15 Intraoperative and Postoperative Transesophageal Echocardiography in Congenital Heart Disease

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Abstract

The early experience with epicardial imaging in patients undergoing surgery for congenital heart disease (CHD) provided strong evidence to the idea that intraoperative echocardiography could guide specific surgical and anesthetic adjustments during this critical period. Since the introduction of transesophageal echocardiography (TEE) to the intraoperative setting in the late 1980s, numerous publications have documented the utility of this imaging modality in the care of patients with CHD. Technologic advances over the years that have included miniaturization of probes and multiplane imaging now allows for comprehensive assessment of structural abnormalities, evaluation of hemodynamics, and very importantly, appraisal of the surgical results in nearly all patients with CHD. The recognition of residual pathology of hemodynamic significance during congenital surgery and the ability of TEE to guide the surgical revision as necessary, represent major contributions to perioperative care. Additional important benefits of this technology in the perioperative period include its role as a monitoring adjunct to facilitate hemodynamic and pharmacologic management and to influence treatment strategies. TEE also provides a framework to assist in the formulation of management plans in the immediate postoperative period and the further characterization of postoperative unexpected/unusual findings or problems.

This chapter provides an overview of the applications of TEE in the intraoperative care of patients with CHD with an emphasis on impact on surgical, medical, and anesthetic management. Data on cost effectiveness, pitfalls, and limitations of intraoperative TEE are reviewed. Lastly, the role of TEE in the postoperative setting in the patient with CHD is addressed.

Keywords

Intraoperative transesophageal echocardiography in congenital heart disease • Postoperative transesophageal echocardiography in congenital heart disease • Applications of intraoperative TEE in congenital heart disease • Intraoperative TEE in children • TEE in the postoperative patient with congenital heart disease • Limitations of TEE in congenital heart disease

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Technological Evolution of Intraoperative Imaging in Congenital Heart Disease

Initial efforts in intraoperative echocardiography in children with congenital heart disease (CHD) explored the benefits of epicardial imaging. Standard transthoracic imaging probes covered in a sterile sheath were directly applied to the surface of the heart in order to assess cardiac anatomy and function prior to the initiation and after separation from cardiopulmonary bypass. This allowed for confirmation of preoperative diagnoses and assessment of the adequacy of the surgical repair [1–3]. Clinical experience over several years supported the benefits of the epicardial imaging approach in the perioperative management of patients with CHD [4–7].

Reports regarding the intraoperative applications of transesophageal echocardiography (TEE) in CHD can be traced to the late 1980s when Cyran and colleagues documented one of the earliest experiences [8]. While using an adult-sized probe, the potential benefits of TEE were examined in older children and young adults undergoing surgical interventions for a variety of structural heart defects. The report noted that TEE was valuable and could be performed safely and reliably in this patient group.

Kyo and associates in conjunction with Aloka Company in Japan developed the first TEE probe with specific applications to infants and young children [9, 10]. This was a single plane, 28-element, 5.0 MHz phased array device mounted on a flexible gastroscope of an external diameter of 6.8 mm. Although the transducer was limited to only transverse (horizontal, 0°) plane scanning, worldwide reports using this probe documented its accuracy and feasibility in the assessment of CHD [11–16].

It was observed that in some cases, TEE had superior diagnostic capabilities as compared to the transthoracic approach, and accuracy equivalent to epicardial imaging in the intraoperative setting [17–20]. Initial reports on the benefits of TEE during surgery for CHD ranged from the assessment of septal defects to complex lesions [21–23].

A major limitation of the technology during the early experience however, was the suboptimal image quality provided by a small probe with a relatively low number of elements and the inability to adequately interrogate the ventricular outflow tracts [24]. Despite these shortcomings, several studies highlighted the fact that when compared to epicardial echocardiography, transesophageal imaging did not interrupt surgery or caused potential distortion of cardiac structures. This imaging modality was also less likely to trigger rhythm abnormalities, produce hemodynamic alterations, or influence the infection risk. Efforts thus continued into improving the TEE technology for pediatric applications.

In the early 1990s a new single plane TEE transducer was introduced (5.0 MHz phased array, 48-element). This allowed for superior image resolution to that provided by previous hardware, in addition to continuous wave Doppler capabilities [25]. Concurrent refinements in Doppler technology allowed for improved assessment of blood flow velocities, jet direction, and overall evaluation of the severity of obstructive/regurgitant pathology.

The subsequent development of biplane probes (48 and 64-elements) for pediatric use enhanced the transesophageal examination by allowing for imaging not only in the transverse plane, as had been the case with single plane devices, but also in the longitudinal or vertical plane (90°) [26, 27]. The additional plane of interrogation improved the diagnostic accuracy of TEE, particularly for pathology affecting the ventricular outflow tracts [28]. The benefits of biplane imaging were not limited to children, but were also reported in adults with congenital cardiovascular malformations [29].

Despite the advantages offered by biplane imaging, several limitations of the technology were recognized at the time. One of these related to the inability to optimally align the spectral Doppler angle of interrogation with the direction of blood flow while imaging from the esophageal windows. This limitation was partly addressed by transgastric imaging, which provided much more favorable angles for Doppler interrogation of ventricular outflow tracts and great arteries using existing single and biplane TEE devices [30, 31].

The introduction of multiplane TEE imaging for children in the mid 1990s represented a major technological advancement. At the time, experience had suggested superiority of multiplane over biplane imaging in adults [32, 33]. This development provided the opportunity for the acquisition of high-resolution images in an unlimited number of planes, a necessity for the comprehensive assessment of complex cardiovascular pathology. The initial pediatric multiplane probe (mini-multiplane device) was a 48-element, phased array, single crystal 5-MHz transducer with two-dimensional, M-mode and full Doppler capabilities [34–36]. The probe was mounted on a transducer shaft of 7 mm, with tip dimensions of 27 mm (length) by 10.6 mm (width) by 7.9 mm (thickness). Steering from an arc ranging from 0° to 180° was performed manually, in contrast to the electronic control then available in the adult multiplane probe. A second knob allowed for flexion of the transducer tip anteriorly and posteriorly (anteflexion and retroflexion respectively). This device, originally designed by Odelft BV (Delft, The Netherlands), was marketed soon thereafter and adapted for use on a number of echocardiographic platforms produced by different manufacturers (refer to Chap. 2).

There has been ongoing interest in further miniaturizing the TEE technology to provide allow for a larger margin of safety. Sporadic reports have acknowledged potential benefits and shortcomings of these imaging probes [37, 38]. Limited experience with an imaging device more suitable for use in neonates and small infants (Odelft micro-multiplane

TEE probe) was reported several years ago. An 8 mm diameter probe tip mounted on a 5 mm gastroscope characterized this 7.5 MHz, 48-element transducer [39–41]. The device allowed the examination of infants as small as 2.5 kg of weight without major complications. Unfortunately, technological challenges stalled the development of this device.

In recent years a miniaturized multiplane device became commercially available (Philips Medical, Andover, MA, USA, micro TEE transducer). This probe has a shaft width of 5.2 mm, transducer tip width of 7.5 mm, and height of 5.5 mm. The 32-element phased array multiplane transducer incorporates two-dimensional, color, full spectral Doppler modalities, and M-Mode. The center frequency of this device is 6 MHz (range 3.2–7.4 MHz). The experience with this probe thus far has demonstrated a highly successful insertion rate in tiny neonates and high-quality diagnostic imaging without respiratory or hemodynamic compromise (refer to Chap. 2) [42].

A prospective study assessed the image quality of the micro-multiplane TEE probe and compared it with that obtained using the standard pediatric or adult probe [43]. A total of 24 studies were performed (23 patients, median weight of 11.7 kg, median age of 3 years). The micro-multiplane TEE probe was found to provide diagnostic image quality in the neonatal age group, however, in children between 10 and 30 kg, standard-sized pediatric probes allowed for better imaging.

A catheter approved for intracardiac echocardiography (ICE) has been used off label for transesophageal intraoperative imaging in tiny infants. This miniaturized device (AcuNav™ Ultrasound Catheter, Siemens Medical), with a diameter of 3.3 mm, carries a 64-element phased-array multifrequency transducer (5.5–10 MHz). Capabilities include longitudinal plane imaging, as well as spectral and color Doppler modalities. The handle controls allow for four-way steering in two planes: anterior-posterior, left-right; with 160° rotation in each direction. A report noted a group of 17 infants (weight between 2.1 and 5.6 kg) undergoing 22 examinations with this device [44]. Most studies were of diagnostic quality and no complications were identified. A case report in an infant with single ventricle also demonstrated the diagnostic utility of this catheter when used for imaging via the esophagus [45].

The principal advantage of this catheter is its slender profile, which allows safe esophageal placement in very small babies, with excellent imaging quality and full Doppler capabilities. The major disadvantage is that there is only a single, longitudinal (90°) imaging plane; a second orthogonal transverse plane (0°) is not available, nor are there multiplane capabilities. This limits the imaging effectiveness of this catheter for certain types of CHD in which the transverse plane is important. Also, no temperature sensing is available on this device raising concerns regarding safety.

Currently, most centers prefer the use of multiplane imaging in patients with CHD as this enables detailed assessment of anatomy, hemodynamics, and function. Biplane imaging may be considered an acceptable, though less desirable option if multiplane interrogation is not feasible.

Impact of TEE on Intraoperative Care

Influences on Surgical Management

An extensive experience over a period of many years has documented the utility of intraoperative imaging in the care of patients with CHD, as well as in children with acquired pathologies. It is well recognized that intraoperative imaging provides detailed anatomic and hemodynamic information prior to the planned surgical procedure, assists in the assessment of the quality of the repair, and allows for real-time monitoring of ventricular loading and performance.

One of the initial reports regarding the utility of echocardiography during surgery for CHD was by Ungerleider and colleagues [46]. Their experience consisted of 1,000 patients at Duke University Medical Center from a period spanning between the years of 1987 and 1994. Surgery in the majority of cases was performed using cardiopulmonary bypass. Intraoperative imaging made use of the epicardial approach during the early years due to lack of miniaturized TEE transducers. Subsequently, the use of TEE was favored, and in many cases, both imaging modalities were employed. The authors reported that during the later years of their experience it was extremely unlikely for the intraoperative prebypass examination to reveal new findings or provide information leading to an alteration in the surgical plan. However, they continued to subjectively perceive value in performing the examination as it provided for baseline images to be obtained for later comparison to the postbypass study and allowed the identification of optimal planes of interrogation that could later be applied to facilitate the postrepair assessment. Regarding the need for surgical revisions, there was a 4.4 % incidence of return to bypass based on the echocardiographic findings. Most patients underwent a successful revision, with success being defined by the fact that the residual defect being revised was either eliminated or considered "acceptable". In recognition of the utility of intraoperative echocardiography, the authors indicated, "it was not possible for the surgeon to predict the need for a revision based on his confidence of the repair".

Numerous reports of the early TEE experience for CHD followed, documenting the benefits of this technology in the intraoperative setting as a diagnostic tool and in regards to surgical decision-making [5, 15, 17, 21–26, 28, 29, 47–57]. Subsequent publications have continued to support the major impact of this modality during surgery not only for congenital pathology but also for pediatric acquired heart disease [58, 59].

The overall incidence of alteration in surgical plan with the aid of preoperative TEE has been reported to be in the range of 3–15 %. A retrospective review of the first 341 intraoperative studies performed at Texas Children's Hospital during the years of 1990–1995, noted that the prebypass TEE resulted in alteration of the planned surgical procedure in as many as 9.4 % of cases [56]. Diagnostic categories in which TEE had the most impact on surgical procedures included ventricular septal defect in association with double-chambered right ventricle or subaortic membrane, isolated subaortic stenosis, atrioventricular valve dysfunction, single ventricle, and pulmonary atresia with ventricular septal defect. More likely, however, was the detection of minor TEE diagnostic findings that did not influence the surgical plan. This was noted in 13.2 % of the cohort. The need for immediate reoperation based on the TEE findings was reported in 8.2 % of patients.

Several years later, Randolph and colleagues at the Mayo Clinic reported the results of their study on a large number of patients, undertaken to further define the impact of intraoperative TEE during congenital heart surgery and determine appropriate indications for the use of this modality [60]. The investigation included patients encompassing a wide age range spectrum, from the neonate to the elderly. A major impact was identified in 13.8 % of cases; findings were considered to have had a major impact when unique prebypass information altered the planned surgical procedure or prompted immediate revision of hemodynamically significant defects. This was more likely to occur in younger patients, during reoperations, and in those undergoing valve repairs or complex outflow tract reconstructions.

Sloth and associates in Denmark described their experience with the use of TEE in 532 consecutive children over a period of 5 years [61]. In this series, findings on TEE led to return to bypass in approximately 3 % of patients. Ma and colleagues from the Paediatric Heart Center in Shanghai examined transesophageal recordings in 350 children with CHD [62]. Preoperative TEE added additional findings or altered prior diagnoses in 9.4 % of patients. The findings modified the planned surgical procedure in 6.6 % of the study group. Residual problems or sequelae were detected by postoperative TEE in 16.3 %, with a total of 3.7 % of patients requiring immediate intervention or return to bypass for revision of the surgical procedure.

Bettex and colleagues in Switzerland, in a two-center observational study, provided further support for the use of TEE during congenital heart surgery in children [63]. Among 865 patients under 17 years of age, alterations in surgical management were reported in 12.7 % of cases and included the need for reinstitution of cardiopulmonary bypass in 7.3 %. Changes in medical management resulting from TEE findings were required in 19.4 % of cases during the intraoperative period.

The contemporary experience among institutions that routinely utilize intraoperative imaging during congenital heart surgery suggests a return to bypass rate as guided by TEE in the range of approximately 3–7 %. Even more compelling is the observation that failure to address significant residual pathology may lead to high morbidity in these patients and in some cases account for perioperative mortality [63, 64].

While the benefits of TEE for assessing the adequacy of the surgical intervention in congenital heart surgery have been well documented, several isolated case reports describe additional benefits of intraoperative TEE in patients with CHD as well as in children with acquired cardiovascular disorders. These include: the detection of complications associated with cannulation during cardiopulmonary bypass, resection of cardiac tumors, evaluation of pulmonary artery flow after the Fontan procedure, identification and guided drainage of pericardial and pleural effusions, and others [65–70].

In addition to the utility of TEE during cases requiring cardiopulmonary bypass, the benefits of this imaging approach have also been reported during other interventions such as in video assisted thoracoscopic procedures for CHD [71–74]. Transesophageal imaging has also been utilized for guiding interventions that involve placement of devices, such as septal occluders or stents via the perventricular or direct approach in the operating room as a hybrid or combined effort by the cardiothoracic surgeon and interventional cardiologist (refer to Chap. 17) [75, 76].

The cumulative experience validates the ability of intraoperative TEE to improve the quality of the surgical interventions in CHD, both in children and adults, as well as other pediatric cardiovascular interventions. This has resulted in imaging during cardiac surgery representing the most common indication for TEE in this patient group. Although formal, rigorous scientific data regarding the impact of intraoperative TEE on clinical outcomes is lacking, this modality is now considered to be of significant benefit, evolving into an important part of perioperative management in patients with CHD, as well as other acquired cardiovascular pathologies in children. As such, TEE has become standard of care practice in many centers that specialize in CHD, in agreement with the indications outlined by various clinical practice guidelines [77–83].

Influences on Medical Management

In addition to the impact of TEE on surgical care, the literature has documented the many contributions of TEE to medical management and other aspects of anesthetic care during congenital heart surgery. Several of these benefits are described in the sections that follow.

Catheter Placement and Guidance

Central venous catheterization is considered an important aspect of perioperative care, providing for vascular access and hemodynamic monitoring. Reports have documented the use of TEE to facilitate percutaneous central venous catheter placement, allowing for visualization of guidewire position prior to the insertion of large bore central venous catheters. This may prevent repeated attempts at cannulation and potential complications, particularly in young patients [84, 85].

The utility of TEE for optimization of catheter tip placement has been reported in adults as well as in children undergoing cardiovascular interventions [86–88]. A prospective, randomized, controlled clinical trial in children examined the role of TEE in guiding proper depth of central venous catheter insertion and confirming superior vena cava cannulation [89]. The study comprised 145 patients (ages 1 day to 29 years) undergoing surgery for CHD. Correct central line catheter placement was defined as a catheter tip visible in the superior vena cava at or above the superior vena cava to right atrial junction and parallel to the wall of the superior vena cava, as determined by either TEE or chest radiograph (CXR). TEE-guided catheter placement resulted in 100 % correct placement when assessed by TEE, versus 86 % in the control group (catheter depth based on external landmarks). If the CXR was used to determine correct position, there were no differences in proper catheter positioning. The investigators concluded that TEE can be use to guide central catheter placement in patients undergoing congenital heart surgery, significantly improving the success rate of proper placement.

The placement of transthoracic intracardiac catheters may be necessary for hemodynamic monitoring in infants and children with congenital or acquired heart disease [90, 91]. Although the utility of TEE in guiding placement of these catheters has not been documented in detail, the confirmation of appropriate catheter position is facilitated and can be verified by TEE. This is also the case with placement and optimal positioning of circulatory support hardware (aortic and venous cannulae, mechanical support devices) and pulmonary artery catheters [92].

Cardiac Dearing and Identification of Intracardiac Air

The bright reflections produced by the presence of air bubbles within the heart and vasculature can be readily identified by echocardiography due to the unique acoustic properties that characterize air, in contrast to other media such as blood. Retained intracardiac air may account for significant morbidity during cardiac surgery, negatively impacting clinical outcomes. Air embolization to the coronary circulation may have immediate and/or late effects that can lead to myocardial dysfunction. This is turn can necessitate prolongation of cardiopulmonary bypass and require interventions such as institution or adjustment of inotropic support or other therapies [93, 94]. Other serious complications include those related to the presence of air in the systemic circulation and potential neurologic injury [95, 96].

Echocardiography has been shown to be exquisitely sensitive in the detection of intracardiac air and TEE provides significant benefit in facilitating cardiac deairing [97–106]. During congenital heart surgery, ensuring the adequacy of cardiac deairing prior to discontinuation of cardiopulmonary bypass is of particular relevance, given that interventions frequently require cardiotomy. Greeley and associates reported the observation of intramyocardial air in patients undergoing repair of congenital heart defects. This was described as the presence of air within the wall of a myocardial segment supplied by a coronary artery branch, suggesting air embolization of this vessel. The relevance of this observation was that this finding could lead to ventricular dysfunction after separation from bypass, regional wall motion abnormalities, and potential hemodynamic instability [107]. The report underscored the fact that the identification of intramyocardial air by intraoperative imaging may allow for the development of a specific management plan because the likely etiology for the functional and hemodynamic alterations can be readily recognized.

Additional contributions of TEE regarding the detection of air apply to procedures performed on a beating heart when aortic cross-clamping is not required or can be avoided. These procedures may involve interventions in the right-heart (e.g., right ventricular to pulmonary artery conduit replacement), left heart (e.g., insertion of inflow cannula during placement of ventricular assist device), or single ventricle (e.g., placement of graft in the right ventricle during the Sano modification of the Norwood procedure). The concern during right-heart surgery is entrainment of air into left-sided cardiac structures across an intracardiac communication (right-to-left shunting) and the risk for paradoxical air embolization. Similarly, air entrained by the left ventricle during coring of the apex for placement of a mechanical support cannula, or in the single ventricle, during right ventricular graft placement, represents a potential risk for paradoxical emboli when/if the aortic (or neoaortic) valve opens.

For the reasons discussed above, in patients with a biventricular circulation undergoing 'beating right-heart surgery' the exclusion of intracardiac communications is of relevance and TEE plays an important role in this assessment. Color flow mapping and contrast echocardiography facilitates the detection of intracardiac shunting. The use of contrast imaging, for example with agitated saline or albumin, in combination with a simulated Valsalva maneuver in intubated and mechanically ventilated patients, increases the detection of intracardiac communications as right-to-left intracardiac shunting can be identified (refer to Chap. 4). Because the reliability of contrast TEE in the detection of intracardiac communications in patients with CHD has been questioned, continuous monitoring for the presence of intracardiac air should be considered during these procedures in order to enhance their safety [108]. A similar vigilant approach applies to interventions on the left ventricle or single ventricle patient during beating heart surgery.

Assessment of Ventricular Loading Conditions

Manipulation of ventricular preload represents a key element in the optimization of cardiac performance and a major focus of hemodynamic management in the care of patients with CHD. Various parameters and techniques have been utilized in clinical practice to provide an estimation of ventricular filling, including TEE [109–111].

The determination of ventricular preload by TEE has mostly focused on the left ventricle [112–114]. Several studies have compared/correlated the assessment of left ventricular preload by TEE with measurements of filling pressures. Echocardiographic indices frequently examined have included the estimation of left ventricular end-diastolic area and/or volume. TEE has been shown to provide a more sensitive method for detecting hypovolemia than traditional hemodynamic parameters of ventricular preload, such as central venous pressure and pulmonary artery capillary wedge pressure [115]. However, a number of limitations are recognized in this assessment, including the fact that measured volumes by two-dimensional TEE are known to be significantly smaller than those obtained by angiography [115, 116].

Data regarding TEE-guided manipulations of ventricular preload in young patients with CHD is extremely limited. An investigation by Reich and co-workers recruited a small number of patients undergoing elective repair of various defects, ranging in weight from 3 to 15 kg in order to determine whether TEE could identify alterations in cardiac filling resulting from manipulations of blood volume. Changes in left ventricular end-diastolic and end-systolic areas were assessed in the transgastric left ventricular midpapillary short axis view (TG Mid SAX). At the same time, hemodynamic data were recorded while several interventions were performed after sternal closure. Measurements were obtained at baseline, upon phlebotomy, and after the reinfusion of blood. The study demonstrated that decreases in blood volume as small as 5–8 % were associated with a reduction in left ventricular end-diastolic area, as well as central venous and systemic arterial pressures. Thus both the qualitative and quantitative measurements documented changes in left ventricular filling, thereby validating the application of TEE as a useful monitor of cardiac preload in pediatric patients.

Estimation of ventricular areas and volumes, however, is known to be time-consuming and impractical in the operating room setting, representing a potential distraction for healthcare providers. In addition, the abnormal and highly variable geometry of structurally abnormal hearts imposes significant limitations upon this assessment. These factors account for the fact that the routine intraoperative evaluation of ventricular filling mostly takes place through a qualitative assessment from the echocardiographic display of the ventricular chamber of interest in multiple planes. For the left ventricle, this translates to the evaluation of changes in end-diastolic area in the TG Mid SAX view, in addition to gross assessment of left ventricular cavity size in the mid esophageal four chamber view (ME 4 Ch). For the right ventricle, a combination of views may be used including the ME 4 Ch, mid esophageal right ventricular inflow-outflow, and additional views at the transgastric and deep transgastric levels.

Assessment of Ventricular Function

The evaluation of ventricular performance is one of the most relevant applications of intraoperative echocardiography since clinical outcomes are greatly influenced by myocardial function. Ventricular performance can be described in terms of global or regional function and can also be considered in reference to the systolic and diastolic contributions.

Echocardiography provides for qualitative and quantitative measurements of ventricular systolic function and contractility (for an in depth discussion on the subject the reader is referred to Chap. 5). The applications of TEE in the determination of left ventricular ejection phase indices such as fractional shortening, fractional area change, ejection fraction, and others have been well described [117]. However, validation of these measurements, have not been thoroughly performed, with a potential error in the measurement of fractional area change in the range of 10 % under optimal conditions [118]. The abnormal ventricular geometry associated with many structural heart defects further complicates this assessment. A study of left ventricular performance in children determined that M-mode indices derived from transthoracic echocardiography and TEE were not directly comparable, presumably because of regional non-uniformity of function [119]. This is not a surprising finding considering that these measurements cannot be obtained in exactly the same plane by the two imaging modalities.

Over the last several years there has been increasing interest in the routine evaluation of diastolic function by echocardiography in both, pediatric and adult age groups, since abnormalities of ventricular relaxation and compliance are known to contribute to perioperative morbidity [120–125]. This effort has relied heavily on the use of Doppler modalities, particularly spectral analysis, in order to examine left ventricular filling alterations that may correlate with diastolic function.

It is well recognized that diastolic dysfunction plays a major role in many congenital and acquired pathologies in the pediatric age group [126–129]. Unfortunately, the evaluation of diastolic function in young patients has met several challenges, including the many confounding variables that influence appropriate Doppler assessment and interpretation of findings. Using criteria developed for transthoracic echocardiography to the transesophageal approach further magnifies these difficulties [130]. Thus the use of TEE to assess diastolic function in children with CHD remains, up to the time of this writing, of limited utility and an important area of future investigation.

Another area that has received limited attention and may benefit from further insight is the evaluation of right ventricular and single ventricular function by TEE [131, 132]. As with diastolic function, limited information is currently available in these areas and they remain important subjects for ongoing research.

Detection of Myocardial Ischemia

TEE has been shown to be a sensitive tool for the detection and monitoring of myocardial ischemia in adults. The sensitivity of TEE for intraoperative ischemia detection is known to be superior to electrocardiography-detected ST segment changes or elevations of pulmonary artery wedge pressure during pulmonary artery catheter monitoring [133]. As such, the qualitative assessment of regional myocardial function by TEE has become a widely used modality in the perioperative care of adult patients at risk for compromised coronary blood flow, either during cardiac or noncardiac surgery [134].

Although limited data is available, a few investigations have focused on the potential applications of this monitor for the detection of myocardial ischemia in children undergoing interventions that involve manipulation of the coronary arteries [135]. Rouine-Rapp and associates prospectively studied a group of neonates undergoing an arterial switch operation to determine if segmental wall motion abnormalities, as identified by intraoperative TEE, represented myocardial ischemia [136]. The investigation demonstrated that when multiple segmental wall motion abnormalities were present, the regional wall dysfunction tended to persist at the time of chest closure. Relative to those with normal wall motion after surgical repair, this group of infants had more postoperative ischemic events based on Holter monitoring (ST segment changes) and elevated cardiac troponin I levels, confirming the correlation between TEE detected regional wall motion abnormalities and myocardial ischemia.

These observations validate the benefits of TEE in the early diagnosis of compromised myocardial blood flow and support the perioperative use of this modality in infants and children at increased risk of myocardial ischemia or infarction during congenital heart surgery. This application likely extends to pediatric patients undergoing interventions for acquired pathology and also to the adult population with CHD who may in addition have comorbidities that impact coronary blood flow.

Impact on Anesthetic and Hemodynamic Management

An extensive literature supports the role of TEE in clinical decision-making in adult patients. Several studies have also demonstrated the benefits of this technology regarding hemodynamic monitoring and modifications of medical management in patients with CHD and children with acquired cardiovascular pathologies. These reports include experiences worldwide.

Two investigations that included large number of patients focused on changes in medical care as a result of intraoperative TEE. Sloth and associates in Denmark evaluated the monitoring value of intraoperative TEE in 532 consecutive children, over a 5-year period undergoing heart surgery [61]. New information was identified by TEE in 45 % of the cohort. This information was judged to have been instrumental in directing, altering or changing medical management in 8 % of cases (43 out of 532). The most frequent interventions included changes in inotropic strategy related to ventricular dysfunction and volume replacement. Bettex and coworkers analyzed reports from 865 intraoperative examinations between two specialized congenital heart surgery centers [63]. Medical management was assisted by TEE in 19.4 % of cases, leading to changes that included optimization of ventricular filling and pharmacologic therapy.

The overall data, although limited, provide support for the extended role of intraoperative TEE outside of its impact on the surgery itself. The data demonstrate the utility of perioperative TEE as a monitoring adjunct to facilitate anesthetic care, hemodynamic and pharmacologic management, medical decision making, and influence on treatment strategies. Moreover, this imaging approach also provides a framework to assist in the formulation of care plans during the immediate postoperative period.

Cost Effectiveness of Intraoperative TEE

The early experience using epicardial imaging during congenital heart surgery acknowledged not only the impact of this technology on surgical management but also suggested that the benefits of this approach justified the associated costs [1]. Ungerleider et al. noted that the costs involved in the performance of the intraoperative studies was justified by savings in operating room time and possible prevention of reoperations because of less than optimal results [3]. In a subsequent report, a more formal cost benefit analysis was performed comparing hospital costs between patients requiring a reoperation versus those undergoing immediate revision of the repair based on echocardiographic data [46]. Not surprisingly, hospital costs were substantially lower in the latter group. These findings provided clear and compelling evidence of the financial benefits of intraoperative TEE.

Other studies have also examined the issue of cost-effectiveness of intraoperative TEE. Relatively early in the experience a cost-benefit analysis was reported by Benson and Cahalan that included various cardiac surgical settings, including surgery for CHD [137]. Based upon published data regarding the impact of TEE in identifying residual defects that required immediate revision during interventions for CHD in infants and children, their analysis estimated a definite financial patient benefit per TEE study performed. In fact, in their assessment, among patients undergoing cardiac surgery, those with CHD derived the greatest overall financial benefits. Their analysis indicated that the financial gain of TEE was substantial, frequently outweighing the costs of repeat surgery.

Siwik and colleagues examined the costs and resources required in performing routine TEE services as an adjunct to congenital heart surgery in a case-controlled analysis of 63 children undergoing elective, complex intracardiac repairs [138]. Their study concluded that the routine use of TEE in these children was cost-effective, based on the observation that it did not significantly increase echocardiography costs in the combined operative and postoperative periods. There was a trend toward fewer echocardiographic studies in the TEE group suggesting that the routine use of TEE avoided the need for some additional postoperative studies in the intensive care unit. It was emphasized that the cost benefit was independent of any impact of TEE on clinical outcomes. No patient in this cohort required return to cardiopulmonary bypass and surgical therapy was altered by TEE findings in 3 % of patients (2 out of 63). Complications were rare, self-limited, and when they occurred these were associated with probe placement or manipulation in smaller patients.

Randolph and co-workers, in a large study defining the impact of TEE, estimated that an intraoperative TEE service would pay for itself, even without considering any benefits derived from the preoperative examination [60]. A retrospective review of a 10-year experience by a European center sought to examine the cost-effectiveness of routine intraoperative TEE in pediatric cardiac surgery [139]. The report comprised 580 studies performed in patients younger than 17 years of age undergoing surgery (mean age 35 months). Thirty-three patients required reinitiation of cardiopulmonary bypass based on TEE findings. The study proposed a savings of $690–$2,190 per patient based on conservative calculations. It was emphasized that this calculation likely represented an underestimate of the true cost-effectiveness of routine intraoperative TEE. The estimates were based upon assumptions regarding the cost of reoperation and complications related to a residual defect.

In summary, although the number of formal investigations that have explored this issue is relatively small, all published work to date has demonstrated substantial cost-benefit regarding the use of TEE during congenital heart surgery, particularly in the pediatric population.

Limitations and Pitfalls of Intraoperative TEE

TEE provides high-resolution images and hemodynamic information that may not be obtainable with other diagnostic tools during the perioperative period. Although the benefits of this approach are widely recognized, the limitations of the technology should also be appreciated [140, 141]. Whereas transthoracic imaging provides for transducer interrogation through various locations over the chest wall, the TEE imaging windows are constrained by the confines of the esophagus and stomach, thus restricting transducer mobility. This also results in limited potential for optimal Doppler angle alignment. Other challenges relate to suboptimal far field imaging, particularly of anterior structures and less than expected image quality in some patients. The air-filled tracheobronchial tree can present difficulties in the evaluation of certain cardiovascular structures, such as the left pulmonary artery beyond its proximal region, the distal ascending aorta, and the transverse aortic arch. In addition, comprehensive evaluation of vascular structures within the thorax, such as high superior vena cava, innominate vein, anomalous systemic or pulmonary venous return, may not be feasible.

Other limitations should also be recognized including the fact that, in the majority of cases, the ultrasound examination is performed under suboptimal ambient lighting that can be challenging. Time constraints or clinical conditions may also limit the time available to undertake a comprehensive study.

The literature extensively documents the utility of TEE in the detection of residual abnormalities that may require immediate revision in congenital heart surgery. Regarding return to bypass decisions to address residual pathology or suboptimal results, it is important to consider that a number of factors, including the level of inotropic support, immediate postbypass catecholamine state, loading conditions, and functional state of the myocardium can influence the echocardiographic findings. These factors may lead to under or overestimation of the hemodynamic severity of the condition in question. The optimal setting for hemodynamic assessment in most postoperative patients is one in which conditions reflect an equilibrium, or steady state. Given the changing and dynamic nature of the respiratory, hemodynamic, pharmacologic, and anesthesia-related management interventions that occur continuously in the operating room, it is not surprising that accurate assessment of a patient's hemodynamic status represents a significant challenge, if not an impossibility, in this setting. Thus, the findings from intraoperative TEE should be interpreted within this context.

A report by Kausal and coworkers highlights some of the difficulties regarding return to bypass decisions [142]. This group explored the question as to whether significant intraoperative right ventricular outflow gradients after repair of tetralogy of Fallot represented an indication for revision. The study population included 166 patients (median age 7 years) undergoing a transatrial repair. A "significant" right ventricular outflow obstruction was identified in 35 % of patients following the repair (gradient greater than 40 mmHg, right ventricular to left ventricular pressure ratio over 85 %). Fixed obstruction, requiring immediate surgical revision, was present in only 12 % of these cases. The remaining 88 % of patients with a "significant" gradient were felt to have dynamic right ventricular outflow obstruction and did not undergo reoperation. It is of interest that, irrespective of the severity of the obstruction detected intraoperatively, outflow gradients declined sharply on follow-up (mean 18.5 months after surgery). No reoperations or late deaths were reported. The authors concluded that intraoperative echocardiography was helpful in distinguishing "fixed" from "dynamic" obstruction, thereby obviating needless revisions. The finding of a decline in dynamic right ventricular outflow tract gradient regardless of initial postoperative severity suggested that this should not be considered in isolation to determine the need for surgical revision in this patient population.

Although TEE plays a significant role in assessing the adequacy of the surgical intervention, it needs to be emphasized that return to bypass decisions should consider an assessment of the overall risk versus benefit ratio. In most cases this decision involves clinical judgment based not only upon the echocardiographic findings, but also a number of other factors, including the likelihood of an adequate or improved result balanced against the risk of potential morbidity related to additional surgery/cardiopulmonary bypass/ischemic time.

Although data regarding the correlation between intraoperative and postoperative echocardiographic data is scarce, there is literature suggesting that in some cases a discrepancy may be found. Lee and associates examined the validity of intraoperative TEE in predicting the severity of mitral regurgitation at follow up in patients after complete repair of atrioventricular septal defects [143]. The assessment of mitral regurgitation was performed using a biplane TEE probe after weaning from cardiopulmonary bypass but prior to chest closure. The ratio of the maximum regurgitant jet area by color Doppler flow imaging, to the left atrial area on two-dimensional imaging was used for quantification of mitral regurgitation. A discrepancy in the grade of mitral regurgitation was noted in 47 % of patients, in most of cases, with a higher grade of valvar regurgitation on follow-up. This suggested that the grade on intraoperative mitral regurgitation by TEE may not predict the degree of regurgitation at follow up. Subsequently, Honjo and colleagues evaluated 42 consecutive children undergoing valve repairs [144]. Significant discrepancies were identified between the assessment of residual atrioventricular valve regurgitation and stenosis between the intraoperative TEE and predischarge transthoracic echocardiogram (disagreement rate of 64 %). The authors noted that in most cases the residual regurgitation was underestimated in the operating room. In contrast, there was reasonable agreement for the evaluation of aortic valve regurgitation. It is not altogether surprising that a discrepancy might exist between intraoperative and postoperative echocardiographic findings. Factors such as the level of sedation/depth of anesthesia and changing hemodynamic conditions likely influence study results, particularly the assessment of valvar stenosis/regurgitation. Moreover, the quality of echocardiographic imaging can differ substantially between TEE and postoperative transthoracic studies. Finally, there are occasionally changes that can occur in a surgical repair, even within a few days postoperatively, and these might also affect the echocardiographic appearance.

Potential pitfalls of TEE, including misinterpretation of findings leading to erroneous diagnoses, should be recognized. The use of TEE in the evaluation of CHD and the assessment of the surgical results requires an advanced level of both skills and knowledge. This assumes a combination of training, experience, and expertise in the field. Unlike most adult cardiovascular disease, the vast majority of abnormalities in children are structural in nature and their characterization require extensive familiarity with the wide spectrum of congenital cardiac pathologies. There is a need for an in-depth and wide-ranging skill set: three-dimensional understanding of normal and abnormal cardiovascular anatomy/pathology, structural variants, physiologic impact and hemodynamic consequences, natural history of the defects, and medical and surgical approaches/options. Furthermore, an understanding of TEE technology is essential, including indications, contraindications, optimization of system settings, benefits and limitations of the modality, and the recognition of artifacts. Finally, a thorough knowledge of the TEE techniques and views/probe manipulations used to evaluate CHD is essential, along with a solid understanding of the echocardiographic appearance of the many different forms of unoperated and operated CHD.

In his review of clinical outcomes in children, Stevenson highlighted the importance of physician skills in intraoperative echocardiography during congenital heart surgery [145]. A positive impact on clinical outcomes was noted when TEE examinations were performed by physicians who met the published guidelines. This publication, accompanied by a thought provoking editorial entitled "*Transesophageal*

Echocardiography Guidelines: *Return to Bypass or to Bypass the Guidelines*?" and several subsequent letters to the editor, outlined the critical importance of sufficient training and expertise by intraoperative echocardiographers regardless of specialty.

Evaluation of Congenital Heart Disease by TEE in the Postoperative Setting

The use of TEE has been extensively documented in the cardiac intensive care unit and other postoperative settings at many centers [146–153]. The fact that the applications of TEE in the critically ill have been reported more frequently in adult patients is likely an indication that children generally have more favorable transthoracic windows and adequate information can usually be obtained by standard transthoracic echocardiography. However in the subset of postoperative pediatric patients (with both congenital and acquired cardiovascular pathology) in whom transthoracic imaging is suboptimal in the intensive care setting, the superior resolution of TEE may facilitate morphologic and functional assessment. In such patients, TEE can overcome limitations related to poor windows, suboptimal image quality due to lung interference, and/or the presence of bandages [154]. In some cases, an open sternum does not allow for accessible transthoracic diagnostic imaging and in this setting TEE may be extremely helpful [155].

In the pediatric age group, mechanical support of the circulation is receiving increasing attention as hardware appropriate for patient-size has become available. Existing technologies continue to be applied, and novel devices are being considered to address circulatory failure in those with CHD and other pathologies. The use of TEE in the operating room and/or intensive care unit may facilitate the care of these patients by providing assistance in cannulae/device positioning, assessment of cardiac chamber decompression, evaluation of ventricular loading conditions, and determination of recovery of myocardial function [156]. In addition, TEE can assist in the optimization of pharmacologic and other medical therapies, and it can provide information regarding the suitability of weaning from support.

Although several investigations have reported on the role of TEE in the assessment of cardiac output and systemic vascular resistance in critically ill adult patients, these types of assessments have not yet been validated in children [157, 158].

TEE may assist in the further characterization of unexpected/unusual findings or pathology following congenital cardiac surgery—findings identified or suspected but not adequately defined by transthoracic imaging. Examples of possible postoperative clinical situations in which TEE can provide significant additional information include (but are not limited to) the evaluation of:

- Residual atrial shunting, particularly in patients with unexplained cyanosis
- Possible pulmonary venous obstruction
- Residual ventricular septal defects
- Atrioventricular and semilunar valve abnormalities
- Mechanism of right or left ventricular outflow tract obstruction
- Prosthetic valve function
- Possible infective endocarditis

Although a subset of patients with a complicated or unanticipated immediate postoperative course may necessitate further diagnostic evaluation, in a number of cases the diagnostic capabilities of TEE can obviate the need for alternate (and sometimes more invasive) imaging studies.

The American College of Cardiology Foundation and the American Society of Echocardiography, in combination with key specialty and subspecialty societies, conducted an appropriateness review for transthoracic and transesophageal echocardiographic imaging in adult patients (18 years of age or older) [159]. This effort assumed that TEE would be used as an adjunct or as a subsequent test to transthoracic echocardiography, when suboptimal images precluded an adequate diagnostic study. With respect to potential applications of TEE in adult patients with CHD in the intraoperative and postoperative settings, indications generally acceptable and considered reasonable by members of the working group included:

- Assessment of known or suspected adult CHD including anomalies of great vessels and cardiac chambers and valves, or suspected intracardiac shunt following repair/operation
- Evaluation of hypotension or hemodynamic instability of uncertain or suspected cardiac etiology
- Evaluation of pericardial conditions including but not limited to pericardial mass, effusion, constrictive pericarditis, effusive-constrictive conditions, patients post-cardiac surgery, or suspected pericardial tamponade
- Evaluation of known or suspected pulmonary hypertension including evaluation of right ventricular function and estimated pulmonary artery pressure
- Re-evaluation of patients with prosthetic valve with suspected dysfunction or thrombosis or a change in clinical status
- Evaluation for cardiovascular source of embolic event (patent foramen ovale/atrial septal defect, thrombus, neoplasm)
- Re-evaluation of infective endocarditis in patients with any of the following: virulent organism, severe hemodynamic lesion, aortic involvement, persistent bacteremia, a change in clinical status, or symptomatic deterioration

Data regarding the applications of TEE in children in the immediate postoperative period are quite limited. Thus, indications comparable to those discussed above have not yet been clearly defined. Nonetheless, many situations are analogous to those encountered in adults, and the clinical experience suggests that TEE, when used in a judicious and appropriate manner, can also provide real and important benefits in the postoperative setting in the pediatric age group.

Summary

The overwhelming contributions of TEE have led to this imaging approach being considered the standard of care for intraoperative assessment of most congenital heart repairs by many centers. Extensive experience has documented significant benefits in patients with CHD that include surgical planning, evaluation of the intervention, guidance of the surgical revision as necessary, and a major overall impact in surgical decision-making. Contributions to anesthetic care include real time monitoring of ventricular filling, myocardial performance, ensuring adequate cardiac deairing, in addition to optimization of hemodynamic management strategies. Intraoperative TEE assists in the formulation and optimization of plans for postoperative care and provides important contributions in this setting. Although not formally assessed in a rigorous scientific manner, the experience regarding the perioperative contributions of TEE is compelling enough to assume a major impact of this technology on clinical outcome in CHD.

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