Echocardiography in extracorporeal life support: A key player in procedural guidance, tailoring and monitoring

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Echocardiography in extracorporeal life support: A key player in procedural guidance, tailoring and monitoring

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Abstract

Extracorporeal life support (ECLS) is a mainstay of current practice in severe respiratory, circulatory or cardiac failure refractory to conventional management. The inherent complexity of different ECLS modes and their influence on the native pulmonary and cardiovascular system require patient-specific tailoring to optimize outcome. Echocardiography plays a key role throughout the ECLS care, including patient selection, adequate placement of cannulas, monitoring, weaning and follow-up after decannulation. For this purpose, echocardiographers require specific ECLS-related knowledge and skills, which are outlined here.

Keywords

echocardiography; ultrasound; extracorporeal life support (ECLS); veno-arterial extracorporeal membrane oxygenation (VA ECMO); veno-venous extracorporeal membrane oxygenation (VV ECMO); left ventricular unloading; acute respiratory distress syndrome (ARDS); acute heart failure; cardiogenic shock; cardiovascular computer simulation

Introduction

Extracorporeal life support (ECLS) is widely used in modern critical care for acute and severe respiratory, circulatory or cardiac failure refractory to conventional management. For patient selection, cannulation, daily management, weaning and follow-up after decannulation, echocardiography is an indispensable imaging tool.

ECLS can be configured for respiratory support as veno-venous (VV) or circulatory/cardiac support as veno-arterial (VA) ECLS.[1–5] VV ECLS can generally be considered as an 'artificial lung' and has a hemodynamically neutral effect.[2] On top of respiratory support, VA ECLS is intended to provide significant perfusion of the systemic circulation. As a downside, VA ECLS may create left-sided cardiac overload.[3,4,6,7]

Given the complexity of ECLS and the multitude of interactions with the patient's native respiratory and circulatory systems, echocardiographers should be well aware of the basic ECLS concepts, its different modes, cannulation techniques and technical elements. Specific knowledge and skills are required to adequately visualize and interpret cardiovascular pathophysiology during ECLS.[8]

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Table 1. Principal echocardiographic parameters to be evaluated before initiation of ECLS.

	Parameter	Exclude
VV ECLS	superior/ inferior caval vein RA morphology RV morphology/ RVEDD RV function/ TAPSE tricuspid regurgitation velocity/ pulmonary hypertension pericardial effusion atrial septal defect	LV failure
VA ECLS	LV morphology/ LVEDD LV function/ LV EF VTI TDSa RV failure pericardial effusion atrial septal defect	aortic dissection aortic valve regurgitation papillary muscle rupture interventricular septal rupture large intracavitary/ mural thrombi calcifications at cannulation site

RVEDD: right ventricular end-diastolic diameter; TAPSE: tricuspid annular plane systolic excursion; LVEDD: left ventricular end-diastolic diameter; EF: ejection fraction; VTI: velocity time integral; TDSa: spectral tissue Doppler imaging mitral annulus peak systolic velocity.

In this review, we outline echocardiographic findings that are specifically relevant for procedural cannulation guidance, patient-specific tailoring of ECLS and daily management. Details of imaging cannulas, cardiac loading conditions and recognition of ECLS-related complications are emphasized.

Patient selection

Before the initiation of ECLS, a comprehensive echocardiographic study should be performed, documenting structural and functional cardiovascular abnormalities. Echocardiographic findings can assist in choosing the most appropriate ECLS mode and cannulation site and may also unmask important, yet undiagnosed, contraindications for ECLS (Table 1).

Veno-venous ECLS. In patients with severe respiratory failure under consideration for VV ECLS support, specific attention should go to right ventricular (RV) morphology and function, as well as the pulmonary circulation. It has long been appreciated that the spectrum of disorders contributing to severe respiratory failure, including acute respiratory distress syndrome (ARDS), can be complicated by pulmonary hypertension culminating in RV failure.[9] Importantly, the initiation of VV ECLS has been shown to decrease pulmonary artery pressures and RV afterload by optimizing gas exchange, reducing intrathoracic pressures secondary to improvements in oxygenation and concomitant lung-protective ventilation strategies.[10,11] Through these mechanisms, pulmonary hypertension and related RV failure may be partially or fully reversible after the initiation of VV ECLS. As such, pulmonary hypertension and RV failure do not deserve the status of contraindications for VV ECLS in ARDS and other indications for severe respiratory failure, especially when considered fully reversible. Care should, however, be taken with the initiation of VV ECLS in patients with a reduced RV function. Although, VV ECLS is hemodynamically neutral, it is important to realize that, when ECLS flow rates are higher than RV output, recirculation may be significant. In that situation, the ECLS flow rates do not well reflect the extracorporeal contribution to the systemic oxygenation since RV output remains a major determinant. In these situations, inotropic RV support is advised as adjuvant therapy or may prompt a switch to VA or V-AV ECLS.[12] When severe pulmonary hypertension and concomitant RV failure are diagnosed, as, e.g., in terminal lung disease, V-AV or novel central VA ECLS approaches should be applied, especially when ECLS is considered as a ‘bridge to lung transplant’.[13–15]

Veno-arterial ECLS. In circulatory shock necessitating VA ECLS, echographic cardiac assessment is of paramount importance. The most common cause of acute circulatory shock is severe heart failure due to acute myocardial infarction.[3] In this specific instance, echocardiography should not only focus on the extent of LV failure and myocardium at risk, but also exclude or visualize concomitant pathologies, such as aortic dissection, aortic valve regurgitation and infarct-related complications, such as RV failure and significant mitral valve regurgitation due to papillary muscle dysfunction or rupture. It is vital in these patients that echocardiography is performed before the initiation of ECLS as these findings will impact on the initiation decision and ECLS strategy. In the case of interventricular septal or free wall rupture complicated by tamponade, the prognosis will be intrinsically linked to the specific surgical intervention preceding any eventual ECLS or, in other circumstances, will allow safe, fast ECLS commencement and stabilization before surgery.[16]

A thorough echocardiographic evaluation is also indicated in patients with cardiogenic shock due to non-ischemic causes of heart failure. The nature and course of non-ischemic cardiac disease or circulatory failure may vary considerably. In patients presenting with acute cardiogenic shock as a first manifestation of non-ischemic cardiomyopathy, the extent of LV and RV failure, wall thickness, atrio-ventricular dimensions and concomitant valvular pathology may shed light on the pre-clinical course of the disease and prognosis. Moreover, acute-on-chronic manifestations of severe heart failure may be complicated by large mural thrombi. These intra-cavitary masses, having direct implications for the ECLS approach and anticoagulation regime, can easily be detected by echocardiography.[17] Also, subacute pulmonary embolism as the underlying cause of shock necessitates detailed echocardiography with a focus on the RV, vena cava and presence of intra-cardiac shunts due to the fact that massive pulmonary embolism with (impending) hemodynamic collapse can be a suitable indication for VA ECLS.[18,19] Venous thromboembolism can be ongoing and lead to right-to-left embolizations through a patent foramen ovale or atrial septal defect, which can also be detected by echocardiography.[20] Moreover, the presence of a large atrial septal defect should be known, as it may beneficially impact on LV unloading in VA ECLS while, at the same time, it may critically impede LV ejection due to a left-to-right shunt.[7] The finding of a severe aortic regurgitation is considered a contraindication for VA ECLS as it inevitably causes severe and refractory LV overload and pulmonary edema. Other contraindications that may be revealed by echocardiography include the presence of an aortic dissection necessitating emergency surgery or severe, site-specific vascular calcification due to atherosclerotic disease in or around potential cannulation sites, which may result in peripheral instead of central cannulation.

Procedural guidance of cannulation during initiation of ECLS

Although it is still common practice to use anatomical landmarks and palpation for central venous and femoral arterial access, serious complications with ECLS cannulation can occur, which may be avoided with ultrasound guidance.[21–24] Therefore, it is generally accepted that ultrasound is beneficial in gaining uncomplicated vascular access, especially in high-risk patients or special circumstances, e.g. extracorporeal cardiopulmonary resuscitation (ECPR) and may also be used to gain percutaneous selective distal perfusion for the lower extremities, if needed, in femoral arterial cannulation.[25,26] It is beyond the scope of this review to discuss the general role of ultrasound for vascular access in detail as it has been extensively reviewed elsewhere.[21–23,26]

Before vascular access is established, pre-procedural echocardiography should rule out pre-existent pericardial effusion in order to exclude procedure-related perforation diagnosed by the presence of a new effusion at a later stage of the cannulation. Also, right atrial (RA) anatomy, a patent foramen ovale, atrial septal defect, position of pacemaker leads and patency of the tricuspid valve should be documented. A severe, high-velocity tricuspid regurgitation, indicating pulmonary hypertension and high pulmonary vascular resistance, needs follow-up and may decrease under ECLS, but could also interfere with ECLS functionality and trigger VA instead of VV ECLS, combined VA and VV modes or even alternative cannulation strategies.[13–15] The superior and inferior caval vein patency and their anatomical relation to the right atrium and hepatic veins is relevant as the superior-inferior caval-vein long axis does not generally follow a straight geometric line. The guidewire or cannula may consequently end up deviating either into the hepatic venous system or the right side of the heart. These complications may be prevented through the aid of echography.

Cannula visualization. The echocardiographer should be familiar with the cannula design and its detailed echocardiographic representation.[27] The echocardiographic image of a specific cannula can be quite distinct and depends on the presence of an obturator and guidewire within the cannula (Figure 1 and Figure 2). In order to clarify what can be expected *in vivo*, echographic imaging of the cannula shaft and tip with and without obturator and guidewire can be performed in the 'ideal setting' of a water bath, as outlined previously.[28] It is nearly impossible to place the cannula tip precisely at a certain anatomic site as the end of the tip cannot be identified when the obturator is still situated in the cannula (Figure 1). Another pitfall during echocardiographic procedural guidance is the identification of the tip of the obturator in relation to the guidewire. Echographic scatter prohibits clear visualization of the transition zone between the obturator and guidewire, as evidenced by *in vitro* echographic imaging in a water bath (Figure 2).

Cannula positioning. In order to assure the correct position of a cannula, procedural echocardiographic guidance starts with visualization of the guidewire. The location of an intra-arterial guidewire can be confirmed by routine transesophageal (TEE) or subcostal

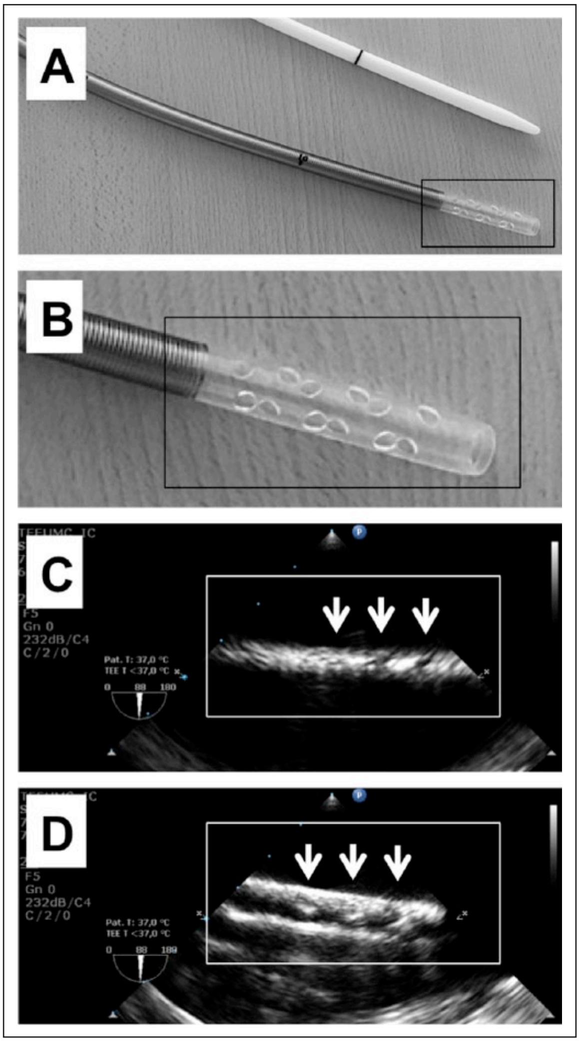

Figure 1. Echographic image of a single-stage drainge cannula tip. A. Single-stage venous drainage cannula (Medtronic Bio-Medicus 25F®) and obturator. B. Magnification of the cannula tip (frame corresponding to A). C. Echographic image of the tip of venous drainage cannula with the obturator inserted in the cannula using a TEE probe in a water bath (frame corresponding to A, B). Please note the small, virtually non-visible, non-echogenic 'black' holes corresponding with the drainage holes in the tip (arrows). The end of the cannula tip cannot be identified due to the obturator. D. Identical echographic view of the cannula tip as in C, but after removing the obturator from the cannula. Please note the 'inverted' echographic image of the cannula tip featuring echogenic 'white' drainage holes in the tip (arrows, frame corresponding to A-C). The end of the cannula tip can clearly be identified after the obturator is removed.

transthoracic echocardiography (TTE) of the descending aorta. A central venous position of a guidewire can best be visualized by a combination of a bicaval TEE view (Figure E1, supplementary figures can be found online with this paper, http://journals.sagepub.com/doi/full/10.1177/0267659118766438) and a subcostal TTE view of the inferior caval vein (Figure E2). The TEE view is relevant to exclude a RV position of the guidewire or looping within the right atrium, often towards the RA appendage (Figure E3). In the case of femoral venous access, a position high up in the superior caval vein can be confirmed by TEE, at the same time excluding perforation of the RA roof.[24] The TTE view is specifically important in the case of jugular venous access to help assure a deep and stable position in the inferior caval vein and avoid cannulation of a hepatic vein (Figure E4) since hepatic venous drainage should not be impaired and can be documented by echography (Figure E5). It may be necessary to repeatedly switch between bicaval TEE and subcostal TTE views of the inferior caval vein throughout the procedure (Figure E1 and E2). This combined TEE-TTE approach may be very helpful in avoiding guidewire migration due to insufficient support while advancing a cannula.[29,30] This important pitfall has been described for the relatively large-sized Avalon Elite® dual-lumen cannula and prompted the introduction of alternative procedures using a super-stiff guidewire instead of the original guidewire.[29,31,32] Importantly, it is generally advocated to use fluoroscopy as the imaging modality for the placement of the Avalon Elite® dual-lumen cannula whenever possible and available, while echocardiography may provide additional and complimentary information.

An optimal cannula position depends on the ECLS mode, its specific configuration and cannula design, as previously outlined.[27] It is possible to visualize the exact position of the cannula only after removing the guidewire and obturator, which allows the identification of the cannula tip (Figures 1 and 2). When using the Avalon Elite® dual-lumen cannula, the subcostal TTE view even allows visualization of both the position of the cannula tip and the infusion port overlying the tricuspid valve, which can be verified by measuring its exact distance (Figure E6), as demonstrated previously.[29,30] Also, in dual-site (femoro-jugular, femoro-femoral) central venous cannulation, the cannula position can be identified by TTE or TEE, yet, it should be realized that optimal cannulation for venous drainage is complex and depends on patient-specific aspects, the cannula type, e.g., single- or multistage, cannula positioning and the ECLS mode.[27,33]

Echocardiographic assessment during veno-venous ECLS

During VV ECLS, it is recommended to follow-up the RV function and size, as well as pulmonary pressures, especially when the latter was already elevated upon initiation of ECLS, as summarized with other important parameters to assess in Table 2. This is feasible at the bedside using TTE, but reliable measurements of regurgitant RV flows as a measure of pulmonary pressures

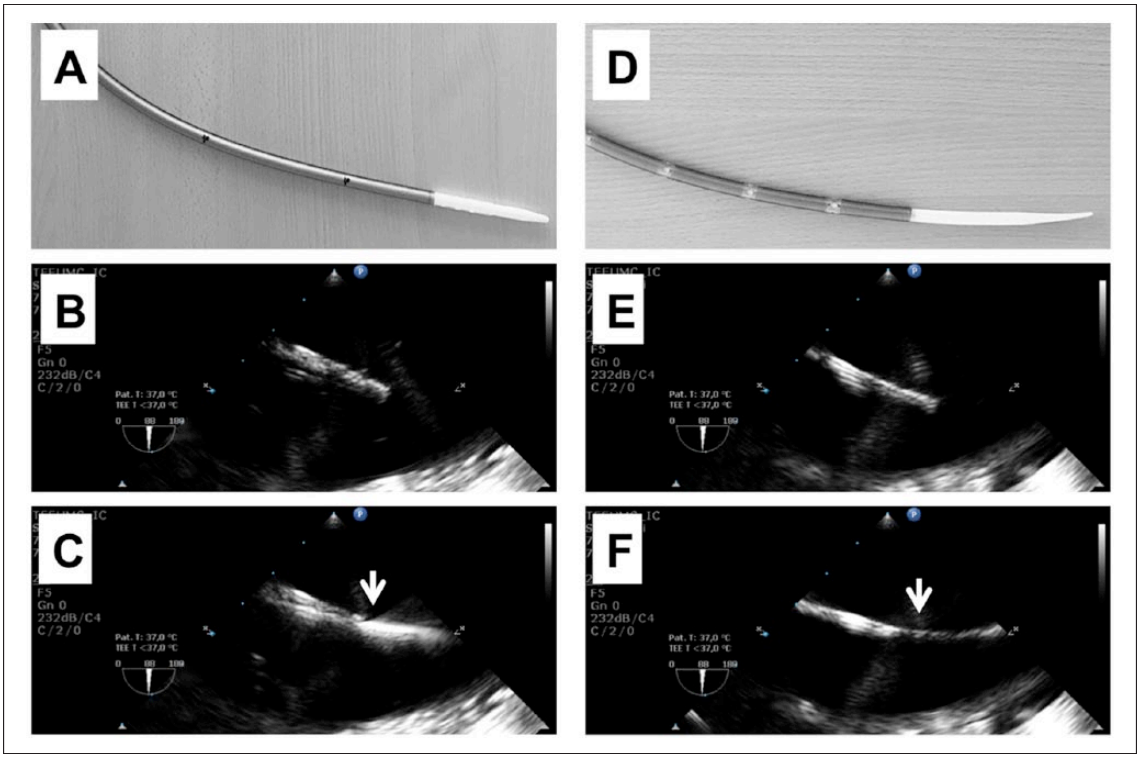

Figure 2. Echographic image of a single-stage and a multistage drainge cannula obturator tip. A. Single-stage venous drainage cannula (Medtronic Bio-Medicus 25F®) with obturator. B. Echographic image of the obturator tip in the venous drainage cannula *without* a guidewire using a TEE probe in a water bath (same single-stage venous drainage cannula as in A.). C. Identical echographic view of the obturator tip as in B, but *with* a guidewire inserted through the obturator. Please note that the tip of the obturator cannot precisely be discriminated due to ultrasound scatter in the transition zone between obturator tip and guidewire. D. Multistage venous drainage cannula (Maquet HLS 25F®) with obturator. E. Echographic image of the obturator tip in the venous drainage cannula *without* a guidewire using a TEE probe in a water bath (same multistage venous drainage cannula as in D.). F. Identical echographic view of the obturator tip as in E, but *with* a guidewire inserted through the obturator. Please note that the tip of the obturator cannot precisely be discriminated due to guidewire-related ultrasound scatter in the transition zone between obturator tip and guidewire.

can be hampered by significant interference of blood flow arising from the return cannula being directed towards the tricuspid valve. This complex 'mixture' of flows within the right atrium can be seen particularly in patients with the Avalon Elite® dual-lumen cannula as its infusion port overlies the tricuspid valve orifice (Figures E5-7), but can also occur with a single-stage return cannula positioned in or close to the right atrium.

Echocardiography (mainly TTE) is the ideal monitoring tool to confirm a proper cannula position throughout the course of ECLS as it is non-invasive and readily available at the bedside. TTE views of a central venous cannula position can be obtained via subcostal (Figures E5-7) and parasternal short axis views (Figure E8 and E9). A direct comparison of echocardiographic images of the current cannula position with the original images obtained during the cannulation procedure may clearly reveal malposition of a cannula due to migration. Early detection of this complication through echocardiography may prevent dislocation, hepatic congestion or inefficient respiratory support or drainage.[34,35] Additionally, it has long been evident that extracorporeal circuit thrombi and thromboemboli commonly occur in ECLS patients, often remain clinically unrecognized and can even arise in the period after the cessation of ECLS.[36,37] Subclinical thrombi can be visualized on or close to the cannula during ECLS support or in the days and weeks after removal of the ECLS cannulas (Figure E10).[37] These findings could prompt an alternative anticoagulation regimen during ECLS in individual patients or even prolonged anticoagulation in the weeks and months after removal of the cannula as a protocolized standard therapy.

Specifically to VV ECLS, the degree of recirculation is of great importance as minimizing recirculating flows will optimize the efficiency of extracorporeal support in respiratory failure.[38] Ultrasound dilution techniques can accurately determine the recirculating fraction of arterialized blood and echocardiographic imaging can add important additional information.[39,40] Here, echocardiography does not only allow visualization of the cannula

Table 2. Principal echocardiographic parameters to be evaluated in serial studies during ECLS.

	Parameter	Exclude
VV ECLS	RV morphology/ RVEDD RV function/ TAPSE tricuspid regurgitation velocity/ pulmonary hypertension cannula position/ recirculation intravascular volume status	cannula malposition/ migration significant recirculation pericardial effusion central venous thrombi
VA ECLS	LV morphology/ LVEDD LV function/ LV EF VTI TDSa intravascular volume status	pericardial effusion/ tamponade LV cavity dilatation LV ejection/ aortic valve opening LV cavity thrombosis aortic root thrombosis central venous thrombi

RVEDD: right ventricular end-diastolic diameter; TAPSE: tricuspid annular plane systolic excursion; LVEDD: left ventricular end-diastolic diameter; EF: ejection fraction; VTI: velocity time integral; TDSa: spectral tissue Doppler imaging mitral annulus peak systolic velocity.

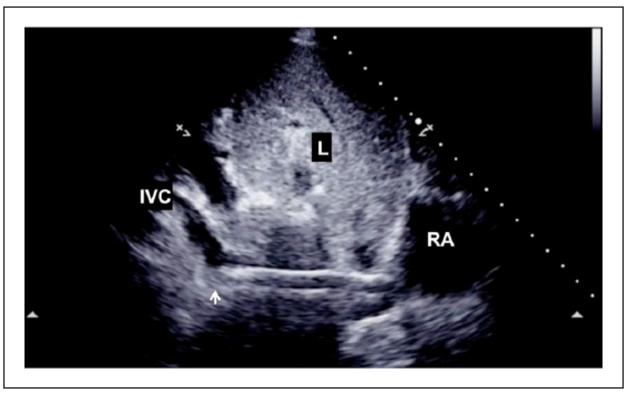

Figure 3. Hypovolemia with dual-lumen cannula in the inferior caval vein. Subcostal TTE view of an Avalon Elite® dual-lumen cannula positioned in the inferior caval vein (IVC) and wedged with its tip against the dorsal wall of the IVC (arrow). RA indicates right atrium, L liver. Please compare to Figure 3 movie (e-supplement).

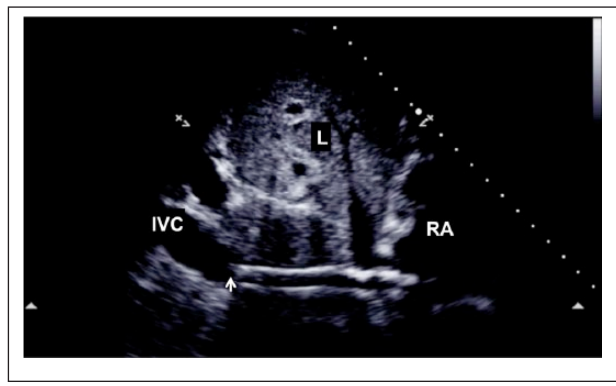

Figure 4. Euvolemia with dual-lumen cannula in the inferior caval vein. Subcostal TTE view of an Avalon Elite® dual-lumen cannula positioned in the inferior caval vein (IVC) and with its tip (arrow) moving freely within the lumen of the IVC after a fluid challenge of 500 mL as compared to the status visualized in Figure 3. RA indicates right atrium, L liver. Please compare to Figure 4 movie (e-supplement).

position, but color and continuous wave Doppler can identify (in-)correct flow directions (Figure E11).[39] Cannula position and degree of recirculation may vary considerably over time and depend on a number of factors, including the respiratory rate and the cardiac cycle (Figure E12 movie and Figure E13, all E figures and movies are available online, please see link at the end of the article.). Importantly, optimal VV ECLS flow also importantly depends on patient position, volume status and specifications of the drainage cannula. When the inflow cannula diameter is too large, it may cause nearly total occlusion of the lumen of the inferior caval vein, which will impede venous drainage and create ‘suction’ phenomena. This can be clearly visualized using echocardiography, whereby the degree of fluid resuscitation needed can also be documented using TTE at the bedside (Figure 3 and 4). This assessment of volume status and fluid responsiveness during ECLS adds another dimension to the well-appreciated value of TTE and TEE in this context in different patient populations.[41–43] Finally, it should be noted that lung ultrasound might also contribute to monitoring of the pulmonary condition of critically ill patients, as highlighted recently.[44,45]

Echocardiographic assessment during veno-arterial ECLS

The central role of echocardioraphy during VA ECLS is monitoring of the cardiac condition, as summarized with other important parameters to assess in Table 2.[3] Echocardiography can also contribute to cardiac diagnostics in severe heart failure of yet unclear origin when VA ECLS initially serves as a bridge to decision.[46] At the bedside, serial echocardiographic studies are a mainstay for imaging of cardiac geometry and function throughout the course of VA ECLS. This approach of close cardiac monitoring allows comprehensive and dynamic

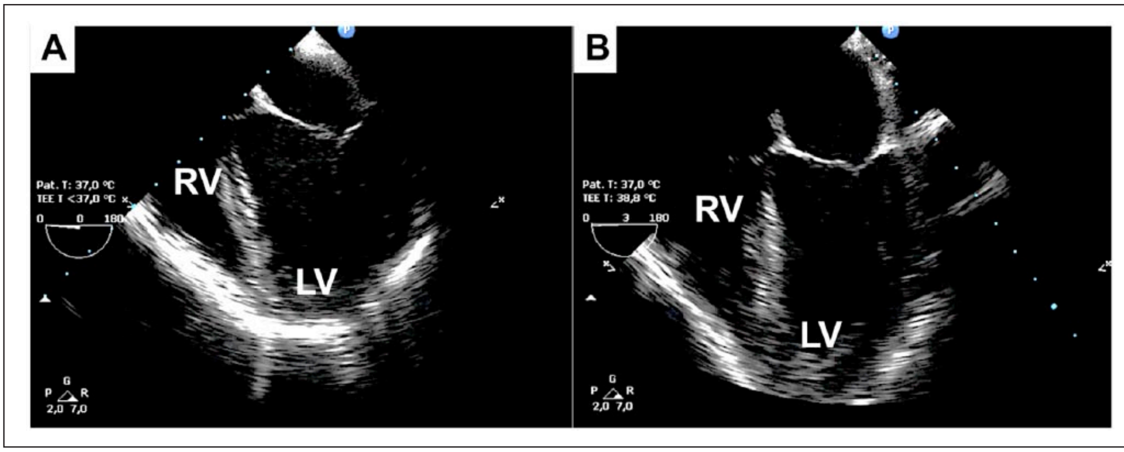

Figure 5. LV overload in peripheral VA versus V-AV ECLS. A. TEE deep transgastric four-chamber view during peripheral VA ECLS (4 L/min venous drainage and retrograde arterial return via the femoral artery). B. Same four-chamber view as in B. during peripheral V-AV ECLS (4 L/min venous drainage and 2 L/min retrograde arterial return via the femoral artery and 2 L/min central venous return of arterialized blood via the internal jugular vein). Please note that, upon switch of VA to V-AV ECLS mode the LV dilatation (A.) directly normalized (B.), due to the reduction of LV afterload with 2 L/min instead of 4 L/min of retrograde support flow during VA ECLS. Please compare to Figure 5A movie and Figure 5B movie (e-supplement).

echocardiographic measurements that can be related to the degree of extracorporeal blood flow and concomitant support, such as mechanical ventilation, fluid loading and inotropic therapy.

Cardiac loading conditions. One of the major clinical challenges in the daily management of VA ECLS is to find the best compromise between the degree of ECLS flow meeting circulatory requirements and unloading the left ventricle to a sufficient degree.[7]

For peripheral VA ECLS, it has been repeatedly shown that arterialized blood directed retrogradely from the extracorporeal circuit into the descending aorta increases LV afterload as a function of flow.[6,7,47] This increased afterload may have deleterious consequences, such as potentially irreversible LV cavity dilatation, increasing filling pressures and pulmonary edema. It is, therefore, of paramount importance to always interpret LV dimensions and contractility as a function of ECLS flow, while also considering filling pressures and the intensity of inotropic support.[7] It is not always easy to detect changes in cardiac geometry upon the increase or decrease of VA ECLS flow alone, yet significant alteration of extracorporeal support, e.g., 4 to 2 L/min, can be expected to directly change cavity dimensions dramatically, as illustrated by converting peripheral VA ECLS to V-AV ECLS (Figure 5 and E14).

Especially in severe cardiogenic shock, when contractility of the native heart can be extremely limited, the echocardiographer should notice if the native LV ejection is (nearly) absent (Figure E14A-D movies and Figure E15 movie). A practical loss of LV ejection and aortic valve standstill can cause thrombi in the aortic root or even complete LV cavity thrombosis (Figure E–15).[48] Here, echocardiography is essential to monitor thrombus formation in the aortic root and LV cavity and confirm opening of the aortic valve. The latter can also be monitored at the bedside using peripheral arterial pressure tracings,[49] yet, when the LV is nearly non-ejecting, echocardiography is more sensitive and also enables differentiation between non-ejection due to diastolic problems, e.g., tamponade or hypovolemia and intrinsic systolic LV failure.

In the case of a non-ejecting LV, an alternative strategy must be implemented to prevent the disastrous consequences, as previously described (Figure E14A-D movies and Figure E15 movie). Strategies include the use of an intra-aortic balloon pump (IABP) or an Impella® device to lower afterload and promote LV ejection.[7] However, when using VA ECLS in combination with an IABP, peripheral arterial pressure tracings may not always reveal opening of the aortic valve since IABP-related pressure changes may occur in the setting of a closed aortic valve mimicking LV ejection (Figure E16). Alternatively, LV venting techniques, such as cannulation of the LV apex (VA-A configuration) in a so-called '1½' ventricular assist device (VAD) configuration or venting via a pulmonary vein V(LA)-A can be considered to lower preload, thereby, preventing LV dilatation.[3,50]

In order to optimize cardiac loading conditions during VA ECLS, extracorporeal blood flow should be tailored to a minimally acceptable level that allows sufficient circulatory support, systemic perfusion pressure to all vital organs and adequate cardiac (un)loading, which, in turn, will maximize cardiac recovery and weaning success.[3] In this context, it is tempting to speculate whether the integration of individual data on cardiac dimensions and hemodynamics as readily available at the bedside will allow the improvement of clinical management of VA ECLS in the near future. In a

Table 3. LV and RV echocardiographic parameters during full ECLS and weaning trials predictive of weaning success.

	Left ventricular function	Right ventricular function
During full ECLS support	Opening of the aortic valve Higher EF Higher VTI	3D EF >25%
During weaning trial	Absence of LV dilatation EF >20-25% VTI >10 cm TDSa >6 cm/s	Not well defined

3D: 3-dimensional; EF: ejection fraction; VTI: velocity time integral; TDSa: spectral tissue Doppler imaging mitral annulus peak systolic velocity.

proof-of-concept study, real-time cardiovascular computer simulation has recently been shown to allow patient-specific simulation of cardiac loading conditions during VA ECLS, using echocardiographic and related hemodynamic data as input parameters, but this approach awaits further clinical investigation.[6]

So far, serial echocardiographic studies focusing on cardiac dimensions and contractile function are imperative in all individuals dependent on VA ECLS. This imaging information can be derived on a daily basis and should allow individualization of the degree of extracorporeal support and also the need for adjuvant interventions to unload the left ventricle during VA ECLS, as reviewed recently.[6,7,24,51–53]

Weaning from VA ECLS tailored by echocardiography. Timing of VA ECLS cessation and weaning is a complex and critical process.[54–56] If LV and/or RV function has/have not recovered sufficiently to meet circulatory needs, cardiogenic shock and death may ensue if patients do not qualify for permanent VAD support.[3] Research efforts have, therefore, aimed at the identification of parameters effectively predicting weaning readiness and weaning success or failure. On top of clinical arguments and invasive measurements, echocardiography has played a pivotal role in this risk assessment. Two phases of prediction can be identified. The first being an assessment of weaning readiness, being evaluated during full ECLS flow. The second phase includes the assessment of echocardiographic weanability during a so-called weaning trial to evaluate the probability of weaning success.

During VA ECLS flow, several combined TTE and TEE measures have been linked to weaning readiness. Although cut-off values have not been clearly specified, a higher LV ejection fraction (EF) and aortic velocity time integral (VTI) during ECLS were both associated with successful outcome.[57] Interestingly, measures of diastolic filling did not correlate with successful weaning.[57] One study investigated echocardiographic characteristics of RV function predicting weaning success.[58] Three-dimensional RV EF was shown to correlate strongly to eventual weaning success, with a cut-off value of around 25%. However, it should be noted that both volumetric quantifications (including EF) and Doppler measurements are pre- and afterload dependent. No other specific criteria have been studied for the assessment of RV function during a weaning trial. Since the right ventricle is significantly unloaded during VA ECLS, it is inherently difficult to judge intrinsic RV contractility when weaning. Whether alternative approaches, such as creating an arterio-venous bridge or initiating a pump-controlled retrograde trial off (PCRTO), for more successful and durable weaning in LV and especially RV failure remains to be determined.[59–62]

In addition to echocardiographic measurements during 'full flow' VA ECLS, changes of parameters during weaning trials seem to add discriminative power in the prediction of weaning failure and success. Although protocols of weaning trials differ throughout studies,[63] regular approaches, mainly intended to judge LV recovery while still considerably unloading the RV, include a (stepwise) reduction of pump flow to a specific value, e.g., 1.5-2 L/min or to a certain percentage of the patient's optimal flow during a certain time-frame. These trials are then accompanied by comprehensive echocardiographic examinations. In a study with continuous TEE monitoring during a stepwise weaning trial, an adequate inotropic LV response without dilatation versus a reduced inotropic response and LV dilatation was associated with improved odds of LV recovery.[64] Both response patterns were, however, not clearly defined. In a study in 51 patients with peripherally and centrally cannulated VA ECLS, LV EF >20-25%, VTI >10 cm and spectral tissue Doppler imaging mitral annulus peak systolic velocity (TDSa) >6 cm/s were associated with weaning success (Table 3).[65]

All in all, echocardiography seems to add predictive power for weaning success in different phases of the treatment. It must be noted, however, that data supporting the use of these parameters are based on a few studies with limited numbers of patients. Therefore, future echocardiographic studies should focus on quantifying the discriminatory power of different parameters in different phases of the course of ECLS and, importantly, the clinical stability of the patient remains a *conditio sine qua non* for successful and long-lasting weaning success from ECLS.

Conclusion

Echocardiography is an essential imaging tool in daily clinical practice before, during and after the completion of ECLS. Specific and detailed knowledge of technical and pathophysiological aspects of all basic ECLS modes is mandatory in order to allow the optimal use of echocardiography. In this sense, echographic techniques facilitate and secure ECLS cannulation procedures and provide mechanistic insights in an individual's cardiac and respiratory condition on ECLS over time.

Future initiatives should focus on comprehensive, patient-specific tailoring of ECLS as can be derived from multimodality imaging where echocardiographic parameters can be integrated in real-time with, for example, hemodynamics and respiration. These approaches may aid to enhance the scientific significance of echocardiography in ECLS, which has not sufficiently been proven nor broadly been incorporated in international guidelines.

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Supplementary Material

All E figures and movie clips can be found online with this paper, http://journals.sagepub.com/doi/full/10.1177/0267659118766438.

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