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AHA SCIENTIFIC STATEMENT

Considerations of Intraoperative Transesophageal Echocardiography During Adult Cardiac Surgery: A Scientific Statement From the American Heart Association

Endorsed by the American Society of Echocardiography (ASE), and the Society of Cardiovascular Anesthesiologists (SCA).

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ABSTRACT: Intraoperative transesophageal echocardiography is used with increasing frequency in cardiac surgery for monitoring and diagnostic purposes. Recent data have shown the impact of improved outcomes in patients undergoing cardiac surgery and the use of intraoperative transesophageal echocardiography in managing complex surgical decisions. However, specialty society recommendations have not been updated to reflect these trends. This scientific statement reviews the state-of-the-art practice of intraoperative echocardiography, summarizes the association of the use of intraoperative transesophageal echocardiography with enhanced outcomes, and provides specific perioperative and procedural transesophageal echocardiography considerations in the cardiac surgical population.

Key Words: AHA Scientific Statements ■ cardiac surgical procedures ■ cardiac valve annuloplasty ■ coronary artery bypass ■ echocardiography, transesophageal ■ heart-assist devices ■ heart transplantation ■ lung transplantation

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The utility of intraoperative transesophageal echocardiography (TEE) has evolved significantly since the latest clinical guidelines were published, and intraoperative TEE has become increasingly important for monitoring and decision-making in cardiac surgery. Recent evidence demonstrates that intraoperative TEE use is associated with decreased mortality and improved clinical outcomes (Figure 1). Specific intraoperative echocardiographic parameters can be used prognostically because they have been shown to be associated with clinical outcomes. This scientific statement summarizes the latest indications for intraoperative TEE use in cardiac surgery, its association with outcomes, and specific considerations for intraoperative TEE for various types of cardiac surgeries in which TEE plays a crucial role.

USE AND GENERAL PRINCIPLES OF INTRAOPERATIVE TEE

Intraoperative TEE Use and Society Guidelines

Intraoperative TEE is a crucial monitoring and diagnostic tool that aids in patient management across a spectrum of cardiac surgeries. Notably, guidelines and statements from various societies have provided differing recommendations for intraoperative TEE use in cardiac surgery. Many of these have not been updated to include recent evidence

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suggesting that intraoperative TEE use improves clinical outcomes, including mortality, after cardiac surgery. The 2010 American Society of Anesthesiology practice guidelines state that "TEE should be used in all open heart (eg, valvular procedures) and thoracic aortic surgical procedures and should be considered in coronary artery bypass graft surgeries" in adult cardiac surgery patients in the absence of contraindications.[1] The 2011 American College of Cardiology Foundation (ACCF)/American Heart Association (AHA) Guideline for Coronary Artery Bypass Graft Surgery (CABG)[1a] endorses intraoperative TEE for coronary artery bypass graft (CABG) with a Class 2a, Level of Evidence B recommendation. In addition, the 2020 American Society of Echocardiography guidelines, in collaboration with the Society of Cardiovascular Anesthesiologists and the Society of Thoracic Surgeons (STS), note that intraoperative TEE use is suggested and that a complete echocardiographic evaluation is always recommended and desirable in patients undergoing cardiac procedures.[2]

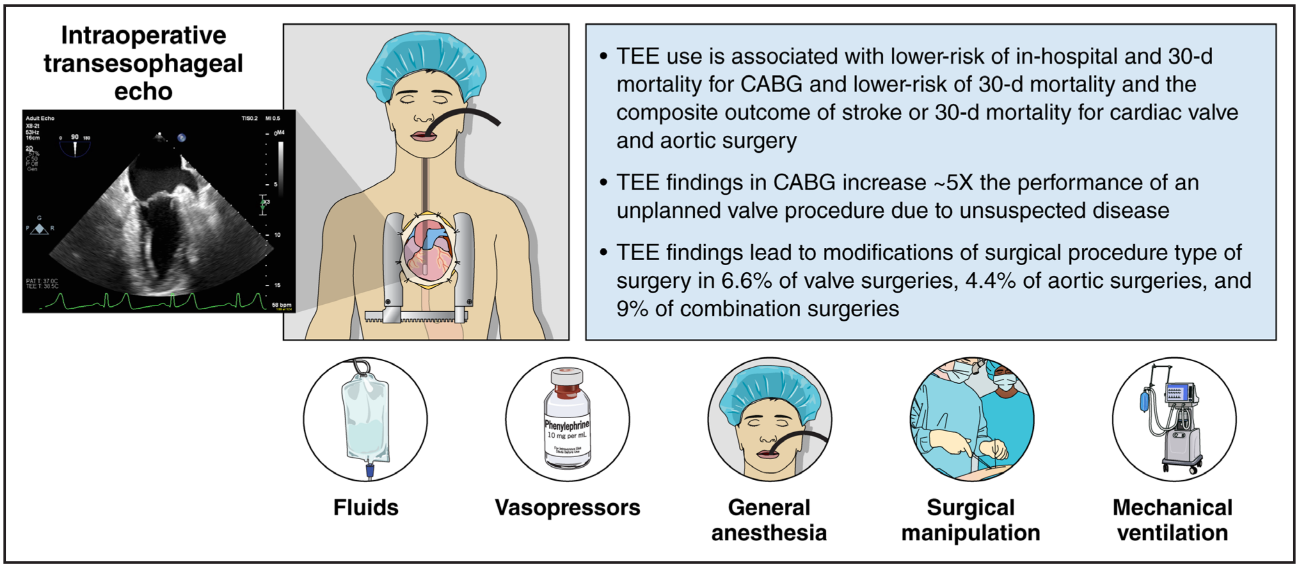
However, the "2020 ACC/AHA Guideline for the Management of Patients with Valvular Heart Disease" provides a Class 2b recommendation for intraoperative TEE in patients undergoing valve repair or replacement of the aortic, mitral, tricuspid, or pulmonic valves, with a Class 1b recommendation reserved only for the management of infective endocarditis or primary mitral regurgitation (MR) valvular surgeries.[3] The updated "2021 ACC/AHA/SCAI [Society for Cardiovascular Angiography and Interventions] Guideline for Coronary Artery Revascularization" kept intraoperative TEE for CABG as a Class 2a recommendation while further delineating that "intraoperative TEE allows real-time assessment of heart valve function and pathology and aids in surgical and anesthetic decision-making as a tool for real-time assessment of hemodynamic status, regional wall motion, ventricular function, valve anatomy, and diastolic function in patients undergoing cardiac surgery."[1a]

Trend of Intraoperative TEE Use Over Time

The intraoperative TEE landscape has evolved considerably with increased use over the past 10 years (Figure 2). In the most updated data from the STS Adult Cardiac Surgery Database from 2017 to 2021, TEE was used in 73% of all open cardiac surgeries, increasing from 71.4% in 2017 to 75.2% in 2021.[6] TEE use has increased most dramatically for isolated CABGs, from 39.9% to 62.1% from 2011 to 2019[7] and from 58.8% to 66.4% from 2017 to 2021, compared with valve replacements and combined CABG/valve procedures in which TEE was already used in >84.1% of cases in 2017, and it continues to increase.[6]

General Principles of Intraoperative TEE

A comprehensive intraoperative TEE study using multiple imaging planes, adhering to established guidelines,[8]



- TEE use is associated with lower-risk of in-hospital and 30-d mortality for CABG and lower-risk of 30-d mortality and the composite outcome of stroke or 30-d mortality for cardiac valve and aortic surgery
- TEE findings in CABG increase ~5X the performance of an unplanned valve procedure due to unsuspected disease
- TEE findings lead to modifications of surgical procedure type of surgery in 6.6% of valve surgeries, 4.4% of aortic surgeries, and 9% of combination surgeries

Figure 1. TEE use is associated with reduced mortality, improved outcomes, and improved surgical decision-making in cardiac surgery.

Bottom icons represent the altered physiological conditions that exist in the anesthetized cardiac surgical patient that could affect intraoperative transesophageal echocardiography (TEE) interpretation of cardiac and valve function. 1. Fluid represents the changing preload conditions that can affect cardiac and valve function (eg, hypovolemia due to preoperative fasting, surgical bleeding, and fluid resuscitation with crystalloid and blood products). 2. Vasopressors represent the vasoactive medications that could affect preload, afterload, heart rate, contractility, valve function, and cardiac function. 3. General anesthesia through intravenous and inhaled agents can cause venous and arterial dilation, decreased arterial and venous tone, and negative inotropy and affect preload, afterload, and heart rate. 4. Surgical manipulation on the heart can alter preload and valve anatomy and transiently change cardiac and valve function. 5. Mechanical ventilation, by increasing intrathoracic pressure and alveolar pressure, and the potential application of positive end-expiratory pressure decrease preload and can alter cardiac and valve function. CABG indicates coronary artery bypass grafting; and echo, echocardiography.

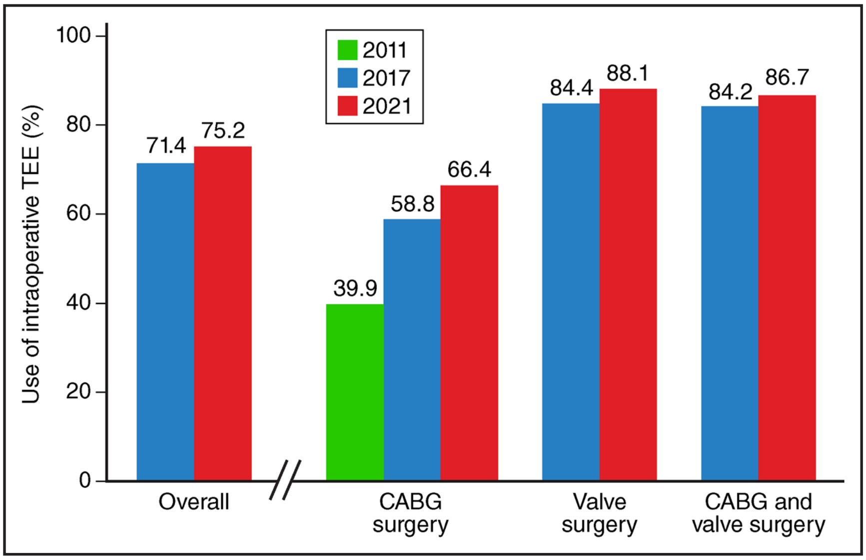


Figure 2. Use of intraoperative TEE in cardiac surgery from 2011 to 2021. Numbers on top of the bars represent the percentage of transesophageal echocardiography (TEE) use in 2011 (green), 2017 (blue), and 2021 (red). CABG indicates coronary artery bypass grafting.

is essential for full characterization of the cardiac chambers, valves, and great vessels.[9] It is imperative that echocardiographers are adept in practical applications of TEE in addition to advanced modalities such as speckle tracking and 3-dimensional (3D) TEE.[10] The prompt communication of preliminary findings to the surgical team is indispensable, as are the digital storage of images and completion of a structured report delivered in a time frame that supports patient care decisions.[9]

The operating room environment presents unique imaging challenges. Echocardiographers use various imaging techniques to confirm preoperative diagnoses, to determine causes of hemodynamic instability, to guide surgical and hemodynamic interventions, and to evaluate surgical outcomes (Table 1). The ideal comprehensive echocardiographic assessment may be constrained by the urgency of surgical situations, competing clinical tasks, or ongoing surgical activities.[2] Effective communication of echocardiographic findings to the surgical team is critical, and alterations to the surgical plan must be thoughtfully considered. After surgery, an early echocardiographic evaluation is essential to assess the surgical result and to check for complications such as regional wall motion abnormalities, iatrogenic aortic dissection, and malfunction of prosthetic valve leaflets. Identifying any issues that might require immediate surgical reintervention is a key goal of postoperative TEE and is specific to each type of surgery (Table 2).

Potential Risks of Intraoperative TEE

The risk of major complications related to intraoperative TEE during cardiac surgery ranges from 0.01% to 0.5% and includes esophageal perforation, bleeding, and mediastinitis. Minor complications occur in 2% to 3% of cases and include transient sore throat and minor mucosal injuries.[45,46] Periprocedural TEE may pose a higher risk because of patient heparinization and potential coagulopathy. Periprocedural TEE, specifically when the procedure is performed with TEE guidance, may have a higher-than-expected rate of TEE-related injury attributable to a longer duration of examination and longer periods of TEE manipulation.[45,46] A recent study of 50 patients undergoing structural heart procedures reported that the incidence of esophageal injuries such as intramural hematoma and mucosal laceration diagnosed on esophagogastroduodenoscopies was as high as 40%. Independent factors associated with an increased risk of these injuries were an abnormal baseline esophagogastroduodenoscopy (70% versus 37%; P=0.04), higher incidence of postprocedural dysphagia or odynophagia (40% versus 10%; P=0.02), longer procedural time under TEE manipulation (10-minute increase in imaging time; odds ratio [OR] 1.27 [95% CI, 1.01–1.59]), and poor or suboptimal image quality (OR, 4.9; [95% CI, 1.10–22.02]).[47] Judicious use of intraoperative TEE should be considered in the context of these findings. Absolute and relative contraindications have been recommended, as well as strategies to reduce the possibility of traumatic probe placement, to avoid long periods of probe contact/pressure to adjacent structures, or both.[45,46,48]

CARDIAC SURGICAL OUTCOMES RELATED TO THE USE OF INTRAOPERATIVE TEE

Short-Term Outcomes

Intraoperative TEE use in cardiac surgery has been increasingly associated with improved outcomes after cardiac surgery. The first study published >25 years ago demonstrated that intraoperative TEE guidance in mitral valve repair leads to better valve durability and reduces the likelihood of subsequent reoperations.[49] Recent large retrospective studies have associated intraoperative TEE use with reduced mortality in patients

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Table 1. Potential Impactful Contributions of Intraoperative TEE in Cardiac Surgery

Intraoperative TEE provides real-time monitoring during cardiac surgery that has the potential to alter, reinforce, or modify the preoperative diagnosis,[7] including examples listed below:
TEE allows real-time monitoring that facilitates prompt diagnosis and treatment in a dynamic and changing environment, including identifying the following:
Cardiogenic source of hypotension
New iatrogenic abnormality caused by manipulation of catheters inside the heart or other external maneuvers
Change in ventricular function and filling/distension in response to inotropes or other medications
Wall motion abnormalities that may indicate inadequate revascularization, poor myocardial protection, or air embolus to a coronary artery
Removal of intracardiac air
TEE provides additional information that may change the operative plan, including the following:
Presence of aortic calcifications
Intracardiac thrombus
New reduced EF or a change in valvular function compared with preoperative echocardiographic imaging
Presence of intraoperative aortic dissection
TEE guides device placement or catheter placement, including the following:
Coronary sinus catheter
Central line, including PA catheter
Intra-aortic balloon pump placement
Venous cannula placement
Wire placement in true lumen during aortic dissection repair
Aortic balloon placement and inflation
Mechanical circulatory device cannula placement
TEE allows assessment of procedural success, including the following:
Valve repair or replacement gradients, degree and location of residual regurgitation, presence of paravalvular leak, or leaflet immobility
Presence of continued flow into an LA appendage after closure
Presence of continued flow across septal or ventricular defects after closure
Incomplete removal of intracardiac masses
TEE can identify the presence of significant pericardial or pleural effusion.

EF indicates ejection fraction; LA, left atrial; PA, pulmonary artery; and TEE, transesophageal echocardiography.

undergoing CABG, valve surgery, and aortic surgery, particularly in intermediate- and high-risk cardiac surgery patients (Figure 1).[7,50–55] This association suggests that TEE is a critical component of care that has allowed us to care for increasingly complex patients without compromising quality or outcomes.

For CABG, an analysis of the STS Adult Cardiac Surgery Database in 1 255 860 isolated CABG surgeries showed that patients with intraoperative TEE had lower adjusted odds of operative mortality overall (adjusted OR [aOR], 0.95; $P=0.025$).[7] The study found that patient risk stratified by STS risk score of low (<4%), intermediate (4% to 8%), or high (>8%) risk of operative mortality was an effect modifier of the relationship between TEE use and mortality. Specifically, TEE was associated with lower odds of mortality in the high-risk group (aOR, 0.89 [95% CI, 0.83–0.95]) and intermediate-risk group (aOR, 0.93 [95% CI, 0.87–0.99]) but not in the low-risk group (aOR, 0.99 [95% CI, 0.94-1.04]; $P_{interaction}=0.0147$), suggesting that the benefits of TEE may be more apparent in higher-risk patients. A smaller propensity-matched analysis of 17 330 patients undergoing CABG similarly found that although intraoperative TEE use was associated with a lower 30-day mortality rate in patients overall (2.63% versus 3.20%; OR, 0.81 [95% CI, 0.71–0.92]; $P=0.002$), there was no mortality benefit in patients undergoing CABG without congestive heart failure (1.83% versus 2.15%; OR, 0.85 [95% CI, 0.70–1.02]; $P=0.089$).[52] In another propensity-matched study of 114 871 patients undergoing CABG with and without intraoperative TEE, TEE use was associated with a lower risk of 30-day mortality (3.7% versus 4.9%; $P<0.001$), lower incidence of the composite outcome of stroke or 30-day mortality (4.5% versus 5.6%; $P<0.001$),[50,52] and no difference in hospital length of stay (10.32 days versus 10.52 days; $P=0.26$) or incidence of esophageal perforation (0.01% versus 0.01%; $P=0.63$).[50,53]

For cardiac valve and aortic surgery, a propensity-matched analysis of 872 936 patients in the STS Adult Cardiac Surgery Database, including 161 610 matched pairs, found that intraoperative TEE use was associated with a lower 30-day mortality, 3.81% versus 5.27% (OR, 0.69; $P<0.001$); a lower incidence of stroke or 30-day mortality, 5.56% versus 7.01% (OR, 0.7; $P<0.001$); and a lower incidence of reoperation or 30-day mortality, 7.18% versus 8.87% (OR, 0.78; $P<0.001$).[55] A study using Medicare claims data of 219 238 patients who underwent open cardiac valve surgery found that 85% received TEE examinations. After adjustment for patient, surgical, and hospital factors, the patients receiving a TEE had lower odds of 30-day mortality (aOR, 0.77; $P<0.001$) but no difference in hospital length of stay.[54] To date, the STS cohort study provides the strongest evidence for routine intraoperative TEE use for cardiac valvular surgeries.[55]

Intraoperative TEE and Decision-Making

Intraoperative TEE also affects decision-making in the operating room. The STS database study of 1 255 860 patients undergoing CABG found that TEE use was associated with a greater frequency of unplanned valve procedures, 0.49% versus 0.09%, and increased odds of an unplanned valve procedure during an isolated CABG (aOR, 4.98; $P<0.0001$), demonstrating that TEE can identify occult valvular pathology and alter the surgical plan.[7] A single-center retrospective study of 12 566 patients undergoing open valve surgery found that pre–cardiopulmonary bypass (CPB) intraoperative TEE changed the

Table 2. Specific Intraoperative TEE Considerations by Type of Cardiac Surgery

Surgery/intervention	Preprocedural (or before CPB) evaluation	Immediate postprocedural (or during and after CPB) evaluation	Post–chest closure (if applicable) evaluation
General concepts	Preprocedural TEE allows immediate confirmation and refinement of the preoperative diagnosis, detection of new or unsuspected pathology, adjustments in the anesthesia management, and changes in the surgical plan	Postprocedural TEE provides real-time assessment of the adequacy of the surgical procedure and the detection of hemodynamically significant residual defects, guides the surgical revision when necessary, and facilitates medical management	Presence of effusions, dissections, and changes in cardiac or valve function and use imaging to optimize postoperative care
Coronary surgery[2,4]	LV anatomy: shape, size, wall thickness Global LV and RV function: 2D and 3D techniques, LV and RV strain assessment Diastolic dysfunction (tissue Doppler, transmitral and pulmonary vein flow) Valvular function, especially mitral and TV function and annular size for possible mitral or tricuspid repair, or both AV function for cardioplegia strategy Ascending aorta atheroma: determination of off-pump CABG	Global LV and RV function in the context of electrocardiographic changes LV and RV filling Regional LV functional changes in grafted areas with potential correlation to the flowmeter Valvular function, especially mitral and TVs in the context of LV or RV dysfunction and filling or both Ascending and descending aorta for potential cannulation complications (eg, dissection, hematoma)	LV systolic function and regional function (eg, graft kinking) at time of chest closure RV function and filling and LV diastolic function for fluid management and vasopressor titration Presence of iatrogenic aortic dissection Presence of a pleural effusion, especially left pleural effusion if left internal mammary artery was harvested
Valve repair or replacement surgery[2,3,8,11–13]	Baseline valvular disease severity for comparison immediately after the procedure Valvular anatomic risk factors prone to postprocedural failure LV and RV function size and function Cardiac structures adjacent to index valve Facilitate surgical cannulation	Cardiac function Presence or absence of residual pathology after valve repair Paravalvular defect after valve replacement Valvular function after repair or replacement New or worsening nonoperative valvular lesions Iatrogenic complications: AV: Anterior mitral leaflet injury or tethering, coronary embolism or injury, aortic dissection MV: circumflex artery injury, conduction system disruption, AV groove disruption, LA dissection, systolic anterior motion of mitral leaflet, interatrial septal shunt TV: right coronary artery injury, coronary sinus injury PV: RVOT injury or stenosis	Valvular function Change in residual pathology (if applicable) Ventricular function, as cardiac edema from prolonged surgical course is of concern Postprocedural baseline for comparison during follow-up visits
Aortic surgery[2,14–20]	Aortic measurements: LVOT and AV annulus in midsystole from inner edge to inner edge Sinuses of Valsalva (sinotubular junction, proximal ascending aorta, mid ascending aorta, distal ascending aorta, aortic arch, descending aorta) from leading edge to leading edge in end diastole Atheroma burden (grade and localize) Presence of any aortic pathologies (eg, dissection, intramural hematoma, thrombus, aneurysm, intimal tear, endocarditis, wall rupture) Arterial cannulation (eg, cannulation over wire in the descending thoracic aorta, proximal ascending positioning in the setting of atheroma burden) Cannula position, iatrogenic dissection from cannulation	Aortic root replacement with coronary reimplantation: coronary flow and ventricular segmental wall motion analysis Presence of iatrogenic aortic dissection Aortic graft material for laminar flow with color flow Doppler Post–aortic dissection repair, flow restoration in true lumen(s) through the extent of the aorta involved in systole After endovascular aortic intervention, endoleak interrogation (eg, presence of spontaneous echo contrast or slower flow in a patent aneurysmal aortic segment)	After aortic root replacement, coronary flow and ventricular wall motion; coronary button or graft kinking may occur After descending thoracic aortic endovascular repair, retrograde aortic dissection Entire aorta for any new changes in the setting of post–chest closure hemodynamic derangements

(*Continued*)

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Table 2. Continued

Surgery/intervention	Preprocedural (or before CPB) evaluation	Immediate postprocedural (or during and after CPB) evaluation	Post–chest closure (if applicable) evaluation
LVAD implantation[2,20–23]	LV and RV function and presence of thrombi in all cardiac chambers, devices, and catheters Interatrial septum to exclude ASD or PFO (agitated saline contrast if no shunt is detected by color flow Doppler) All heart valves to identify significant pathology; AV for more than mild AR or the presence and function of a prosthetic valve PA systolic pressure Aorta: presence of aneurysm, dissection, and complex atheroma Baseline pericardial effusion	Residual air during removal from CPB: LV, RV, LA, RA, coronary ostia, and aorta Note pump type, baseline speed, and any speed change LV size and septal position Position, orientation, and flow of the inflow cannula RV function; compare with baseline All heart chambers, devices, and catheters for any new thrombus Interatrial septum: repeat color Doppler and agitated saline contrast evaluation Heart valves: degree of AV opening and exclude new or more than mild AR; inflow cannula interference with MV apparatus; exclude new MR Presence of PR, measure RVOT stroke volume, worsening tricuspid regurgitation, PA systolic pressure Pericardium: assess for new effusion/hematoma Aorta: exclude new dissection Outflow graft: interrogate conduit path adjacent to RV/RA, anastomosis to the aorta	Improvement of previously identified abnormalities with chamber structure and function, for example, LV or RV dysfunction
Orthotopic heart transplantation[2,24,25]	Intracardiac thrombi, including evaluation of the LV apex, LA, and LA appendage Pacing leads or devices, including LVAD inflow cannula and outflow graft if present Anastomosis sites for masses, thrombi, or stenoses, including ascending aorta, PA, SVC, and IVC	Residual air during removal from CPB: LV, RV, LA, RA, coronary ostia, and aorta LV and RV function and exclude thrombi in all cardiac chambers, devices, and catheters Atrial or SVC and IVC anastomoses: exclude stenosis or thrombus at the anastomosis site Interatrial septum: exclude ASD or PFO with color Doppler and agitated saline if appropriate All heart valves to identify significant pathology PA systolic pressure Pericardium: assess for new effusion/hematoma	Improvement of previously identified abnormalities with chamber structure and function, for example, LV or RV dysfunction
Orthotopic lung transplantation[26–30]	Presence of PFO by color flow Doppler and agitated saline RV assessment, septal position, baseline RV systolic pressure LV assessment Baseline pulmonary veins diameter (normal >5 mm) and velocity (normal <100 cm/s)	RV response to PA clamping RV size and function and RV systolic pressure If a PFO was present, check reversibility of shunt	PV anastomoses: diameter, turbulence, velocity <100 cm/s, presence of thrombus or air PA anastomosis: diameter should be >75% of proximal PA, color-flow Doppler for turbulence RV and LV size and function, septal wall position If a PFO was present, determine direction of flow
ECMO[31–35]	LV and RV size and function Obstructive lesions in the path of the cannulas such as tumors or thrombus Cardiac anatomy and abnormalities that may affect flow such as cor triatriatum Presence of intracardiac shunts	Guide wire position Adequacy of cannula placement Direction of flow using color Doppler Intracardiac shunts that may have been unmasked New pericardial effusion LV and RV size, filling, and function	Cannula position and flow acceleration LV and RV size, filling, and function

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Table 2. Continued

Surgery/intervention	Preprocedural (or before CPB) evaluation	Immediate postprocedural (or during and after CPB) evaluation	Post–chest closure (if applicable) evaluation
Adult congenital surgery[36–44]	Baseline evaluation of anatomy, hemodynamics, and ventricular function Preoperative structural or functional abnormalities or both New or different pathology and exclusion of additional defects Presence of intracardiac communications that may affect beating heart surgery (color Doppler evaluation and agitated saline contrast study)	Surgical cannulation Adequacy of cardiac emptying or filling based on the surgical stage Intracardiac air and adequate cardiac deairing Results of the surgical intervention according to the nature of the procedure(s) (eg, exclusion of residual shunts, obstructive or regurgitant pathology of potential hemodynamic significance, confirmation of conduit patency, evaluation of prosthetic valve function) Ventricular size and function Problems associated with weaning from CPB Surgical revision when indicated	Potential extrinsic sternal compression of cardiac structures or prosthetic material Distortion in the anatomy that may result in hemodynamic changes Results of the surgical intervention, particularly if there are concerns related to residual pathology or disease severity LV and RV ventricular filling and function

2D indicates 2-dimensional; 3D, 3-dimensional; AR, aortic regurgitation; ASD, atrial septal defect; AV, aortic valve; CABG, coronary artery bypass graft; CPB, cardiopulmonary bypass; ECMO, extracorporeal membrane oxygenation; IVC, inferior vena cava; LA, left atrial; LV, left ventricular; LVAD, left ventricular assist device; MR, mitral regurgitation; MV, mitral valve; PA, pulmonary artery; PFO, patent foramen ovale; PR, pulmonary regurgitation; PV, pulmonary valve; RA, right atrial; RV, right ventricle; RVOT, right ventricular outflow tract; SVC, superior vena cava; TEE, transesophageal echocardiography; and TV, tricuspid valve.

scheduled procedure in 6.6% of mitral valve and 4.4% of aortic valve surgeries. In addition, post-CPB TEE evaluation identified abnormalities that required surgical reintervention, including perivalvular leak, immobilized leaflet, coronary obstruction, and incompetent xenograft.[51] The occurrence of procedural changes was even greater for multivalvular surgeries (9.1%) and combined CABG plus valvular surgeries (12.3%).[51] Another study of 417 patients undergoing valve replacement showed that unexpected post-CPB TEE findings contributed to 3.6% of patients needing immediate surgical reintervention.[56]

The cost-effectiveness of routine use of intraoperative TEE in cardiac surgery was studied in an innovative decision analytic simulation in 10 000 virtual patients undergoing CABG, aortic valve, and mitral valve surgery. This study found that routine intraoperative TEE use was associated with lower cost (US $1750) and greater quality of life-years per patient (0.036 with an incremental cost-effectiveness ratio of $33 000/quality of life-year), making TEE highly cost-effective. In addition, the results showed a decrease in long-term complications, including stroke, cardiac complications, and death.[57]

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Specific TEE-Related Parameters and Outcomes

Many studies have also demonstrated the association between specific intraoperative TEE parameters and perioperative or in-hospital outcomes. This suggests that TEE may be used (1) to risk-stratify cardiac surgical patients during open valve repair,[58–61] (2) to aid in perioperative stroke risk assessment by identifying aortic disease and intracardiac thrombus,[62] or (3) to risk-stratify surgical patients for the likelihood of adverse outcomes according to their left ventricular (LV) and right ventricular (RV) functional assessments.[63–70] In summary, the use of intraoperative TEE allows the identification of higher-risk patients who may benefit from alterations in surgical technique or closer postoperative monitoring to improve outcomes Supplemental Table 1.

Long-Term Outcomes

Data on the association between intraoperative TEE and long-term outcomes remain sparse. Studies suggest that cardiac surgical patients with more severe valvular regurgitation on preprocedural TEE have increased risk of long-term mortality.[71,72] A single-center database study over a 24-year period of 23 685 patients reported that moderate or severe intraoperative tricuspid regurgitation (TR) was associated with increased all-cause mortality (hazard ratio [HR], 1.24, $P<0.0001$; HR, 2.02, $P<0.0001$, respectively), however, patients who subsequently underwent tricuspid valve surgery had an increased likelihood of survival (HR, 0.74; $P=0.004$).[71] In patients with moderate MR, prebypass TEE assessment of MR had a better association with long-term mortality compared with preoperative transthoracic echocardiographic (TTE) assessment (HR, 1.31 versus 1.02; $P=0.025$).[72] More prospective, granular research on the specific TEE interventions used for surgical or hemodynamic guidance is needed to expand our knowledge of how exactly TEE contributes to improving outcomes.

SPECIFIC INTRAOPERATIVE TEE CONSIDERATIONS BY TYPE OF CARDIAC SURGERY

CABG Surgery

Many patients undergoing CABG surgery may not have a comprehensive preoperative TTE. The indication for revascularization hinges on cardiac angiography alone to define anatomy and to assess lesion severity, and routine preoperative TTE is not yet standard of care.[73] The ACC/AHA 2004 Guideline Update for CABG list preoperative TEE as a Level 2b recommendation in a limited subset of patients with recent anterior myocardial infarction.[73] However, TEE is becoming increasingly valued as an intraoperative evaluation tool, as demonstrated by its increased utility and the 2011 ACCF/AHA Guideline for CABG that endorsed intraoperative TEE for CABG surgery with a Class 2a, Level of Evidence B recommendation.[1a]

Intraoperative TEE may be the first comprehensive evaluation of valvular function for patients undergoing CABG and provides updated information on regional and global biventricular function, which may have changed since the preoperative assessment. The data from intraoperative TEE allow accurate patient risk stratification and inform hemodynamic and fluid management. Mitral and tricuspid valves, which may be affected by myocardial ischemia, are assessed for abnormalities that may require surgical intervention. After separation from CPB, intraoperative TEE is critical for assessing deairing and graft function through regional and global ventricular function evaluation. At chest closure, global and regional function should be reassessed with clinical hemodynamic correlation to confirm the absence of acute graft ischemia (eg, graft kinking or other occlusive events; Table 2).

Valve Repair or Replacement Surgery

Intraoperative TEE has been a mainstay of cardiac valve surgery, and one of its important functions is to confirm valvular lesions identified preoperatively. Detailed intraoperative considerations are given in Table 2. However, qualitative and quantitative intraoperative TEE findings established before the initiation of CPB should be interpreted within the context of the altered physiological conditions that exist in the anesthetized surgical patient. These include relative hypovolemia due to preoperative fasting, general anesthesia, mechanical ventilation, and surgical manipulation of the heart, which can significantly alter cardiac and valve function (Figure 1).[74] Studies have shown frequent discrepancies in Doppler-derived parameters between the presurgical TTE and intraoperative TEE in mitral, aortic, and tricuspid valve surgery, resulting in discordant valvular pathology grades.[75–78] Certain parameters may be more affected than others. In a study of 319 patients, peak velocity and mean gradient in aortic stenosis were different by 0.59 m/s and 12.5 mm Hg, respectively ($P<0.001$), and the intraoperative TEE grades of aortic stenosis severity agreed preoperatively only ≈50% of the time. However, when the dimensionless index (also known as velocity ratio) was used, agreement with the preoperative TTE increased to 83.3%.[77] Supplemental Table 2 summarizes studies that have compared valve grading by preoperative TTE and intraoperative TEE.

Anesthesiologists can attempt to mimic normal loading conditions by giving medications to increase afterload and intravenous fluids to increase preload. However, awake or baseline conditions are not necessarily fully replicated. A meta-analysis of 6 studies including 273 patients compared MR severity on preoperative TEE or TTE and intraoperative TEE with hemodynamic matching using pharmacologically increased afterload. Intraoperative TEE under general anesthesia before hemodynamic matching resulted in a mean misdiagnosis rate of 48% (39% underestimation, 9% overestimation), and misdiagnoses remained high at 41% even after hemodynamic matching. However, only ≈10% of misdiagnoses were clinically relevant in both groups.[74] Other small studies have shown that intraoperative MR severity may be underestimated in secondary but not primary MR and that the 3D vena contracta area was less likely to underestimate 2-dimensional (2D) MR assessment in 20% versus 44% of cases.[79] Quantitative assessments such as effective regurgitant orifice area and regurgitant volume may be more accurate in grading MR severity under anesthesia because they are less dependent on loading conditions.[74,79,80]

Intraoperative TEE is often used to determine the feasibility of valve repair over replacement. Factors such as leaflet or annular calcium burden, leaflet height,[81] overall valvular symmetry,[82] and chordal length[83] can be evaluated intraoperatively and used for surgical repair planning (Supplemental Table 1). Risk factors for systolic anterior motion of the mitral leaflet after repair can be identified before initiation of CPB, which provides valuable information for the surgeon on the surgical repair strategy and informs the anesthesiologist about post-CPB hemodynamic management.[84] Immediate post-CPB TEE after valve repair or replacement can identify significant residual pathology, prosthetic valvular malfunction, paravalvular defects, and other conditions that may require surgical reintervention (see the Short-Term Outcomes and Intraoperative TEE and Decision-Making sections).

Real-time 3D TEE can be used intraoperatively as an adjunct to the 2D TEE examination. Prospective studies have shown that intraoperative 3D compared with 2D TEE can more accurately identify segmental and complex valvular lesions without compromising examination efficiency.[85,86] For the mitral valve, 3D TEE compared with 2D TEE allows better accuracy and improved sensitivity and specificity in the identification of clefts and prolapsed scallops, including multisegment or commissural lesions.[87,88] Three-dimensional analysis assists with identifying the risk of postrepair systolic anterior motion.[89] Automated or semiautomated software allows rapid 3D analysis of the valve structure, which correlates well with multidetector computed tomography–derived structure. Quantitative measurements of MR by 3D TEE such as effective regurgitant orifice area and regurgitant volume

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have been shown to be accurate and feasible compared with cardiac magnetic resonance.[90] High-resolution 3D TEE images for improved visualization of complex lesions can potentially improve the successful repair rate when valve repair techniques are adapted according to the 3D TEE evaluation.[91] After valve repair or replacement, 3D TEE also incrementally improves paravalvular leak localization and quantification.

Aortic Surgery

The "2022 ACC/AHA Guideline for the Diagnosis and Management of Aortic Disease" states that intraoperative "TEE is particularly useful in the intraoperative evaluation of patients with aortic aneurysm syndromes in guiding both operative and endovascular repair strategies and the assessment of true and false lumen flows before and immediately after aortic repair."[14,15] However, the impact of TEE use on outcomes in aortic surgery has only recently been investigated.[55] Intraoperative TEE of the aorta provides superior image quality compared with TTE and allows imaging of nearly the entire thoracic aorta, aside from a "blind spot" near the distal ascending aorta and proximal aortic arch.[15] Tw-dimensional and 3D TEE, simultaneous orthogonal-plane imaging, and Doppler flow interrogations with and without color are the widely used modalities that assist in intraoperative evaluation of the aorta.[16] In proximal aortic surgery, TEE assists decision-making by providing information on arterial site cannulation guidance, aortic cannula position, identification of true and false lumen in aortic dissection, aneurysm size, thrombus location, and the presence of pericardial effusion (Table 2).

Aortic endovascular techniques also benefit from TEE guidance, which enables visualization of the guide wire and stent placement,[17] as well as interrogation for potential poststent endoleak and retrograde aortic dissection.[18] Hybrid procedures combining conventional approaches with endovascular techniques in extensive aortic disease also benefit from intraprocedural TEE for both the conventional and the endovascular surgical segments. Combination aortic valve repairs with aortic procedures benefit from TEE to evaluate the need for aortic annular size adjustment and to confirm adequate external annular stabilization.[92,93] Lastly, use of rescue TEE in blunt thoracic trauma management can also aid in quickly identifying a need for emergency aortic surgical intervention.[2,94,95]

LV Assist Devices

Durable LV assist devices (LVADs) are surgically implanted in patients with advanced heart failure refractory to medical therapy, as a bridge to transplantation, as a bridge to recovery, or as destination therapy. A thorough intraoperative TEE assessment is essential before and during LVAD implantation, activation, and optimization (Table 2). Implementing a perioperative protocol and checklist facilitates consistent imaging at each procedural stage.

TEE evaluation before implantation is particularly important in emergency scenarios or when TTE is inadequate. Key parameters include LV and RV size and function and valvular function. Evaluation for conditions that would alter the surgical procedure or even exclude the patient from LVAD eligibility should be performed. The presence of more than mild aortic regurgitation, intracardiac thrombi, interatrial and intraventricular defects, and ascending aortic pathology should be assessed (Table 2). A qualitative evaluation should be complemented by semiquantitative and quantitative techniques that allow a more reliable assessment of chamber size and function and assist with risk stratification.

After durable LVAD initiation, transient RV dysfunction is common due to increased preload, but worsening RV dysfunction may necessitate decreasing pump speed. Table 2 reports specific echocardiographic considerations preoperatively and after LVAD activation. Echocardiographic predictors of RV failure after LVAD insertion can be measured during the preoperative TTE or TEE evaluation and include indices of RV systolic function, RV diastolic dysfunction (tricuspid E/e', right atrial strain), and RV–pulmonary artery coupling (incorporating pulmonary artery systolic pressure). Literature supports integration of echocardiographic, clinical, and hemodynamic parameters into risk scores which have been associated with better accuracy in predicting RV failure than any individual parameter.[96] Increased velocities in the outflow graft may suggest obstruction or kinking, an uncommon but serious complication that may require surgical graft adjustment.[21,22]

Orthotopic Heart Transplantation

Immediately after orthotopic heart transplantation, a thorough TEE assessment of LV and RV function is required. Acute RV dysfunction may be due to air embolism; ischemia, stunning, or both; volume overload; acute increase in pulmonary vascular resistance; and primary graft dysfunction or hyperacute rejection.[24,25] Attention should also be paid to the ascending aortic, pulmonary arterial, caval, and atrial anastomoses, depending on the surgical technique used.[97] Retrospective studies have shown that ≈20% of patients after orthotopic heart transplantation have mild or greater TR on the post-CPB TEE, which has been associated with RV dysfunction and increased mortality.[98] A study including 542 patients with orthotopic heart transplantation reported that significant (more than mild) TR after CPB was associated with increased mortality at 30 days (5.3% versus 0.7%; P=0.002) and 1 year (19.3% versus 8.7%; P=0.004) compared with patients whose TR was mild or less. Patients with significant

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TR also had longer hospital stays and higher maximum creatinine values.[98]

Orthotopic Lung Transplantation

Clinical practice guidelines on intraoperative TEE from the American Society of Anesthesiology/Society of Cardiovascular Anesthesiologists recommend intraoperative TEE use in lung transplantation,[1] particularly for assessment of hemodynamic instability and evaluation of pulmonary vasculature anastomoses.[27,28] The 2003 American Society of Echocardiography recommendation for TEE use is Class 2b.[99] Key intraoperative echocardiography assessment considerations are provided in Table 2.[26,29,30] Intraoperative TEE is critical to diagnose significant pulmonary vein obstruction using velocities >100 cm/s, which occurs in 1% to 24% of patients.[27,28] This can be caused by thrombus, sutures, kinking, or external compression. In a systematic review and meta-analysis, pulmonary cuff dysfunction was diagnosed by intraoperative TEE in 10 of 63 reported cases (15.7%),[100] and timely intervention was associated with improved outcomes.

Venoarterial Extracorporeal Membrane Oxygenation

TEE plays a critical role in decision-making at the time of venoarterial extracorporeal membrane oxygenation (ECMO) initiation for cardiogenic shock. The utility of TEE in this setting is linked to appropriate titration of inotropic therapy, determination of the need for pharmacological or mechanical LV unloading,[31] and assessment of LV volume status during extracorporeal cardiopulmonary resuscitation with venoarterial ECMO.[32,33] Intraprocedural TEE for central or peripheral venoarterial ECMO helps diagnose potential procedure-related complications and allows immediate assessment of LV unloading (Table 2).[32–35] In a study of 421 patients, early LV unloading within 2 hours of ECMO initiation was associated with a 36% lower adjusted relative risk of 30-day all-cause mortality compared with delayed active LV unloading (>2 hours; HR, 0.64; *P*<0.01) and was associated with a higher likelihood of successful ventilator weaning (aOR, 2.17; *P*<0.01).[101]

Postprocedural TEE is used to ascertain the absence of new pericardial or pleural effusions and to optimize ECMO flow rate. Qualitative assessment of RV and LV response as ECMO flow is decreased provides useful information in myocardial recovery and predicts the likelihood of successful weaning. TTE studies have shown that improvements in many echocardiography parameters during the period that ECMO flow is reduced are associated with successful ECMO weaning. Useful parameters to monitor for TEE-guided ECMO weaning include the LV outflow tract velocity time integral, tissue Doppler-derived mitral septal annular systolic velocity (S'),[102] mitral lateral e' velocity, tricuspid annular S' velocity,[103] and LV and RV ejection fraction (EF).[104]

Venovenous ECMO

TEE is useful in assisting with dual-lumen bicaval central venovenous ECMO cannula insertion, which requires precise positioning of drainage ports in the superior vena cava and inferior vena cava and the return port in the mid right atrium directed toward the tricuspid valve. Complications such as RV wall perforation attributable to cannula migration can be quickly and efficiently visualized on TEE.[105]

For peripheral venovenous ECMO, the position of the cannula in the right atrium can be verified with chest radiography using radiopaque markers at the cannula tips. However, echocardiography is often needed for troubleshooting and for assessing cardiac function. TEE may be required in cases of poor or absent surface sonographic windows in TTE or if there is a need for field avoidance.

In cases of combined respiratory failure and RV dysfunction, a percutaneous RV assist device that allows an oxygenator connection cannulation may be needed. TEE is used to evaluate the right side of the heart for any structural abnormality or implantable devices that may affect the function and position of the cannula and to verify the correct positioning of the cannula inlet and outlet. In cases of biventricular dysfunction with respiratory failure requiring complex cannulation strategies, TEE is similarly used to assess the function and position of cannulas, unloading of both ventricles, significant valvular abnormalities, and intracardiac shunts.[106]

Adult Congenital Surgery

Adult congenital heart disease encompasses a wide variety of cardiovascular malformations from anatomically simple defects to complex anomalies of variable disease severity. The growing adult congenital heart disease population can be attributed to advances in the care of children with congenital heart disease, including those related to advances in intraoperative TEE.[107] Improvements in long-term clinical outcomes and increased survival rates in congenital heart disease account for the growing number of adult patients with congenital heart disease, who are increasingly older with complex pathologies.[108,109]

Since the introduction of TEE into the perioperative environment, extensive clinical experience has supported the utility of this imaging modality in the care of patients with congenital heart disease.[36] Pre-CPB TEE and post-CPB TEE provide real-time assessment of the adequacy of the surgical procedures (Table 2). In 2019, the American Society of Echocardiography proposed a set of guidelines and recommendations for the comprehensive TEE examination in this patient population, considering

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the unique aspects of TEE evaluation in congenital heart disease.[37]

Although rigorous scientific data on the impact of intraoperative TEE on clinical outcomes in adult congenital heart disease are lacking, the cumulative literature, derived mostly from moderate-quality evidence and observational studies in the pediatric age group, indicates that intraoperative TEE is critical to evaluate the quality of the surgical intervention in adult patients with congenital heart disease. Recent data show that intraoperative TEE in the congenital population can alter the surgical plan in ≈1% to 2% of cases and can facilitate a prompt return to CPB in 4% to 6%.[38–40] The routine use of TEE during congenital heart surgery is paramount to detect residual lesions such as hemodynamically significant shunts, valve regurgitation, and outflow obstruction, which account for major morbidity and mortality after congenital heart disease repair.[38–44] Therefore, TEE is considered an integral part of intraoperative management in centers that specialize in the surgical care of patients with congenital heart disease and is supported by various clinical practice guidelines.[1,8,110,111]

ARTIFICIAL INTELLIGENCE IN PERIOPERATIVE ECHOCARDIOGRAPHY

Artificial intelligence (AI), a new frontier for imaging and clinical decision-making in medicine, is rapidly being developed in echocardiography to assist with atrial and ventricular chamber quantification and clinical diagnosis. High-quality image acquisition that facilitates AI use can be challenging in the perioperative environment. A study of 300 patients who underwent TTE demonstrated that automated 3D echocardiography analysis afforded accurate quantification of left atrial and LV function in 66% of patients, with unreliable performance in 34% of patients because of image quality.[112] Thus far, perioperative TEE studies on AI have been limited to (1) studies comparing the accuracy of 3D TEE–based mitral[113] and tricuspid[114] AI-assisted valvular modeling measurements with direct surgical measurements and (2) the application of a convolution neural network, trained and validated with intraoperative data, to predict standardized TEE views. In the latter study, the deep learning–based, multicategory TEE view classification model could accurately identify 8 standard TEE views with area under the curve ranging from 0.898 to 0.971.[115]

To date, most studies have focused on AI-assisted automation and analysis of 2D and 3D TTE–based data. The FAST-EFs multicenter study (Fully Automated Versus Standard Tracking of Left Ventricular Ejection Fraction and Longitudinal Strain) tested the agreement between automated EF and longitudinal strain from the apical 4- and 2-chamber views and found 98% feasibility of automatic measurements and good agreement between manual and automatic assessments.[116] Another study compared machine-learning LV ejection estimates derived from apical 4-chamber, apical 2-chamber, and parasternal long-axis views with biplane measurements by experienced echocardiographers in 166 point-of-care echocardiography examinations. The study found good agreement with the reference EF values in categorizing LV function as hyperdynamic (EF >73%), normal (53%–73%), mildly to moderately reduced (30%–52%), or severely reduced (<30%), with intraclass correlation ranging from 0.86 to 0.95 and biases <2%. The accuracy of machine learning–estimated EF compared with physician measurements was also good in 85% to 90% of cases.[117] Automatic volumetric quantification comparisons have also been conducted between 3D TTE and cardiac magnetic resonance for evaluating left atrial and LV volumes,[118] LV volumes and associated EF,[119] and RV volumes and EF.[120] Some studies demonstrated excellent agreement between automatic 3D quantification and cardiac magnetic resonance, but have limited sample sizes,[118] and others showed that full automation of 3D echocardiography RV quantification was possible in only 32% of patients, with the remaining 68% of patients requiring manual endocardial contour editing.[120] In 300 patients with a history of myocardial infarction, deep convolutional neural networks trained on 256 cases and 786 images were used to detect regional wall motion abnormalities on apical and short-axis LV TTE views. The study reported similar results between the deep learning algorithm and cardiologists' abilities, respectively, for detecting the presence (area under the curve, 0.99 versus 0.98; P=0.15) and the location (area under the curve, 0.97 versus 0.95; P=0.61) of wall motion abnormalities.[121] Another study used preoperative 3D TTE clips to accurately predict RV failure in 121 patients after LVAD placement with an area under the curve of 0.729. Notably this AI system outperformed clinical risk scores (Penn Score and CRITT score)[122] and traditional echocardiographic metrics of RV function (RV strain, RV EF, tricuspid annular plane systolic excursion).[123]

The clinical utility of such AI techniques in intraoperative TEE has the potential to increase the speed and accuracy of diagnoses and predict clinical outcomes. Thus, AI should be the subject of imminent future studies despite its current limitations. Future integration of AI into intraoperative echocardiography practice can enhance the perioperative echocardiography workflow, diagnosis, risk stratification, and management of increasingly complex cardiac surgical patients, ultimately improving patient outcomes.

FUTURE APPLICATIONS OF INTRAOPERATIVE TEE

The utility and practice of intraoperative TEE have evolved dramatically since the latest clinical guidelines were published.[1–4,8] The indications for intraoperative TEE will need to be expanded and subsequently endorsed by societies to match the current literature and clinical practice. As intraoperative TEE for cardiac surgery becomes universal, using TEE for risk stratification and tailored hemodynamic and fluid therapy, especially for high-risk patients, is crucial. TEE use should be considered across the entire spectrum of cardiac diseases and should be implemented equitably across all populations. Future studies are needed to further define the standardized use of TEE to improve outcomes during cardiac surgery and how the application of AI may enhance these benefits for each patient. The current prognostic and diagnostic utility of TEE in the intraoperative space is driven largely by clinical experience, expertise, and multidisciplinary decision-making.

ARTICLE INFORMATION

The American Heart Association makes every effort to avoid any actual or potential conflicts of interest that may arise as a result of an outside relationship or a personal, professional, or business interest of a member of the writing panel. Specifically, all members of the writing group are required to complete and submit a Disclosure Questionnaire showing all such relationships that might be perceived as real or potential conflicts of interest.

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