Transesophageal echocardiography during lung transplantation (Review)

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Abstract. Lung transplantation (LTx) continues to be the primary curative intervention for end-stage lung disease, with post-transplant outcomes demonstrating substantial improvements in recent years. The present review summarizes recent advancements in the application of transesophageal echocardiography (TEE) during LTx as a diagnostic strategy for associated complications. TEE offers notable benefits for intraoperative monitoring during LTx, including the assessment of cardiac function, vascular anastomosis evaluation, support for cannula positioning and the management of extracorporeal membrane oxygenation. Comprehensive TEE knowledge is essential for anesthesiologists to optimize pharmacological interventions and enable early detection of intraoperative complications. This technique enhances clinical decision-making, thereby supporting the efficacy and safety of anesthesia management.

Contents

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1. Introduction

Lung transplantation (LTx) is a key therapeutic option for patients with end-stage pulmonary disease, particularly when other medical and interventional treatments-such as long-term oxygen therapy, pulmonary rehabilitation, pharmacological management (e.g., bronchodilators, corticosteroids) or noninvasive ventilation-fail to achieve adequate disease control (1). With advancements in anesthesia and surgical techniques in the past decades, short- and long-term survival have improved and the use of LTx has gradually expanded (2-4).

Anesthetic management involves specific challenges, particularly during the critical periods of LTx, such as the induction of anesthesia, the start of positive pressure ventilation, establishment and maintenance of single-lung ventilation, clamping and unclamping of the pulmonary artery (PA) and reperfusion of the transplanted lung (5). Tailoring anesthesia management to the underlying lung disease of the patient and the surgical process, with a particular emphasis on maintaining hemodynamic stability, is critically important (5). Although standard non-invasive monitoring-such as electrocardiography, non-invasive blood pressure measurement, pulse oximetry and capnography-is commonly used, hemodynamic monitoring during LTx must be tailored to the specific needs of each patient. PA catheters are a standard monitoring tool that provide valuable hemodynamic data, including PA pressure, cardiac output and mixed venous oxygen saturation, which are essential for guiding anesthesia and fluid management (6). However, transesophageal echocardiography (TEE) works by inserting a catheter with an ultrasound probe into the esophagus, enabling close-proximity, multi-plane scanning of cardiac structures. This allows for high-resolution, real-time imaging of cardiac anatomy, blood flow and functional status. In addition, during intraoperative extracorporeal membrane oxygenation (ECMO) support, hemodynamic measurements obtained via pulmonary artery catheters or other standard monitors may be compromised due to altered flow patterns and non-pulsatile circulation; however, TEE provides direct visualization of vascular structures and cardiac function, offering multidimensional parameters and thereby allowing for a more comprehensive and accurate hemodynamic evaluation (6).

TEE was first proposed in 1976, and can produce both two-dimensional (2D) and three-dimensional (3D) images with high resolution (5,7). This enables clinicians to detect critical intraoperative pathophysiological changes, such as right ventricular dysfunction or pulmonary vascular anastomotic abnormalities, at an early stage and to implement timely interventions to prevent serious complications (5). The guidelines established by the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists in 2020 recommend the use of TEE in the management of patients undergoing LTx (8). Notably, the latest guidelines from the International Society for Heart and Lung Transplantation for the first time classify the use of TEE in LTx as class I recommendation, indicating that there is evidence and/or general agreement that the procedure is beneficial, useful and effective in clinical practice (9). Current guidelines consistently recommend initiating TEE promptly, as standard hemodynamic assessments do not adequately inform clinical decision-making (7-9). As a multidisciplinary diagnostic and monitoring modality, the intraoperative application of TEE necessitates close collaboration among anesthesiology, surgical and critical care teams for integrated image interpretation and real-time decision support (10). Furthermore, TEE has been integrated into critical care ultrasonography protocols, particularly in mechanically ventilated patients, where its bedside evaluation of cardiac function has been widely validated (11). Perioperative use of TEE facilitates optimized hemodynamic management, thereby improves patient outcomes by enabling timely interventions, reducing perioperative complications, and supporting better organ perfusion (12). Nevertheless, comprehensive and updated evidence summarizing the role of TEE during LTx remains limited.

The present review summarizes the latest advances in the application of TEE in LTx, with a particular focus on its role in diagnosing and managing intraoperative complications. Compared with previous reviews, the present review provides updated insights into the integration of TEE in the intraoperative management of ECMO (13,14).

2. Monitoring of LTx with TEE

TEE provides comprehensive, real-time data that enable precise management tailored to each phase of LTx (8). Table I outlines the essential TEE monitoring contents recommended throughout the four main stages of the procedure (8,13,14). After anesthesia induction, initial hemodynamic fluctuations are common (5). Therefore, once hemodynamic stability is achieved during Period 1, a baseline TEE examination should be performed prior to chest opening, providing a reference for the assessment of subsequent changes (13). During Period 1, preparatory steps such as positive pressure ventilation and single-lung ventilation may also induce hemodynamic fluctuations, requiring close TEE monitoring to assess changes and adjust the management plan (13). Period 3, defined as the release of the PA and atrial [or pulmonary vein (PV)] clamps and subsequent reperfusion of the transplanted lung, occurs in rapid succession. Therefore, for monitoring and management purposes, they are considered as a single critical period (Table I) (13,14).

3. Intraoperative TEE during hemodynamic instability

Due to the proximity of the probe to the heart and major blood vessels, TEE offers an ultrasonic window that facilitates detailed visualization of cardiac anatomy and hemodynamic characteristics during LTx (15). In 2021, the International Consensus Recommendations for Anesthetic and Intensive Care Management of LTx approved the use of TEE for hemodynamic monitoring during the preoperative, intraoperative, and postoperative phases of perioperative management (16).

Hemodynamic instability due to right cardiac dysfunction. Pulmonary impairment in patients undergoing LTx typically leads to cardiac compensation that can result in long-term structural changes, often manifesting as pulmonary hypertension (PH), right ventricular (RV) dilation and abnormal ventricular septum (such as thickening or morphological changes) (17,18). Before transplantation (designated as period 1 in Table I), the heart and PA should be systematically assessed to establish baseline values, which helps identify the cause of hemodynamic instability (14). During transplantation (periods 2 and 3, Table I), acute hemodynamic changes caused by PA clamping/release, increased pulmonary vascular resistance (PVR) due to reperfusion, or shifts in RV load upon ECMO initiation/withdrawal can worsen pre-existing right heart dysfunction (19,20). RV function and PA pressure show improvement and a trend towards normalization after LTx (period 4, Table I) and post-transplant RV function may serve as a prognostic indicator for patient outcomes (21). Although RV dysfunction is not unique to LTx, it is commonly observed during the procedure; therefore, continuous intraoperative monitoring of right heart function is highly recommended (13). TEE is regarded as a valuable and widely accepted technique to guide the intraoperative management of PH and RV failure during LTx.

For the assessment of RV dysfunction, 2D TEE imaging reveals RV dilation with a corresponding decrease in left ventricular (LV) size (14). An example case in Fig. 1 shows intraoperative RV failure, with an enlarged right ventricle compressing the left ventricle into a distinct D-shaped configuration, indicative of RV pressure overload (22,23). Normal RV diameters are defined as 2.5-4.1 cm at the basal level and 1.9-3.5 cm at the mid-level, with a longitudinal dimension of 5.9-8.3 cm (24). RV dysfunction is often associated with tricuspid valve (TV) abnormalities. Severe tricuspid regurgitation is typically associated with tricuspid annular dilation, indicated by a jet area >10 cm^2 and a venous constriction width >7 mm (14,25). RV systolic dysfunction is identified by a tricuspid annular plane systolic excursion (TAPSE) of <17 mm and a RV fractional area change (RVFAC) of <35% (25).

Hemodynamic instability due to left cardiac dysfunction. To date, reviews on LTx have primarily focused on right heart function but have rarely mentioned left heart function; however, LV function serves a critical role in maintaining the overall hemodynamic stability during and after LTx (13,14). LV preload is reduced by frequent RV dysfunction in patients with chronic lung disease (26). If prolonged, this reduction may lead to LV myocyte atrophy, which can be related to reduced myocardial contractility and diastolic dysfunction (27).

Table I. Transesophageal echocardiography monitoring recommended across the LTx procedure.

	Critical periods of LTx			
TEE monitoring	Period 1[a]	Period 2[b]	Period 3[c]	Period 4[d]
Cardiac structure	Y	Y	Y	Y
Cardiac systolic function	Y	Y	Y	Y
Cardiac diastolic function	Y	Y	Y	Y
Guide ECMO cannula placement	Y	N	N	N
Troubleshooting for ECMO	N	Y	Y	Y
PV flow	Y	N	Y	Y
PA flow	Y	N	Y	Y
Anastomotic site	N	N	Y	Y
Air embolism	N	N	Y	N
Thrombosis	N	N	Y	Y
Pulmonary edema	N	N	Y	Y
Atelectasis	N	N	N	Y
Pericardial effusion	N	N	N	Y
Pleural effusion	N	N	N	Y

[a]Post-induction, pre-surgical phase; [b]PA, atrial or PV clamping; [c]release of PA, atrial or PV clamp and reperfusion of the transplanted lung; [d]chest closure. LTx, lung transplantation; TEE, transesophageal echocardiography; ECMO, extracorporeal membrane oxygenation; PV, pulmonary vein; PA, pulmonary artery; Y, yes (TEE applicable); N, no (TEE not applicable).

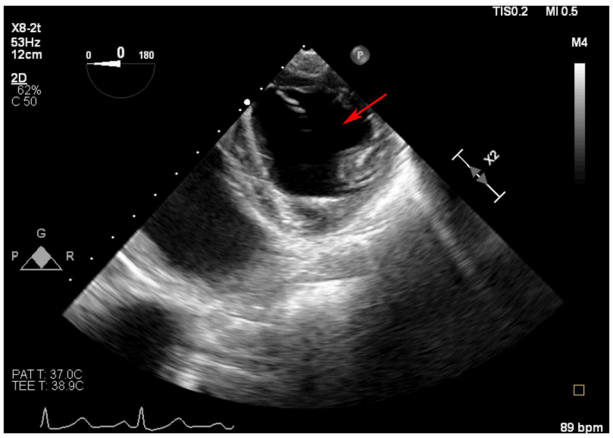

Figure 1. A 2D transesophageal echocardiography image obtained by the authors from a 14-year-old male patient undergoing lung transplantation for obliterative bronchiolitis. The image demonstrates an enlarged RV alongside a relatively compressed LV, with the D-shaped deformation of the LV serving as a hallmark of RV pressure overload. The D-shaped LV is marked by the red arrow. RV, right ventricle; LV, left ventricle.

LV diastolic dysfunction increases left atrial pressure and pulmonary venous congestion, thereby worsening cardiogenic pulmonary edema and risking primary graft dysfunction (PGD) misdiagnosis (28). Therefore, monitoring of LV function is crucial for identifying potential issues, optimizing fluid management, assessing the indirect effects of RV function and preventing postoperative complications.

By monitoring the blood flow velocity and cross-sectional area of the LV outflow tract, TEE can calculate the stroke volume and cardiac output per beat, thereby reflecting the overall function of the left ventricle (29). Numerous conventional parameters used to evaluate diastolic function, including early (E) and late transmitral inflow velocities and deceleration time, are influenced by loading conditions, limiting their ability to reliably assess impaired relaxation (30). By contrast, the E/mitral annular velocity (E/é) ratio is less affected by elevated filling pressures and is closely associated with the isovolumic relaxation time constant, making it a more accurate reflection of delayed relaxation (30). Elevated E/é ratios are indicative of more severe diastolic dysfunction and increased filling pressures, with an E/é value of >8 considered highly sensitive for diagnosing diastolic dysfunction (30). The present review provides a summary of the latest research on TEE monitoring of left heart function in LTx. Notably, there may be future possibilities to combine artificial intelligence with TEE to automatically evaluate LV function during hemodynamic monitoring.

Hemodynamic instability due to vascular anastomosis-related complications. LTx is a complex procedure involving vascular anastomosis between the two PAs, and between the PV and left atrium (31). To date, five types of vascular anastomosis-related complications have been described in the literature (32). Type I is described as anastomotic buckling (due to excessive donor vessel length) and anastomotic deformation (due to insufficient donor vessel length), or hilar malalignment, leading to anastomotic stenosis and thrombosis. Type II is caused by transposition of the donor vessel relative to the recipient vessel. Type III refers to true anastomotic stenosis caused by suture overtightening or misalignment. Type IV is caused by intraluminal obstruction, secondary to thrombosis or occlusion. Type V refers to stenosis with an additional luminal

mass effect. The presence of anastomotic complications in the PA may impede blood flow to the lung allograft, thereby increasing RV afterload and leading to PH, RV dysfunction, hypotension, hypoxemia, PGD, and eventually allograft failure and death (33-36). Anastomotic obstruction of the PV may lead to similar adverse outcomes. In severe cases, obstruction of the PA and PV may require extracorporeal life support (ECLS) (37). To prevent these complications, early intraoperative diagnosis is crucial. Utilizing TEE to assess vascular anastomoses during periods 3 and 4 can aid the timely identification of PA or PV obstructions. This proactive approach may help stabilize hemodynamics, reduce the risk of allograft failure and improve patient survival outcomes (35,38).

The mid-esophageal ascending aortic short- and long-axis views are key TEE views for the evaluation of PA anastomoses after transplantation (35). For right PA anastomosis, optimizing the probe angle and multiplane angle (0-60˚) allows for improved assessment of hemodynamic parameters, including turbulence, peak velocity and pressure gradients (35). Due to anatomical obstructions, left PA anastomosis is challenging to visualize directly and often requires indirect assessment through PV Doppler signals or intraoperative contact echocardiography for additional imaging support (35). A previous case series and review of vasculopathy concluded that a diagnosis of obstruction after vascular anastomosis requires a diameter of ≥75% of the native PA and evidence of laminar, nonturbulent flow (35). Clinically significant symptoms of PA obstruction occur with a mean peak pulmonary arterial velocity of >2.6 m/sec or a pulmonary arterial lumen diameter of <0.8 cm postoperatively (39). If the pressure gradient at the anastomotic site is >64 mmHg, it may indicate a serious obstruction (35).

The assessment of PV anastomoses following LTx using TEE requires optimization of specific imaging views to visualize individual PVs. The left upper PV is optimally assessed using the mid-esophageal 2-chamber view, with slight probe withdrawal to visualize its position super posterior to the left atrial appendage (35). The left lower PV, often challenging to visualize due to its deeper location, requires the mid-esophageal 4-chamber (ME_4Ch) view, with probe rotation and advancement to enhance imaging (35). Similarly, the right upper PV and right lower PV are accessed via the ME_4Ch view, with appropriate probe rotation and positional adjustments (35). Color Doppler helps locate PVs and detect turbulence or abnormal flow, while spectral Doppler quantifies velocities and triphasic waveforms to diagnose anastomotic issues such as stenosis or thrombosis (10). In vascular anastomosis-related complications, TEE can monitor obstruction. Peak PV velocities >100 cm/sec suggest possible obstruction; velocities >170 cm/sec with a clearly elevated baseline strongly indicate obstruction. If velocities fall between 100 and 170 cm/sec, additional signs such as turbulence or elevated baseline should be assessed (34,40). However, hyperdynamic myocardial function can be caused by drugs that have a positive inotropic effect or reduce PVR, increase cardiac output and thus PV flow velocity, which needs to be differentiated from true vascular obstruction. If possible, all four PVs should be examined, as a notable increase in flow velocity in one PV is indicative of severe obstruction. A PV diameter >0.5 cm has been shown to reduce the risk of thrombosis and unilateral pulmonary edema, whereas a PV diameter <0.25 cm has been described as the threshold for transplant failure (28,32).

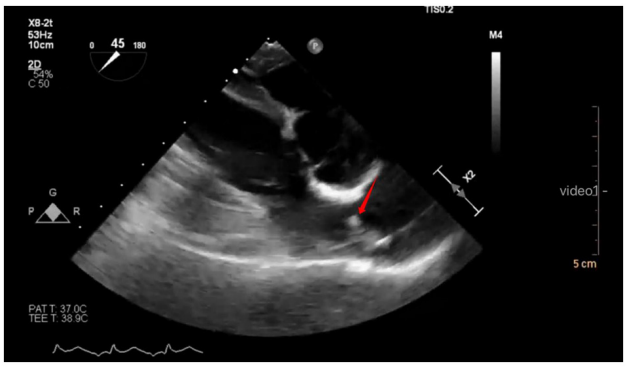

Figure 2. Transesophageal echocardiography image obtained by the authors from a 59-year-old female patient undergoing lung transplantation for interstitial lung disease. The image of a right ventricular inflow and outflow tract view, showing a floating thrombus near the pulmonary valve in the right ventricular outflow tract, marked by the red arrow.

An echogenic mass originating from one of the PVs and extending into the left atrium observed on 2D echocardiography suggests the presence of a thrombus (33). When a thrombus appears in the cardiovascular system, TEE shows visible bright floating objects (Fig. 2). A clearer dynamic visualization is provided in Video S1. Even in the absence of a visible mass, Doppler imaging should be utilized to assess for PV thrombosis or obstruction (33). Normal systolic (S wave) and diastolic (D wave) flow velocities typically range between 30-60 cm/sec (33). A spectral Doppler velocity >100 cm/s, the presence of turbulence or a shift in the usual systolic flow dominance (S wave > D wave) may indicate marked PV obstruction, warranting further investigation (33). The diagnostic accuracy of TEE in identifying intracardiac thrombi is well-established. TEE has a sensitivity of 100% and a specificity of 99% for detecting thrombi within the left atrium (41).

At present, pulmonary vascular occlusion after LTx is treated with surgical revision of the anastomotic site, endovascular angioplasty, endovascular stenting of the anastomosis, conservative thrombolysis and anticoagulant therapy (39,42,43). Given that thrombosis is detrimental to allograft and patient survival, clinicians should be familiar with the clinical and echocardiographic patterns of thrombosis during the early postoperative period after LTx (44). Based on the TEE findings, the size and flow velocity of a thrombus at the anastomotic site can be used to guide postoperative management (44). Systemic anticoagulation therapy is recommended if clinically feasible. If anticoagulation is not feasible, the thrombus is small or the blood flow velocity does not indicate severe obstruction, conservative management is recommended. In cases of acute thrombosis with large thrombi or hemodynamic instability, thrombectomy and anastomotic repair should be considered (45).

Other causes of hemodynamic instability. In addition to the aforementioned causes, other causes of hemodynamic instability during LTx can be diagnosed using TEE. A hallmark of LTx is the restrictive fluid replacement strategy commonly employed during the perioperative period to minimize

complications such as graft edema and RV overload (46). While this approach is crucial for protecting graft function, it can lead to low intravascular volume and reduced preload, potentially resulting in hypotension and impaired cardiac output. These hemodynamic challenges require precise volume assessment and management. TEE is an indispensable tool for the evaluation of the volume status of the heart and large vessels in this context. For example, in the transgastric short-axis view, under conditions of low volume, particularly during LV contraction, the papillary muscles may draw closer together, even making contact, which is a phenomenon referred to as 'kissing papillary muscles' (Video S2) (47). While 'kissing papillary muscles' are observed in some cases as a result of reduced afterload, they are more frequently associated with hypovolemia during LTx. This highlights the importance of considering both preload and afterload when assessing volume status. It is also critical to note that volume assessments should be made during diastole, as systolic measurements do not accurately reflect ventricular volume. Combining this understanding with other TEE parameters-such as left ventricular end-diastolic area, stroke volume variation, velocity-time integral and collapsibility of the inferior vena cava-allows for precise fluid administration to optimize hemodynamics while avoiding volume overload, a key consideration in the restrictive fluid management strategy of LTx (48).

If the size of the chest cavity does not match that of the donor lung, hemodynamic instability may occur because of chest wall compression during chest closure (49). In this case, TEE findings reveal donor lung compression with reduced LV filling, elevated PA pressures and septal shift toward the left, indicative of increased RV strain. These findings strongly suggest a donor/recipient size mismatch; therefore, delayed chest closure may be considered an appropriate intervention to alleviate lung compression and restore hemodynamic stability (50).

Use of drugs for hemodynamic management under TEE guidance. Hypervolemia is associated with pulmonary edema in patients undergoing thoracic surgery; therefore, it should be prevented in patients undergoing LTx (51). Drugs can be used to maintain hemodynamic stability and prevent pulmonary edema (46); however, if drugs fail to maintain organ tissue perfusion, fluid resuscitation should be considered. Inotropic support should be administered based on baseline cardiac function, particularly RV function and the degree of vasodilation in patients with elevated PA pressure (52). The management of hemodynamic instability in patients undergoing LTx involves the use of drugs to support positive muscle strength and the restoration of systemic vascular resistance (SVR) and PVR (52). Certain patients may experience notable blood loss during surgical procedures, necessitating volume resuscitation to restore hemodynamic stability (53). TEE monitoring serves a critical role in guiding therapeutic decisions, including the selection of appropriate drugs or blood products. For instance, the appearance of 'kissing papillary muscles' on TEE, which are indicative of severe hypovolemia, may indicate the need for volume resuscitation, while a reduced TAPSE or RVFAC may suggest compromised RV function and the need for inotropic support (14,25).

During surgery, pulmonary arterial hypertension is primarily managed with inhaled nitric oxide (NO), inhaled prostaglandin E_1 analogs, and intravenous milrinone or prostaglandin E_1 analogs (54). NO is essential for reducing PVR in ischemia-reperfusion injury (55). Prior to the adoption of inhaled NO, prostaglandin E_1 analogs were the mainstay for controlling RV load in patients with PH; however, their long half-life often causes hypotension, especially in patients with RV dysfunction reliant on adequate coronary perfusion pressure (39,56). Milrinone, a phosphodiesterase-3 inhibitor, has exhibited efficacy in reducing lung injury in acute lung injury models; however, its use in LTx remains limited (57). Vasopressin can increase SVR without elevating PVR, optimizing RV perfusion without adding to the afterload (58). Additionally, dopamine, adrenaline, norepinephrine and dobutamine are commonly employed as positive inotropes during LTx.

TEE also facilitates real-time monitoring of the response to these therapies. For example, improvements in TAPSE and RVFAC can indicate effective inotropic support, while reductions in tricuspid regurgitation velocity reflect successful pulmonary vasodilation. Morphological changes, including resolving RV dilation or septal flattening, may further confirm the efficacy of interventions. By enabling continuous assessment of RV function and load, TEE ensures timely adjustments to pharmacological therapies, helping to optimize fluid management, maintain hemodynamic stability and prevent complications such as pulmonary edema or right heart failure.

TEE effectively utilizes real-time imaging and quantitative parameters to assess the potential causes of hemodynamic instability, including cardiac dysfunction, complications related to vascular anastomosis and abnormalities in volume status. TEE also provides valuable guidance for clinical interventions, including determining the need for pharmacological support, optimizing drug selection and evaluating whether to initiate ECLS.

4. TEE during guided ECMO in LTx

The use of ECLS in LTx has steadily increased over the past decade, since the first successful LTx involving cardiopulmonary bypass (CPB) (59,60). In cases of limited donor availability and poor overall recipient condition, ECLS is used during LTx to ensure hemodynamic stability (61). The main advantage of ECLS is that it prevents volume overload and reperfusion injury in the first transplanted lung during bilateral LTx (62). The types of ECLS include CPB, venovenous ECMO (VV ECMO) and venoarterial ECMO (VA ECMO) (52).

ECLS is an important tool used to enhance surgical safety. The use of VV ECMO or VA ECMO as alternatives to CPB has become more popular (59). In 2022, the American Association of Thoracic Surgeons published an expert consensus document on the use of MCLS in LTx (59). This document provides 36 recommendations to guide professionals involved in the care of patients with end-stage lung disease who are considering transplantation. Among the recommendations, TEE is emphasized as a critical tool for evaluating ECMO dysfunction and related complications. These complications, including malpositioned cannulas, thrombosis, pericardial tamponade or inadequate ventricular unloading, require prompt and accurate assessment. The importance of TEE in this context is

underscored by a strong consensus and a 92% agreement score among experts (59). Several studies have reported the use of TEE to guide ECMO; however, a comprehensive summary is lacking (63-65). Therefore, the present review summarizes the findings of the relevant studies.

ECMO involves cannulation of blood vessels to create a bypass circuit consisting of a pump and a membrane oxygenator (63). Bicaval VV ECMO is a well-recognized and validated therapy that requires the use of single or double peripheral venous access for the insertion of two different-sized cannulas to achieve adequate blood oxygenation (65). Traditionally, VV ECMO was performed using two cannulas [a femoral venous drainage cannula and an internal jugular (IJ), subclavian or second femoral venous cannula] to return blood to or near the right atrium (RA); however, the recently developed dual-lumen cannula can be used independently in the IJ vein (63). To ensure correct cannula positioning during surgery, TEE is an invaluable tool for both initial placement and continuous monitoring. Proper positioning requires the drainage port to reside in the superior vena cava (SVC) and the return port in the RA, with flow directed toward the TV (63). Using TEE, the mid-esophageal 4-chamber view can confirm the flow direction toward the TV, while the mid-esophageal SVC long-axis view verifies the location of the drainage port in the SVC (63). Additionally, the transgastric RV inflow-outflow view can confirm that the return port is in the RA without entering the right ventricle or contacting the atrial wall (63). In cases of malpositioning, TEE may reveal abnormal flow patterns, turbulence or mechanical compression of cardiac structures. These findings highlight the importance of continuous monitoring and adjustment to ensure optimal cannula function and prevent complications.

TEE provides guidance for all three key steps of cannulation: Wire placement, assessment of the precise depth of cannulation in the inferior vena cava (IVC) and orientation of the reperfusion port to the TV (66). Proper insertion and accurate positioning of the cannula are important for the safety and optimal performance of the dual-lumen cannula. Malpositioned cannulas can result in hemodynamic instability. For example, a misaligned return port may direct flow against the atrial wall, causing turbulence or inadequate flow (63). Similarly, an improperly placed drainage port may fail to fully capture venous return. TEE findings such as turbulence, low flow velocity or changes in chamber size (such as RV dilation) can indicate malpositioning (63). Structural injuries, such as atrial wall damage or vessel perforation, may be identified on TEE by the presence of hematomas, pericardial effusion or abnormal contact between the cannula and cardiac structures (63). Early detection of such issues allows for immediate correction of cannula position and, if necessary, surgical intervention to address injuries (67-69).

Thrombosis is the main complication associated with low ECMO flow (70). TEE is used to guide the diagnosis and treatment of thrombosis during ECMO (71-73). Obstruction of the cannula in ECMO is detected based on reduced blood flow velocity, hemodynamic instability and poor blood oxygenation. In addition, if refractory hypoxemia occurs during surgery after other causes (e.g., inadequate ECMO support due to insufficient flow, sweep gas failure or oxygenator dysfunction) have been excluded, TEE should be used for the early detection of a malpositioned cannula (63). In most cases, malpositioning of the cannula is predicted by deteriorating oxygenation during ECMO (63). TEE can be used to detect other complications related to cannulation such as hemothorax, pneumothorax and mediastinal or pericardial bleeding (63).

The risk of catheter malpositioning and tamponade may be higher in children than in adults because children have smaller, thinner blood vessels and smaller heart chambers (65,74). In addition, a particular concern in the pediatric population is the formation of a conduit loop, despite TEE images revealing the entry of the guidewire tip into the RV (63). After 2D TEE is used to guide the guidewire position, 3D TEE should be used to exclude the possibility of the formation of a guidewire loop during advancement. The oxygenation efficiency of the ECMO circuit depends on the flow rate of the pump relative to the cardiac output of patients. Accordingly, oxygenation in patients should be increased with increasing ECMO flow rate. If this does not occur, blood should be suspected to recirculate between the inflow and outflow cannulas, indicating the formation of a conduit loop (64). A case report of cardiac perforation during placement of a dual-lumen catheter in neonates highlighted that slight movement of the catheter in this population may lead to tip misalignment, and that using wire navigation to connect the RA to the IVC may be particularly difficult and dangerous (74). Direct contact between the tip of the wire or dilator and the IVC wall should be avoided. Neonatal experts recommend that TEE should be performed after catheter placement and before initiating ECMO to predict complications related to ECMO and to prevent cardiac arrest during immediate drainage (74).

A recent study has shown that TEE-guided ECMO is increasingly used in LTx due to its low radiation dose and bedside convenience (75). The present review summarizes specific monitoring of TEE in patients undergoing ECMO during LTx. However, studies on ECMO weaning during LTx and data validating the effectiveness of TEE in guiding ECMO are lacking.

5. Use of TEE in other aspects of LTx

Before LTx, the interatrial septum should be checked for the presence of a patent foramen ovale or an atrial septal defect (34). In the presence of a large atrial septal defect, RV pressure after LTx may lead to severe left-to-right shunting, resulting in high blood flow and transplant failure (76).

TEE can be used to detect the formation of a bronchovenous fistula (BVF) during LTx, especially in patients with severe pleural adhesions (77). BVF is a rare complication that can cause arterial gas embolism in important organs (including the heart and brain), leading to high mortality rates. Taguchi *et al* (77) reported that patients often receive high airway pressure ventilation during LTx and the surgical procedure can easily damage the bronchi and pulmonary vessels, leading to BVF. TEE can detect bubbles in the left side of the heart, facilitating early diagnosis and prompt treatment of BVF. The treatment goal is to maintain hemodynamic stability and minimize air entry into the bloodstream (reducing airway pressure and single-lung ventilation). Timely administration

of pure oxygen can effectively treat hypoxemia and reduce air bubbles by eliminating nitrogen. TEE is an effective tool for the early diagnosis of BVF during LTx, which can improve the prognosis (77).

As mentioned in the 2020 Guidelines for the Use of TEE to Assist with Surgical Decision-Making in the Operating Room, TEE can help diagnose gas embolism in the left ventricle during reperfusion when the left atrial clamp is removed and the donor lung is implanted (8).

For certain specialized intraoperative support techniques, including the novel hybrid VA ECMO/CPB circuit, TEE monitoring can be utilized to adjust the ECMO flow rate and determine whether mode conversion is necessary (78,79).

After chest closure, TEE should be performed to determine the presence of atelectasis and pulmonary edema, or pulmonary tamponade occurring during severe emphysema or excessive lung inflation, providing a reference value for subsequent patient ventilation and volume management (80).

6. Conclusion and future perspectives

LTx is a complex procedure for both surgeons and anesthesiologists. Successful anesthesia during LTx can maintain hemodynamic stability and improve the prognosis. Therefore, anesthesiologists should possess expertise in TEE to manage intraoperative anesthesia and care. In addition, communication between anesthesiologists and LTx teams during surgery is crucial for achieving an optimal prognosis.

Current research primarily focuses on intraoperative monitoring, lacking comprehensive integration and analysis of continuous perioperative TEE data, thereby limiting a thorough evaluation of its clinical value and the assessment of multidisciplinary collaboration on patient outcomes (13,77). Future research should establish a robust multidisciplinary integration framework, spanning preoperative assessment, intraoperative monitoring, intensive care unit applications and postoperative follow-up. Such an integrative approach would not only provide cohesive support for perioperative decision-making but also identify dynamic clinical changes often overlooked by intermittent monitoring, ultimately optimizing patient management strategies and improving clinical outcomes.

Moreover, the application of TEE in pediatric LTx remains underexplored. Current practice in this population primarily relies on experience extrapolated from adult cases, with limited evidence from large-scale studies or pediatric-specific guidelines. Future investigations should focus on assessing the role of perioperative TEE in improving graft survival and reducing complications in children. Additionally, efforts are warranted to develop TEE probes and imaging modalities tailored to the unique anatomical features of pediatric patients.

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Authors' contributions

JX and ZX conceived and designed the review, conducted the literature search and analysis, drafted the main sections and revised the manuscript. GL, YL and YY assisted with the literature search, data integration and discussion and contributed to manuscript revision. JZ and QG prepared the figures, organized the literature and contributed to content editing. XT and RW ensured the scientific accuracy and clinical relevance of the review and participated in the final revision. MY supervised the study, guided manuscript preparation and conducted the final review. Data authentication is not applicable.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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