemia and right ventricular dysfunction precipitated by altered gas exchange, acute respiratory distress syndrome (ARDS), and increased airway pressure. While the choice of configuration is usually unambiguous for patients in CS, in patients with respiratory failure and concomitant cardiac dysfunction and/or inotrope/vasopressor dependence, the choice of configuration (VV over VA ECMO) is driven by the adequacy of cardiac index (obtained by echocardiography), cardiac filling pressures, predicted reversibility of the ventricular dysfunction, and vascular size in pediatric patients. Venovenous ECMO can reduce RV afterload by decreasing

Table 2. Ultrasound Use During Cannulation

Cannulation steps using ultrasound[12,32]
1. Image both arteries and veins, for patency, anatomical abnormalities, stenosis, using long and short-axis views
2. Measure vessels (maximum cannula size in Fr [outer diameter] = 3× vessel diameter in mm). Exceptions may include smaller size patients and severe vasoconstriction
3. Ultrasound-guided vascular access
4. If cannulating the femoral artery for VA ECMO, whenever possible, one would ideally place the DPC using ultrasound first, as flow and visualization of the SFA may be significantly reduced once the return femoral cannula is in place. As the deep femoral artery is an end-artery, insertion of a DPC within it will not provide adequate leg perfusion. Ultrasound is, therefore, critical to confirm SFA cannulation.
5. Confirm wire in the vessel before dilation using TTE or TEE
   a. Reverberation artifact may falsely create the appearance of two wires in a chamber and can negatively impact the identification of the wires at greater depths.[33]
   b. The guidewire can appear blurred due to beam width and side lobe artifact.
   c. For femoral vein cannulation, confirm using a bicaval, subcostal/transhepatic view that the wire is advanced into the SVC to not perforate the right atrium. If two wires are used simultaneously, confirm two wires are visible on ultrasound.
   d. For IJ cannulation and dual-lumen bicaval cannula, confirm on bicaval view, esophagogastric IVC, or transhepatic and subcostal (longitudinal and sagittal) views that the wire is in the SVC, RA and deep into the IVC
   e. For venous cannulation, also ensure that the wire(s) is or are not in one of the hepatic veins
   f. For femoral artery cannulation, place DPC first; confirm that the wire for the return cannula is in the aorta.
   g. For RA-PA cannulation, confirm the wire is in the pulmonary artery using TEE.
6. Confirm the wire is not looped in the RA, right atrial appendage nor right ventricle
7. Perform the cannulation through serial dilations followed by cannula insertion while continuously monitoring the wires' position
8. It is important to remove the obturators before confirming the cannula tip location on ultrasound[34]
9. Confirm tips of cannulas in proper location after patient's repositioning and modification of ventilatory settings (Table 3)
   a. Refer to the manufacturer specifications for cannula lengths and locations of drainage and reinfusion ports to aid in confirming adequate location.
   b. For femoro-jugular cannulation, confirm on ultrasound that the tip of the drainage cannula is deep enough to maximize drainage and optimize the position of the return cannula to prevent clinical recirculation[12,35]
   c. For femoral-femoral VA cannulation, differential oxygenation may be improved by insertion of the drainage cannula higher, into the SVC instead of RA, which can be safely confirmed by ultrasound[36]

DPC, distal perfusion cannula; IJ, internal jugular; IVC, inferior vena cava; RA, right atrium; RA-PA, right atrium-pulmonary artery; SFA, superficial femoral artery; SVC, superior vena cava; TTE, transthoracic echocardiogram; TEE, transesophageal echocardiogram; VA ECMO, venoarterial extracorporeal membrane oxygenation; VV ECMO, venovenous extracorporeal membrane oxygenation.

pulmonary vascular resistance through improved oxygenation, decarboxylation, and less aggressive positive pressure ventilation.[23–25] Patients with ARDS and moderate to high inotropic support have similar or better survival outcomes on VV ECMO compared with VA ECMO, with fewer complications, both in pediatric and adult patients, and have a low percentage of conversion to VA ECMO (~4%).[26–29]

Additionally, patients with ARDS and acute RV failure may be at risk of differential oxygenation when placed on peripheral VA ECMO. Finally, venopulmonary ECMO (VP ECMO) has been described in ARDS-induced RV failure but data comparing VV, VA, and VP ECMO is currently lacking.[30]

Conversely, as patients with pulmonary hypertension may be insufficiently supported on VV ECMO, it is essential to identify signs of chronic RV overload such as right ventricular hypertrophy and pulmonary artery dilatation with adaptation to higher pulmonary artery pressures.[14,31]

Specific Neonatal and Pediatric Considerations

As the prevalence of CHD is higher in the neonatal and pediatric population, it is crucial to rule out CHD in patients in shock. Indeed, undiagnosed pathologies such as left-sided obstruction (aortic stenosis, mitral stenosis, aortic coarctation, aortic arch interruption), congenital coronary artery anomalies, and others (e.g., obstructive total anomalous pulmonary venous return) may present as CS.

Vascular size is a major determinant in guiding the choice of ECMO modality in children and patients with vasculopathy. Ultrasound assesses vascular diameter, patency, presence of thrombus, and anatomy (inferior vena cava-to-right atria continuity, existence of a left superior vena cava with a bridging vein, presence of patent duct). Vascular anatomy is especially important in patients with CHD as these patients have a higher incidence of vascular anomalies and obstruction (previous indwelling vascular catheters, surgeries, and cardiac catheterization).

Finally, for postcardiotomy ECMO patients, residual lesions should be searched.

Role of Ultrasound for Cannulation

The use of ultrasound is critical for percutaneous cannulations using the Seldinger technique (Table 2). Different anatomical sites can be visualized using ultrasound to determine vascular patency and size and prevent complications such as inadvertent arterial cannulation (during VV ECMO), piercing of the inguinal ligament, vascular dissection, arteriovenous fistula creation, or cardiac perforation during cannulation.[32,37]The formula: maximum cannula size in Fr (outer diameter) = 3 × vessel diameter in mm is useful to guide the choice of cannula size, although some exceptions exist, *e.g.*, severe vasoconstriction in the context of shock. Additionally, thorough assessment of atrial anatomy, specifically of the right atrium, is needed to exclude normal variants or pathologies that may hinder advancement of the cannulas (*e.g.,* prominent Chiari network, atrial thrombi). Compared to TTE, TEE provides better visualization of the wires correctly traversing the SVC and IVC and not entering the RV on the midesophageal bicaval view. Real-time visualization is needed at each step of the procedure, including guidewires' insertion, serial tissular dilation, and cannulas' insertion to promptly detect wire migration or complications.[12,38]

Table 3. Echocardiographic Views for the Most Frequent ECMO Configurations

Cannulation/Cannulas	Ultrasound Monitoring Considerations	TTE	TEE
V-A ECMO in neonates (neonatal/pediatric)[39]	- Tip of arterial cannula within the innominate artery near the aorta - Tip of venous cannula within the right atrium, remote from atrial septum	For arterial cannula: suprasternal notch window	N/A
Femoro-jugular V-V ECMO	- Tip of drainage cannula in RA[10] - Return IJ cannula within SVC or RA	- Subcostal longitudinal (4 chamber) - Subcostal bicaval sagittal view (marker at 12 o'clock) - Transhepatic view	Midesophageal bicaval view (90°± 10°)
Jugular-femoral V-V ECMO	Drainage cannula in RA and return within lower IVC[40]	Subcostal longitudinal and sagittal view (marker at 12 o'clock), transhepatic view	Midesophageal bicaval view
Femoro-femoral V-V ECMO	- Drainage cannula at the SVC-RA junction[41] - Return cannula at the mid RA level	- Subcostal longitudinal - Subcostal sagittal views - Transhepatic view	Midesophageal bicaval view
V-P ECMO with single stage return PA limb	- Tip of the cannula 2–3 cm above the pulmonary valve and not in one of the pulmonary artery branches	Parasternal and subcostal RV inflow–outflow	- Midesophageal RV inflow–outflow - Midesophageal view of pulmonary valve and PA upper esophageal view
Dual-lumen RA cannula	Tip in the RA not abutting the right atrial appendage	- Subcostal sagittal view (marker at 12 o'clock) - Subcostal 4- chamber view	Midesophageal bicaval view
Dual-lumen bicaval cannula[42]	- Infusion jet pointing at tricuspid valve using color flow Doppler - Tip of cannula within the IVC (and not within a hepatic vein) - Drainage ports in IVC and SVC	- Subcostal sagittal view (marker at 12 o'clock) - Transhepatic RA/IVC view	- Midesophageal bicaval or modified bicaval view - Esophagogastric IVC view
Dual-lumen RA-PA cannula (V-P ECMO)	- Tip of the cannula 2–3 cm above the pulmonary valve and not in one of the pulmonary artery branches Confirm drainage ports are in the RA	Parasternal and subcostal RV inflow–outflow	- Midesophageal RV inflow–outflow - Midesophageal view of pulmonary valve and PA upper esophageal view
Bicaval multistage cannula	Drainage ports in both SVC and IVC	Subcostal sagittal view (marker at 12 o'clock)	- Midesophageal bicaval - Esophagogastric IVC view
Peripheral V-A ECMO	- Tip of the drainage cannula at SVC-RA junction or above - Doppler ultrasound to assess flow in the cannulated legs - CEUS over the popliteal arteries can assess proper functioning of a distal perfusion cannula[43]	Subcostal sagittal view (marker at 12 o'clock)	Midesophageal bicaval view
Central cannulation	- Venous drainage within the RA through the right atrial appendage or 2 drainage cannulas in SVC and IVC; - Also possible is, dual-stage drainage cannula with drainage within the RA and IVC or SVC - Return in the ascending aorta	Usually N/A	- Midesophageal bicaval view for drainage - Midesophageal distal ascending aortic - Upper esophageal aortic arch view

CEUS, contrast-enhanced ultrasound; ECMO, extracorporeal membrane oxygenation; IJ, internal jugular; IVC, inferior vena cava; N/A, not applicable; PA, pulmonary artery; RA, right atrium; RV, right ventricle; SVC, superior vena cava; TEE, transesophageal echocardiography; TTE, transthoracic echocardiogram; V-A, venoarterial ECMO; V-V, venovenous ECMO.

A postcannulation echocardiogram is needed to confirm adequate cannula location after ventilatory settings adjustment and patient's repositioning (before final cannula securement) and rule out new or expanding pleural or pericardial effusion or aortic dissection (for VA ECMO).[12]

Use of Ultrasound for Monitoring on ECMO

Cannula Monitoring

Monitoring of ECMO cannulas with ultrasound is crucial to prevent flow impediment, recirculation, cannula malposition, or worse decannulation and should be performed with clinical changes. Confirmation of the position of the cannulas' tips is extremely important as the radiolucent tips may not be visualized on radiographs. Suboptimal positioning of cannulas can lead to complications, structural damage, cardiac perforation, hepatic congestion, and recirculation.[42,44,45] Determining the degree of recirculation by dilutional ultrasound is possible.[46,47] Ultrasound can also assess thrombus formation at the tip and around the cannulas.[34]

For bicaval dual-lumen cannula, color flow Doppler (CFD) is helpful to identify the reinfused flow directed toward the tricuspid valve. Direction of the reinfusion flow should be ascertained in case of persistent hypoxemia and cannula position may need to be readjusted accordingly.

For right atrial (RA) cannulation with a dual-lumen cannula in neonates and children, echocardiography with CFD is essential to check the correct cannula position (upper to mid-atrium) and the direction of the reinfused flow (the jet should

Table 4. Ultrasound Monitoring on ECMO

Monitoring on ECMO		
Echocardiography		
	VV ECMO	VA ECMO
	Biventricular size and function with emphasis on RV function (TAPSE, RV FAC, S at tricuspid annulus, RVSP estimation), paradoxical septum Hypoxemia: CO estimation, direction of reinfused flow with CFD for dual-lumen cannula, recirculation	Biventricular size and function *(LVEF may decrease with increasing ECBF)* Ventricular interdependence Biatrial size and volume Mitral (including diastolic MR)/aortic regurgitation, flow reversal in pulmonary veins *(these may increase with increasing ECBF)* Opening of aortic valve *(may decrease with increasing ECBF)* LVOT VTI *(may decrease with increasing ECBF)* Intracavitary spontaneous echo contrast/intracavitary thrombus Aortic root thrombosis: *(may increase with increasing ECBF)* Absence of systolic reversal in suprahepatic veins Position of mixing zone in descending aorta[48]
	All ECMO configurations Follow up of any other pre-existing pathology Cannula position Drainage insufficiency (intravascular volume, pericardial effusion) Cannula-related thrombosis IVC and SVC size and respiratory variations	
Extracardiac ultrasound		
	VV ECMO	VA ECMO
Lung ultrasound	Lung score, signs of pneumonia Pneumothorax, hemothorax	Pulmonary edema, signs of pneumonia Pneumothorax, hemothorax
Cerebral ultrasound	TCD: Peak, diastolic, and mean flow velocities, pulsatility index, estimated ICP and CPP Optic nerve sheath diameter, midline shift Microembolic signals if intracardiac or intrapulmonary shunt	Peak, diastolic, and mean flow velocities, pulsatility index with and without IABP when applicable, estimated ICP and CPP Optic nerve sheath diameter, midline shift Microembolic signals
Vascular ultrasound	DVT	Arterial flow with Doppler ± contrast Deep vein thrombosis Placement of percutaneous vascular closure device
Weaning phase		
	VV ECMO	VA ECMO
	RV size and function Ventricular interdependence Absence of a significant pleural effusion or a pneumothorax Absence of significant lung consolidation or atelectasis on CUS	Adult: LVOT VTI >10 cm. LVEF >20–25%[49] Pediatric: VTI >7.9 cm, EF> 41%, stable MR[50,51] *S*' wave at lateral mitral annulus >6 cm/s[49] and delta lateral *e*'>3.2[52] RV size and function, TAPSE, *S*', and delta *S*' >9% at tricuspid annulus,[52] FAC, 3D RVEF> 25%[53] TR and RVSP Ventricular interdependence[54] Biventricular strain[55,56] and RV-PA coupling[56] Absence of significant mitral regurgitation and dilatation of mitral annulus
	Right-to-left shunt	Right-to-left shunt
Post-ECMO		
	All ECMO configurations	
	Vascular ultrasound of previous cannulation sites and IVC to exclude complications (vascular stenosis, thrombosis, pseudoaneurysm, and arteriovenous fistula) RA, RV thrombus Right-to-left shunt	

Adapted from Douflé *et al*.[12]

3D RVEF, three-dimensional right ventricular ejection fraction; CFD, color flow Doppler; CO, cardiac output; CPP, cerebral perfusion pressure; CUS, chest ultrasound; DVT, deep vein thrombosis; ECBF, extracorporeal blood flow; ECMO, extracorporeal membrane oxygenation; FAC, fractional area change; IABP, intra-aortic balloon pump; ICP, intracranial pressure; IVC, inferior vena cava; LV, left ventricle; LVEF, left ventricular ejection fraction; LVOT VTI, left ventricular outflow tract velocity-time integral; RA, right atrium; RV, right ventricle; RV FAC, right ventricular fractional area of change; RV-PA coupling, right ventricle-pulmonary artery coupling; RVSP, right ventricular systolic pressure; SVC, superior vena cava; TAPSE, tricuspid annular plane systolic excursion; TCD, transcranial Doppler; TR, tricuspid regurgitation; VV ECMO, venovenous ECMO; VA ECMO, venoarterial ECMO.

be directed towards the tricuspid valve and should start from the junction between the SVC and the RA). In neonates with CHD and central shunts, the arterial cannula position must be monitored by ultrasound to prevent migration and obstruction of the shunt.

Each cannulation strategy has distinctive ultrasound monitoring considerations (Table 3). Monitoring of cannulas in unique populations such as patients who have undergone a Glenn or Fontan procedure is recommended, however, exact location of cannula placement is beyond the scope of this review as this may be very specific to individual patient's anatomy.

Cardiac Function Monitoring on Venoarterial Extracorporeal Membrane Oxygenation

Echocardiogram in VA ECMO is required to assess preload, biventricular contractility, afterload, and potential need for unloading (Table 4).

VA ECMO greatly changes cardiac preload and afterload, thus significantly impacting cardiac function evaluation and interpretation.[57,58] Inotropic support, ECMO, and ventilatory settings need to be reported and accounted for when interpreting echocardiographic findings.

The most used parameter to stratify LV systolic function is the left ventricular ejection fraction (LVEF) calculated with the biplane Simpson's method. While LVEF is load-dependent, it has been shown to be higher and to increase early in patients who are successfully weaned off ECMO.[49,50]

Left ventricular outflow tract (LVOT) velocity-time integral (VTI) is another widely used parameter to trend LV function recovery. Although load-dependent, it is consistently reported across studies to detect cardiac improvement and to predict successful weaning.[49,59,60] Finally, tissue Doppler systolic velocities such as mitral annular systolic velocity and lateral *e'* velocity have been shown to improve in successfully weaned patients.[49,52]

For neonates and pediatric patients with CHD supported on VA ECMO, echocardiography is useful to evaluate residual lesions or worsening function that may require further surgical intervention.

Valvulopathy. By increasing LV afterload and subsequently, LV end-diastolic pressure, VA ECMO may lead to new onset of left-sided valvular regurgitation or worsening of pre-existing regurgitation, typically due to mitral annular dilatation. Therefore, both mitral and aortic valvular function should be closely monitored while on VA ECMO.[61,62]

LV distension. A subset of VA ECMO patients benefit from addition of a mechanical unloading device.[63,64] For all ages of ECMO patients, the indication for LV unloading must be guided by clinical and echocardiographic parameters.[65–67] A detailed description of possible unloading devices is beyond the scope of this review but options include percutaneous (IABP, microaxial pump, atrial septostomy, transseptal cannulation, pulmonary artery vent) and surgical (direct LV vent, LA vent *via* pulmonary veins) approaches. Echocardiography may help choose the optimal unloading strategy by excluding contraindications to a specific unloading device (*e.g.,* LV thrombus contraindicating the use of a microaxial pump) and guide insertion and adequate positioning. In contrast to other unloading devices, Impella increases flow in the aortic root, thus potentially improving coronary perfusion. A successful application of the device is contingent on its daily echocardiographic monitoring and prevention of axial and lateral malposition.[68]

Irrespective of LV size, the following echocardiographic signs (in conjunction with clinical parameters, such as worsening pulmonary congestion, minimal pulse pressure) may indicate the need for LV unloading: very severely reduced ejection fraction (*i.e.,* LVEF <10%, LVOT VTI <5 cm) and/or presence of AR, absence of aortic valve opening (or only intermittent opening), retrograde diastolic mitral flow, worsening mitral regurgitation, systolic flow reversal in the pulmonary veins, spontaneous LV echocardiographic contrast, and/or LV thrombus.[69,70]

When considering unloading, determination of the presence of ongoing subendocardial LV ischemia on VA ECMO can be challenging, as traditional regional wall motion scoring is unreliable. The demonstration of post-ejection shortening, and/or the use of echocardiographic myocardial perfusion scanning can be useful in expert hands. Nevertheless, the optimal timing of LV unloading remains a matter of debate.

Right ventricular monitoring. VA ECMO also significantly affects right ventricular function; however, the complex RV morphology compared to the LV, makes it more challenging to accurately measure its geometry or quantify its function. Additionally, the definition of RV failure remains inconsistent, more so on mechanical circulatory support (MCS).[71]

While there is no specific separate set of parameters for RV assessment on ECMO, the conventional echocardiographic assessment is applicable (Table 4).[14] However, values need to be interpreted cautiously given the inherent decrease in RV preload on VA ECMO.

Additionally, tricuspid *E/A* and *E/e'*, as measurements of RV diastolic function, have not been validated against the gold standard of end-diastolic elastance and should therefore be used and interpreted with caution.

Ultrasound for combined MCS. While specific recommendations on the use of ultrasound for other forms of MCS are beyond the scope of this review a few points are worth mentioning.

Transvalvular assist devices, such as Impella, are commonly used to address LV distension during VA ECMO. Echocardiography plays a pivotal role in facilitating insertion, titration, detection of complications, and weaning of these devices.[65,72] Adequate position of the device depends on its size and should be frequently monitored to ensure optimal functioning and in case of dysfunction.[73] The distal part of the catheter should be directed towards the LV apex to avoid interaction with the ventricular wall and the subvalvular mitral valve apparatus.[74] Notably, with an Impella, certain measurements of ventricular performance may need to be extrapolated from other measurements due to Impella interference, such as the LVOT VTI that may be inferred from the RVOT VTI measured in the proximal pulmonary artery.

Similarly, adequate positioning and repositioning of IABP can be guided with echocardiography, using the supraclavicular view on TTE or TEE short and long-axis aortic view.[73]

VA ECMO is also used in postoperative RV failure following left ventricular assist device (LVAD) insertion.[75,76] Echocardiography plays a crucial role in this context by facilitating the adjustment of ECMO and LVAD flows, ensuring hemodynamic stability, maintaining adequate LV preload, and right ventricular decompression.

Cardiac Function Monitoring on Venovenous Extracorporeal Membrane Oxygenation

Cardiac function, and more specifically RV function should also be monitored on VV ECMO as a significant subset of patients will develop RV dysfunction during VV ECMO support, which may prompt a change of ECMO configuration to V-A, V-VA, or V-P ECMO.[23,30,77,78] The frequency of cardiac monitoring on VV ECMO should be guided by the patient's clinical condition.[71]

Troubleshooting

Drainage Insufficiency, Hypoxemia, and Recirculation

Drainage insufficiency is frequent in any type of ECMO configuration.[32,79] We recommend performing an ultrasound to identify causes of drainage insufficiency, such as cannula malposition, hypovolemia, tension pneumothorax, cardiac tamponade, intracardiac, or cannula-related thrombosis.[12,80]

The differential diagnoses of hypoxemia on VV ECMO are multiple and can be secondary to ECMO or patient-related etiologies. ECMO-related causes include membrane lung dysfunction, drainage insufficiency, recirculation, and insufficient extracorporeal blood flow (ECBF) in relation to cardiac output. Patient-related diagnoses include tension pneumothorax or hemothorax, and pulmonary atelectasis. Performing an echocardiogram and lung ultrasound to assess hypoxemia unrelated to membrane lung failure is recommended to identify factors contributing to drainage insufficiency and recirculation. In case of hypoxemia or suspected recirculation, the orientation of the reinfusion flow with CFD should also be assessed, particularly with dual-lumen cannulas and V-P configurations.[12] Furthermore, contrast echocardiography can be used to estimate recirculation.[11] Echocardiography also allows the determination of cardiac output to assess the ratio of ECBF to patient's cardiac output. Contrast-enhanced ultrasound can also be used to find the location of the mixing point to assess differential oxygenation on peripheral VA ECMO.[48] In case of differential oxygenation on VA ECMO, performing a comprehensive ultrasonographic examination (including heart and lung) is crucial to determine the cause of hypoxemia and implement the appropriate treatment (*e.g.,* pleural drainage or pulmonary optimization, change of configuration to V-AV, or LV unloading).

Tamponade

Tamponade is an infrequent but important complication of ECMO, occurring in 2.6% of adult patients receiving ECMO.[81] In ELSO registry data, tamponade was most frequent in VA ECMO (78% of cases) followed by VV ECMO (18%) and extracorporeal cardiopulmonary resuscitation (12%). Additionally, cardiac tamponade was associated with worse outcomes (35% hospital survival *vs.* 49%).[81] Tamponade may result from cannula malpositioning (demonstrated by echocardiography) or RA or RV rupture. Tamponade may be associated with drainage insufficiency and increasingly negative inlet pressures (with or without a rise in central venous pressure (CVP)), patient's instability, or may be concealed until presenting as loss of pulsatility or failure to wean from VA ECMO.[12,82] There are numerous echocardiographic features supporting the diagnosis in the native circulation, including demonstration of a pericardial collection, exaggerated respiratory variation in transtricuspid, transmitral and transaortic flow, and the presence of chamber collapse. Importantly, these echocardiographic features of tamponade may be absent on ECMO and in case of localized pericardial collections.[82] On VV ECMO with low tidal volumes secondary to severely reduced lung compliance and lung rest strategy, transvalvular respiratory variations may be absent even in the presence of tamponade.[83] As reliance on traditional clinical and echocardiographic features of tamponade may mislead, serial echocardiograms are recommended if a pericardial effusion is present, at least daily and more frequently in case of deterioration or ongoing drainage insufficiency.

Vascular Ultrasound

Vascular complications on ECMO remain frequent and include venous and arterial thrombosis, pseudoaneurysm, arteriovenous fistula, arterial dissection, and post-ECMO vascular stenosis.[37,84,85] While deep venous thrombosis (DVT) may be clinically insidious on ECMO, recent systematic reviews reported a high incidence of thromboembolic events and ECMO itself was a positive predictor for DVT.[85,86–88] As patients on ECMO are in most cases on systemic anticoagulation, the benefit of systematic ultrasonographic detection of DVTs on ECMO is uncertain. However, given the high frequency of cannula-associated DVT (CaDVT), it is recommended to systematically perform a post-decannulation ultrasound of the previous cannulation sites and vena cavae to exclude CaDVT, as ongoing systemic anticoagulation may be required in case of post-ECMO DVT.[85,88,89]

Arterial vascular complications are usually symptomatic, but early detection of perfusion loss is crucial to limit progression to limb ischemia. For peripheral arterial cannulation, insertion of an antegrade distal perfusion cannula (DPC) on ipsilateral arterial cannulation site is usually warranted and should be placed under ultrasound guidance in the superficial femoral artery (SFA).[32,90] Visualization of the wire in the SFA and CEUS in the popliteal artery can help confirm adequate position of the DPC.[43] Ultrasound guidance can also be used for retrograde DPC placement in the posterior tibial artery. Even in the presence of a DPC, frequent Doppler ultrasound assessment is needed to ensure the presence of adequate flow, in conjunction with clinical examination and other monitoring tools, such as near-infrared spectroscopy. Ultrasound can also be used to assist placement of arterial closure devices and diagnose post-decannulation vascular stenosis, thrombosis (including thrombus between the antegrade DPC and retrograde cannula before decannulation, which may influence the choice between percutaneous or surgical closure), pseudoaneurysm, and arteriovenous fistula.[91]

Chest Ultrasound

Including in ECMO patients with severe ARDS, a combination of chest ultrasound (CUS), echocardiography, and chest X-ray provides a high diagnostic yield to detect complications.[92] Chest ultrasound is reproducible and can quantify pulmonary involvement.[93–96]

Quantitative and qualitative assessment of pleural space with ultrasound are essential for decision on pleural fluid drainage, which may improve oxygenation, ventilation, RV function and may facilitate weaning of ECMO support.[97–99] Importantly, in heavily consolidated and less buoyant lungs, the estimated amount of fluid using classical methods may be underestimated.[98] As pleural drainage may have an increased risk of bleeding on ECMO, identification of the intercostal vessels with ultrasound may be of interest.[100]

The incidence of barotrauma was around 12–26% in high-volume ECMO centers during the COVID-19 pandemic.[101] A prompt diagnosis and management of pneumothorax with ultrasound is essential in ventilated patients.[102] Chest ultrasound, including the high specificity of a lung point, helps diagnose and assist in drainage.[103] However, the lung point has a sensitivity of only 66% and is absent in larger circumferential pneumothoraces. Other CUS indicators of pneumothorax are absence of lung sliding, lung pulse, and B-lines.[102,104] Caution needs to be exercised in absence of lung sliding in patients with ultraprotective MV. Similarly, lung pulse may be absent in patients on VA ECMO with non-ejecting hearts.[12]

While normal alveolar air content and alveolar distension cannot be distinguished on lung ultrasound, it may help monitor lung aeration and PEEP titration on ECMO including in pediatric patients. Lung recovery can be monitored using the lung ultrasound score on VV ECMO and persistently high scores portend worse outcomes.[105–107] The presence of dynamic bronchogram and lung pulse helps differentiate lung consolidation from atelectasis and has been used in conjunction with CFD to support the diagnosis of pneumonia on ECMO.[108]

Neurological Ultrasound

Screening for acute neurologic complications in newborns and infants relies on bedside transcranial brain ultrasound. Even though this modality can underestimate both minor hemorrhagic and ischemic injury compared to computed tomography or magnetic resonance imaging.[109] Nonetheless, early detection of brain hemorrhages may be helpful to tailor anticoagulation during ECMO.[110–113]

However (both in neonates, pediatric, and adult patients), while changes in estimated cerebral perfusion pressure (CPP), intracranial pressure (ICP), and pulsatility index (PI) derived from cerebral blood flow velocities may be signs of acute brain injury, data on the optimal frequency and duration of transcranial Doppler (TCD) monitoring is lacking.[114,115] Notably, absent PI in any vessel has been linked to a heightened risk of intracranial hemorrhage. However, as PIs correlate with LVEF and may be absent in patients on VA ECMO with LVEF below 20% and may be impacted by the presence of an IABP, PIs should be interpreted with caution. Similarly, the clinical significance of microembolic signals is uncertain and needs further investigation.[116,117]

Brain ultrasound can also be used to detect changes in optic nerve sheath diameter and increase in diameter can be indicative of high ICP even in ECMO patients.[118,119] Finally, caution should be used while interpreting signs of cerebral circulatory arrest on TCD in the presence of minimal cardiac ejection and repeated examinations by the same operator are needed.[120–122]

Ultrasound to Guide ECMO Weaning

Venovenous Extracorporeal Membrane Oxygenation (Adults)

Monitoring of LV filling pressures and right heart function in combination with lung ultrasonography may facilitate VV ECMO weaning.[105,107] Chest ultrasound and echocardiography should help exclude elevated LVEDP and set goals for preload, heart contractility, and afterload.[123] Monitoring of the presence of a right-to-left shunt may be helpful in case of repeated failure of ECMO weaning trial.[124]

Venovenous Extracorporeal Membrane Oxygenation (Pediatric)

Venovenous ECMO weaning depends mostly on the degree of lung function recovery allowing gradual decrease of the sweep gas flow while continuing ECBF. Echocardiogram in VV ECMO evaluates RV function and the presence and degree of pulmonary hypertension. Estimation of PAP, assessment of right-to-left shunt at the atrial or ductal level, interventricular septum motion, TAPSE, and pulmonary artery acceleration time of >100 ms are useful during weaning trials together with clinical and laboratory parameters supporting suitability to come off ECMO.[15,16,19,77,125]

Venoarterial Extracorporeal Membrane Oxygenation (Adults)

Extracorporeal blood flow should be maintained at the lowest level tolerated to allow sufficient organ perfusion and avoid further LV distension while maintaining patency of the circuit. Weaning trials should start as soon as possible, once ventricular function has recovered sufficiently to meet circulatory needs.[54,126–128] Assessment of readiness for liberation must integrate clinical, biological, echocardiographic parameters and invasive cardiac monitoring when available. Although protocols differ between studies, regular approaches include a stepwise reduction of ECBF with echocardiographic reassessment at each step (as low as 0.5–1 L/min or transient clamping) and subsequent return to baseline flows or slightly lower.[129] This process may require an anticoagulation adjustment. A gradual reduction of ECBF diverts circulating stress volume from the extracorporeal circuit to the right heart and pulmonary circulation, thus increasing RV preload while decreasing LV afterload. Importantly, most echocardiographic parameters used to assess readiness are load-dependent and should be interpreted and integrated with caution (Table 4). Initially described parameters, such as LVEF >20–25%, LVOT VTI >10 cm, and tissue Doppler imaging of the mitral annulus peak systolic velocity (TDSa) >6 cm/s, were associated with weaning success.[49,55] An adequate inotropic LV response to stepwise ECBF reductions without dilatation *versus* a reduced inotropic response and LV dilatation was associated with improved odds of LV recovery.[130] The LV longitudinal contractility may be assessed during ECMO weaning by tissue Doppler velocity of the mitral annulus rather than by two-dimensional strain rate imaging.[55] Indeed, studies failed to demonstrate LV global longitudinal strain prognostic value and ability to predict successful weaning.[55] However, a load-dependent cardiac reserve was identified by an increase in strain in patients weaned from ECMO. Notably, new or worsening ventricular interdependence is associated with weaning failure and assessment of RV function is critical to determine readiness for liberation.[54,131] Since the RV is significantly unloaded during VA ECMO, it is inherently difficult to judge its intrinsic contractility unless assessed during weaning trial. Three-dimensional RVEF was shown to correlate strongly with weaning success with a cutoff value of 25%.[132]

Dynamic changes of echocardiographic parameters in response to flow decrements may be more predictive than single values.[52] Similarly, markers of RV-PA coupling may be better predictors than the originally described parameters.[56]

Venoarterial Extracorporeal Membrane Oxygenation (Pediatric)

In neonates and pediatric patients, smaller circuits make weaning of VA ECMO more challenging, as it requires decreasing the ECBF to evaluate native cardiac function while maintaining circuit patency. To better assess native cardiac function, ECBF may be reduced by the use of bridges, Hoffman clamps, or by performing a Pump Controlled Retrograde Trial Off (PCRTO).[133] As in adults, cardiac function should be high enough to allow adequate oxygen delivery which is assessed in conjunction with clinical, biological, and invasive monitoring parameters. As LVOT VTI significantly varies with age and body size, absolute cutoff values may not be applicable in the pediatric population.[50] Nonetheless, a recent multicenter study (including neonates and pediatric patients) showed an increase in LVOT VTI and LVEF in all patients during VA ECMO weaning and demonstrated that LVOT VTI <7.9 cm, LVEF <41%, worsening MR, and a disproportionate increase in CVP during ECMO wean were associated with unfavorable outcomes (*i.e.*, death, heart transplant, need for VAD, second ECMO run).[50,51] Left ventricular outflow tract VTI is a promising parameter in CHD patients with altered ventricular shape or univentricular hearts in whom measurement of LVEF is challenging or not possible.

Conclusions

Ultrasound is ubiquitous and indispensable in the care of ECMO patients, from indication to choice of configuration, cannulation, monitoring, weaning and post decannulation. Clinicians managing ECMO patients should be cognizant of ultrasonographic parameters to assess on ECMO and of the impact of ECMO support on these parameters for optimal decision-making.

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