Intraoperative echocardiography

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Introduction

The transesophageal approach is recognized as an effective window for imaging intracardiac and vascular structures due to the proximity of the esophagus to the heart and major blood vessels. Initial consideration of using the esophagus as a site of echocardiographic imaging was made in the mid-1970s by Frazin et al. who described the use of an esophageal M-mode ultrasonic crystal. The early 1980s marked the introduction of a gastroscope with a two-dimensional transducer. Since the introduction of transesophageal echocardiography (TEE) to the intraoperative setting in the late 1980s, multiple publications have documented the utility of this imaging modality in adult cardiac patients in the evaluation of valvular repair and prosthetic valve function, and for monitoring of myocardial ischemia and left ventricular preload. As surgical advances in the care of patients with heart disease rapidly evolve, the contributions of TEE continue to be demonstrated. Immediate detection of suboptimal surgical interventions by TEE has been shown to improve surgical outcomes, thereby avoiding subsequent reoperations and reducing morbidity, mortality, and cost. Until the early 1990s, intraoperative evaluation of infants and children undergoing surgery for congenital heart was not feasible via the transesophageal approach due to the fact that probe sizes were not suitable for examination in young children. The subsequent development of miniaturized technology initially generated a number of studies which demonstrated that TEE can be performed safely in the pediatric age group and provides substantial benefit as well. This experience has been substantiated over the last decade.

This chapter focuses on the evolution of intraoperative echocardiography for the evaluation and monitoring of pediatric cardiovascular surgery, the benefits of this technology, and the practice of pediatric TEE as it stands today.

History of pediatric intraoperative epicardial echocardiography

In 1989 Ungerleider et al. provided one of the first demonstrations of the use of intraoperative echocardiography in congenital heart surgery. Transducers covered in sterile latex were directly applied to the anterior surface of the heart in order to assess ventricular function before and after cardiopulmonary bypass, and to document the adequacy of the surgical repair. Their findings “directed specific and efficient repair immediately so that all patients left the operating room with documented surgically acceptable results. Comparison of ventricular function between pre- and post-bypass studies enabled appropriate application of pharmacologic agents in the operating room if necessary.” These data provided strong support to the notion that intraoperative echocardiography could guide specific surgical or anesthetic adjustments in pediatric cardiac surgery. These observations were supported by additional investigations and underscore the useful role of epicardial echocardiography in the surgical management of congenital heart disease (CHD).

Epicardial echocardiography at the present time is reserved for tiny infants in whom the currently available transesophageal probes cannot be used because of size constraints and in patients with contraindications to esophageal instrumentation. Despite its benefits, epicardial echocardiography may have limitations related to transducer size, inadequate windows of interrogation, potential for hemodynamic alterations, and requirement for participation and experience in cardiovascular imaging by the surgeon.

History of pediatric intraoperative transesophageal echocardiography

Cyran et al. described the first experience in pediatric intraoperative TEE in 1989 using an adult-sized probe in children as young as 7.5 years of age. The report noted that this
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of interrogation allowed for a more complete examination of the ventricular outflow tracts, but the Doppler angle of incidence still did not permit accurate assessment of pressure gradients. Several investigators subsequently demonstrated that advancing the single-plane probe into the fundus of the stomach could provide a view that favorably imaged the outflow tracts, allowing for quantitative assessment of outflow tract obstructions.44,45 Accordingly, the transgastric views overcame some of the limitations of single and biplane imaging.

Recently multiplane imaging has become available for pediatric patients (Fig. 9.1).46 A high-resolution minimultiplane TEE probe (5 MHz, 48-element, 9.5–10.0 mm diameter) now allows for the acquisition of images in several planes, which is of particular benefit in the assessment of complex structural heart defects. An even smaller prototype device (micromultiplane TEE probe) with high resolution capabilities (7.5 MHz, 48-element, 8.2 mm diameter), developed by General Electric Corporate Research in association with Odelf Corporation (the Netherlands), has been investigated and proposed as an ideal probe in infants under 2 kg.47 However, technologic limitations related to the small size of the probe have hindered the further development of this device.

To date, most institutions use a combination of all approaches, transesophageal and transgastric, for comprehensive evaluation of the pediatric heart. Transesophageal echocardiography has been a rapidly evolving field and is considered the standard of care in many cardiac surgical centers for intraoperative evaluation of pediatric patients undergoing surgery for congenital and acquired heart disease.48,49

**Fig. 9.1** Types of transesophageal echocardiographic probes. The left panel displays the single plane (monoplane probe) that allows for transverse (horizontal) plane imaging. The middle panel depicts the biplane device that provides for both transverse and longitudinal (vertical) plane interrogation. The right panel depicts the multiplane (omniplane) probe that provides for any number of views from planes acquired in a 0–180° arc.

**Indications for transesophageal echocardiography**

Transthoracic echocardiography provides excellent definition of cardiovascular anatomy in most infants and young
children. Accordingly TEE should be considered a complimentary imaging modality and not a substitute to the transthoracic exam. Transesophageal echocardiography provides diagnostic-quality images in the majority of congenital cardiac anomalies when transthoracic examination or other studies have not successfully elucidated the necessary clinically relevant information. By overcoming limitations related to poor windows, suboptimal image quality or lung interference, TEE is able to facilitate morphologic and functional assessment of structural cardiac abnormalities. Transesophageal echocardiography might be superior to routine transthoracic echocardiography in the adolescent or adult for the evaluation of malformations such as specific types of atrial septal defects, anomalous pulmonary venous connections, and complex cardiac malformations. This technology is also key in confirming or excluding diagnoses of major clinical relevance in CHD such as atrial baffle pathology (leak or obstruction), Fontan obstruction or related venous thrombus, as well as acquired cardiovascular pathology (valve vegetations, aortic root abscess).50

Transesophageal echocardiography also plays an important role in the catheterization laboratory in guiding and monitoring of interventional procedures and evaluating their successes, failures and complications.51

Indications for TEE in children have been proposed by various groups. Initial efforts were by the Committee on Standards for Pediatric Transesophageal Echocardiography, Society of Pediatric Echocardiography in 1992.52 In 1996, task forces of the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists published practice guidelines for perioperative TEE.53 Shortly thereafter, the American College of Cardiology (ACC)/American Heart Association (AHA) Task Forces, in collaboration with the American Society of Echocardiography (ASE), published recommendations for the clinical application of echocardiography.54 The ACC/AHA/ASE recently reconvened to update these guidelines.55 The indications for pediatric intraoperative TEE from the four reports respectfully are summarized as follows:

(a) Intraoperative and post-repair examinations are indicated when operations are performed on cardiac defects in which there are significant residual abnormalities such as outflow tract obstruction, valve regurgitation or stenosis, or intracardiac communications are anticipated or suspected.52

(b) Most cardiac defects requiring repair under cardiopulmonary bypass are a category I indication for intraoperative TEE, including pre- and post-cardiopulmonary imaging (defined as that being supported by the strongest evidence or expert opinion substantiating that TEE is useful in improving clinical outcomes).53

(c) Monitoring and guidance during cardiothoracic procedures associated with the potential for residual shunts, valvular regurgitation, obstruction or myocardial dysfunction is a class I indication (defined as conditions for which there is evidence and/or general agreement that a given procedure or treatment is useful and effective).54

(d) Surgical repair of most congenital heart lesions that require cardiopulmonary bypass is a class I indication. The updated guidelines list assessment of residual flow after interruption of a patent ductus arteriosus as a class IIb indication (conditions for which there is conflicting evidence and/or a divergence of opinion about the usefulness/efficacy of a procedure or treatment). Repair of an uncomplicated secundum atrial septal defect is considered a class III indication (defined as conditions for which there is evidence and/or general agreement that the procedure/treatment is not useful/effective and in some cases may be harmful).55

In general the recommendations for use of TEE in pediatric heart surgery apply to all cases in which this imaging approach may allow for real-time clinical decision making, hemodynamic monitoring, and immediate assessment of the surgical results.

### Transesophageal echocardiography technique

#### Equipment

A number of transesophageal probes are commercially available for use in the pediatric age group. The most commonly used echocardiographic platforms in North America include Philips Medical Systems (former Hewlett Packard, Agilent and ATL Technologies, Andover, MA), Acuson/Siemens (Siemens Ultrasound, Mountain View, CA) and General Electric/Vingmed (General Electric Medical Systems, Milwaukee, WI). Frequently used transesophageal probes and their specifications are listed in Table 9.1. Other TEE probes suitable for pediatric use are marketed by several companies in Europe and Asia.

In general, probes are not interchangeable among echocardiographic platforms. Although there is an increased recognition from companies to allow for probes to be interchangeable between systems in their own platform, in some cases this is not feasible due to differences between older and newer equipment related to advances in technology.

#### Probe selection

Although TEE probes can be inserted in tiny neonates, even in those as small as 1.4 kg, the usual weight range for infants and children who can be safely imaged with the current commercially available pediatric probes is over 3 kg.56 There are minimal differences between the actual transducer dimensions of commercially available pediatric probes, although clinically the biplane probes are sometimes easier to insert.
Intraoperative echocardiography

This probe has the advantage of being extremely small. The single plane may however limit its usefulness.

**Probe insertion**

The anesthetic preparation for outpatient TEE includes a careful history, physical examination, and informed consent. The standard safety precautions associated with an endoscopic procedure should be followed. Although serious complications during TEE are rare, it should be considered that this is a semi-invasive/invasive procedure that may result in some degree of patient discomfort and potential risks. In the outpatient setting several options are available for anesthetic management. A combination of oropharyngeal topical anesthesia and intravenous sedation may be suitable for the adolescent or young adult. Younger children, however, will frequently require deep sedation or general anesthesia.

The superior resolution capabilities of the adult-sized multplane probes make these devices preferable for children above 15–20 kg. The experience with multplane probes favors these over biplane transducers, as the ideal positioning of the interrogating plane is feasible and not dictated by the fixed plane of the transducer(s).

A miniaturized 5.5–10.0 MHz single longitudinal plane transducer with a 3.3 mm diameter used for intravascular and intracardiac imaging has been described in pediatric patients for transesophageal applications, four of whom weighed less than 2.5 kg. This probe has the advantage of being extremely small. The single plane may however limit its usefulness.

### Table 9.1 Commonly used transesophageal probes in pediatrics.

<table>
<thead>
<tr>
<th>Transesophageal probes</th>
<th>Tip dimensions (W × H × L, in mm)</th>
<th>Shaft dimensions (W × L, in mm)</th>
<th>No. of elements</th>
<th>Imaging frequencies (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philips (Hewlett Packard/Agilent)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pediatric biplane</td>
<td>9.3 × 8.8 × 27</td>
<td>8 × 80</td>
<td>64</td>
<td>5.5–7.5</td>
</tr>
<tr>
<td>Pediatric multplane</td>
<td>10.7 × 7.2 × 25.4</td>
<td>7.4 × 70</td>
<td>48</td>
<td>4.0–7.0</td>
</tr>
<tr>
<td>Adult multplane (Omni II)</td>
<td>14.5 × 11.2 × 42</td>
<td>10.5 × 100</td>
<td>64</td>
<td>4.0–7.0</td>
</tr>
<tr>
<td>Acuson (Siemens)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pediatric biplane (V7B)</td>
<td>9.5 × 8.5 × 31</td>
<td>8.5 × 85</td>
<td>48</td>
<td>5.0–8.0</td>
</tr>
<tr>
<td>Pediatric multplane (V7M)</td>
<td>10.7 × 8 × 36*</td>
<td>7 × 70</td>
<td>48</td>
<td>4.0–8.0</td>
</tr>
<tr>
<td>Adult multplane (V5M)</td>
<td>14.5 × 11.5 × 45</td>
<td>10.5 × 110</td>
<td>64</td>
<td>3.5–7.0</td>
</tr>
<tr>
<td>General Electric (Vingmed)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pediatric multplane (8T, MPTE)</td>
<td>10.7 × 7.5 × 37.5*</td>
<td>7 × 70</td>
<td>48</td>
<td>3.3–8.0</td>
</tr>
<tr>
<td>Adult multplane (6T/6Tv and 5T/PAMPT)</td>
<td>14 × 12.5 × 40</td>
<td>10.5 × 110</td>
<td>64</td>
<td>4.4–8.0</td>
</tr>
</tbody>
</table>

*Length of inflexible distal part of the probe.

**Fig. 9.2** Hemodynamic alterations in a neonate associated with insertion of a transesophageal echocardiography (TEE) probe. The graphic illustrates dramatic decreases in systemic arterial blood pressure (recorded from a femoral artery catheter) associated with TEE probe insertion in infant with total anomalous pulmonary connection. Hypotension was most likely the result of compression of the pulmonary venous confluence by the probe.
nomenclature standards may also be considered applicable to pediatric patients. A systematic and complete exam is emphasized in the document; however, it is recognized that various factors may influence the ability to perform a comprehensive study. In addition to an organized approach for acquisition of the echocardiographic information in patients with CHD, a focused interrogation of the structural cardiac abnormalities in question and their hemodynamic impact is essential.

In the operative setting after the induction of general anesthesia and endotracheal intubation, gastric contents may be suctioned in order to optimize image quality. Some centers prefer nasal over oral endotracheal intubation in view of concerns related to the stability of an oral endotracheal tube during probe manipulation. Regardless of the intubation route, the endotracheal tube should be securely taped to minimize potential for displacement. The lubricated unlocked probe should be advanced gently into the esophagus with the head in midline position. A forward thrust of the mandible frequently assists in the passage of the probe. On occasion direct guidance of the probe with a gloved finger may be helpful. If significant difficulty is encountered and attempts at probe insertion are unsuccessful, direct visualization of the oropharynx with a laryngoscope may assist in esophageal intubation. The probe should never be advanced if resistance is encountered. Once the transducer is positioned behind the heart, the patient's head can be turned to the side to avoid interference with the surgical procedure during manipulation of the probe.

**Imaging technique**

The TEE probe can be manipulated in three general directions; advanced or withdrawn, anteflexed, or retroflected, and rotated clockwise or counterclockwise relative to the sagittal plane (Fig. 9.3). The multiplane probe obviates some of the manipulations required in single and biplane devices. As general principles of transducer manipulation, anteflexion of the transducer brings structures anterior and toward the base of the heart into view, clockwise rotation allows imaging of rightward structures, and counterclockwise rotation permits viewing of left-sided structures. In the smallest neonates, minimal adjustments in probe position are adequate to change from view to view.

Guidelines have been published for performing a comprehensive intraoperative multiplane echocardiographic examination. Although these recommendations represent a consensus among physicians primarily involved in the care of adults, the guidelines regarding image orientation and nomenclature standards may also be considered applicable to pediatric patients. A systematic and complete exam is emphasized in the document; however, it is recognized that various factors may influence the ability to perform a comprehensive study. In addition to an organized approach for acquisition of the echocardiographic information in patients with CHD, a focused interrogation of the structural cardiac abnormalities in question and their hemodynamic impact is essential.

All examinations should include careful two-dimensional imaging, spectral and color flow Doppler interrogation. To evaluate for small intracardiac shunts contrast injection with agitated saline into a peripheral or central vein may be used as the microbubbles are readily apparent even when a very
small number of these cross an intracardiac defect (right-to-left shunt). Contrast echocardiography may also be useful in the identification of anomalous systemic venous connections as seen in patients with persistent drainage of a left superior vena cava into the coronary sinus.60,61

The basic examination described in the sections that follow assumes levocardia (heart in the left thoracic cavity, apex pointing to the left), situs solitus (normal arrangement: stomach to the left, liver to the right, normal systemic and pulmonary venous pathways) and concordant atrioventricular and ventriculoarterial connections. The wide spectrum of structural cardiovascular malformations dictates a modified scheme from the basic examination in many patients. Although a particular sequence for the examination is not emphasized it is extremely helpful for each individual to develop an organized approach in order to perform a comprehensive interrogation in an expeditious manner.

**Transverse plane examination**

The short axis views obtained with single or biplane probes consist of cross-sections oriented in an axial plane, and are therefore slightly oblique relative to a true short axis of the heart. This limitation is overcome by multiplane echocardiography allowing for optimal alignment of the imaging plane with the structures of interest. Manipulation of the probe (advancement or withdrawal) provides images from the base to the apex of the heart. The most cranial short-axis view is obtained at the base of the heart from which the probe is anteflexed slightly to display the aorta, the main pulmonary artery, and its bifurcation. The proximal branched pulmonary arteries can be readily imaged (Fig. 9.4a); however, interposition of the left mainstem bronchus between the esophagus and left pulmonary artery makes imaging of this vessel challenging. Advancement of the probe displays the aortic valve in short axis, the proximal ascending aorta and the origins of the coronary arteries. A 30° retroflexion of the multiplane probe at the level of the base of the heart defines the anatomy of the aortic valve, cusps, commissures, and valve motion throughout the cardiac cycle (Fig. 9.4b). Rotation of the probe in counterclockwise fashion from this position displays the left-sided pulmonary veins; clockwise rotation shows the right-sided pulmonary veins, superior vena cava, and right atrial appendage. Advancement of the probe into the esophagus allows for the four- and five-chamber views to be obtained (Fig. 9.4c,d). This demonstrates the atrial, atrioventricular and ventricular septae, and atrioventricular valves. Further advancement of the probe into the stomach provides for left ventricular short axis images to be obtained seen as multiple cross-sectional views of the left ventricle, mitral valve, and papillary muscles (Fig. 9.4e). Oblique sections of the right ventricle are obtained by slight probe flexion and/or rotation at this level.

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**Fig. 9.4** Transverse plane examination. (a) Pulmonary artery view. The main and branched pulmonary arteries are depicted in this view, obtained at 0° at the base of the heart. (b) Aortic short axis view. The aortic valve cusps are well seen in this short axis view obtained with 30–40° of angulation at the base of the heart. (c) Four-chamber view. This view demonstrates the atrial and ventricular chambers and septal structures. This view is obtained at 0° in the mid-esophagus. (d) Five-chamber view. The structures demonstrated in this view include the right and left atria, right and left ventricles, and left ventricular outflow tract/aorta. (e) Left ventricular mid-papillary short axis view. This view provides for short axis sections of the left ventricle and portions of the right ventricle (obtained at 0–20°). The left ventricular papillary muscles are well demonstrated in this view. This is a frequently used view in the evaluation of left ventricular systolic function (global and segmental) and assessment of preload. Ao, aorta; AoV, aortic valve; LA, left atrium; LPA, left pulmonary artery; LV, left ventricle; LVOT, left ventricular outflow tract; MPA, main pulmonary artery; RA, right atrium; RPA, right pulmonary artery; RV, right ventricle; RVOT, right ventricular outflow tract.
two-chamber view (left atrium and left ventricle) can be obtained with additional counterclockwise probe rotation (Fig. 9.5c). The multiplane probe allows for the bicaval view to be obtained at 90° with the probe rotated rightward, for the two-chamber view at 90° with the probe rotated leftward, a “true” left ventricular outflow tract view at 120°, and a right ventricular inflow and outflow view at 60° (Fig. 9.5d).

Transgastric examination

Transgastric examination allows for additional two-dimensional and Doppler information to be obtained. This helps refine the data obtained from the transesophageal windows, and in some cases additional diagnostic details are added that would not be possible otherwise. This is of particular utility when only a single-plane probe is available.

The suggested approach to the transgastric exam is as follows: the probe is advanced into the stomach, anteflexed maximally and positioned anterior to the fundus. When the patient’s abdomen is exposed during this maneuver, it is frequently possible to observe the tip of the probe outpouching the abdominal wall. If there is difficulty in achieving the views, the probe is relaxed and withdrawn, then re-advanced and withdrawn with maximal anteflexion to ensure adequate probe contact. Anteflexion should not be performed if resistance is encountered. From this position, rotation of the probe to the left with moderate deflexion provides images of the right ventricular outflow tract and the proximal pulmonary trunk as it courses anteriorly across the surface of the heart (Fig. 9.6a); clockwise rotation and slight flexion from this position permits similar evaluation of the left ventricular outflow tract (Fig. 9.6b). The flexion of the probe is then increased slightly to define the inlet and outlet components of the ventricular septum as well as the atria and atrioventricular valves (Fig. 9.6c). The entrance of the pulmonary veins into the left atrium is demonstrated from this plane, and with rotation of the probe to the right the venous connections to the right atrium can also be seen. Because the probe is some distance from the heart with a portion of the liver interposed, small movements of the transducer subtend large imaging arcs, permitting examination of the heart from the posterior atrial wall to near the anterior surface of the right ventricle. Once imaging of the outflow tracts is completed, pulsed-, continuous-wave Doppler and color flow mapping are performed. The transgastric approach allows for favorable alignment of the Doppler angle of interrogation with the direction of flow in the outflow tracts optimizing spectral Doppler signals.

Segmental morphologic analysis

The variety of cardiac malformations, wide spectrum of anatomic arrangements and complexity of the defects present
Assessment of pressure gradients

The transgastric approach provides for axial alignment of the Doppler cursor for estimates of pressure gradients across outflow tracts. Doppler predictions are performed using the modified Bernoulli equation (peak pressure difference = $4(V^2)$) (Fig. 9.10). Good correlation has been documented between Doppler estimates of pressure gradients and direct pressure measurements. It is important to note that preoperative determination of pressure gradients obtained when patients are awake or lightly sedated may differ from those obtained in the operating room under general anesthesia.

Assessment of ventricular filling and function

Transthoracic echocardiography is extremely useful in the evaluation of factors that directly affect cardiac output such as preload, contractility, and afterload. This technology has been shown to be a reliable monitor of left ventricular filling changes in pediatric patients. In a study designed to evaluate whether TEE would identify changes in cardiac filling resulting from manipulations of blood volume in children, blood was withdrawn until the systolic blood pressure decreased by 5 and 10 mmHg. Experienced anesthesiologists—echocardiographers blinded to study events were able to identify with high sensitivity and specificity these mild reductions in blood volume by TEE changes in left ventricular end-diastolic area.
Several investigations have also documented the utility of TEE in the evaluation of ejection fraction. Transesophageal echocardiography estimation of ejection fraction reached a good correlation ($r = 0.98$) when compared to measures of ejection fraction by transthoracic echocardiography. A comparison made between transthoracic and transesophageal echocardiography for assessment of ventricular function in pediatric patients showed poor correlation likely due to technical limitations.

Transesophageal echocardiography is frequently used to monitor myocardial ischemia in adults, and it has also been suggested that segmental wall motion abnormalities as detected in pediatric patients may be a surrogate of compromised myocardial blood flow. This is particularly applicable to patients undergoing procedures that involve coronary artery manipulations.

**Influences of intraoperative transesophageal echocardiography on anesthetic and surgical management**

The overall incidence of change in surgical management with the aid of intraoperative TEE has been reported to be in the range of 3–15%, and does not differ significantly from that previously described for epicardial echocardiography. Various studies have suggested that preoperative diagnoses can be changed in 3–5% and the return to bypass rate as directed by TEE to be in the 3% range. A recent report on intraoperative TEE during congenital heart surgery in a wide range of patients (2 days to 85 years) described a major impact in 13.8% of cases.

Transesophageal echocardiography in the catheterization laboratory

Cardiac catheterization is used selectively in the anatomic proximity of the defect to the semilunar valves is shown. (e) Muscular ventricular septal defects. Color Doppler interrogation of the muscular septum in the four-chamber view documents multiple levels of ventricular shunting. Also reproduced in color, facing p. 146. (f) Complete atroventricular septal (canal) defect. Two-dimensional mid-esophageal four-chamber view of complete atroventricular septal defect illustrates a defect in the inferior portion of the interatrial septum known as ostium primum atrial septal defect (noted as arrow with asterisk) and inlet type of ventricular septal defect located in the superior-posterior aspect of the interatrial septum (arrow). Also reproduced in color, facing p. 146. (a) Secundum atrial septal defect. Four-chamber view demonstrates the typical appearance of a secundum type atrial septal defect located in the central region of the interatrial septum (arrow). (b) Sinus venosus atrial septal defect. Color Doppler exam a of superior vena cava-type sinus venous atrial septal defect in the bicaval view. Left-to-right shunting across the defect is noted in the superior aspect of the interatrial septum (arrows). Also reproduced in color, facing p. 146. (c) Perimembranous ventricular septal defect. Transgastric left ventricular outflow tract view displays tricuspid valve aneurysmal tissue (arrows) partially occluding a defect in the region of the membranous ventricular septum. (d) Subarterial (supracristal) ventricular septal defect. Long axis view demonstrates herniation of aortic valve cusp through subpulmonary ventricular septal defect (arrows). The

Additional benefits of TEE in pediatric heart surgery include ensuring adequacy of cardiac de-airing, a significant concern in this patient population where interventions frequently require a cardiotomy, and guidance during placement of intravascular and intracardiac catheters.
<table>
<thead>
<tr>
<th>Cardiac pathology</th>
<th>Presurgical echocardiographic information of interest</th>
</tr>
</thead>
</table>
| Atrial septal defect              | Define location and size of defect  
Evaluate pulmonary venous drainage  
Assessment of atrioventricular valve regurgitation  
Baseline determination of ventricular function |
| Ventricular septal defect         | Define location and size of defect  
Evaluate for additional intracardiac shunts  
Investigate for associated pathology (aortic valve herniation/prolapse, aortic regurgitation, subaortic membrane, pulmonary valve stenosis, double chamber right ventricle, atrioventricular valve regurgitation)  
Baseline determination of ventricular function |
| Atroventricular septal defect     | Define location, size and type of defects  
Evaluate for additional septal defects  
Assessment of atrioventricular valve (Rastelli type, atrioventricular valve regurgitation, relation of valvar structures to ventricles, balanced vs. dominant type, valvar support apparatus)  
Interrogation of ventricular outflows (for obstruction)  
Baseline determination of ventricular function |
| Aortic stenosis                   | Evaluate location and severity of obstruction (subvalvar, valvar, supravalvar)  
Define aortic valve anatomy  
Evaluate for aortic regurgitation  
Assess for ventricular hypertrophy and function |
| Pulmonic stenosis                 | Evaluate location and severity of obstruction (subvalvar, valvar, supravalvar)  
Define pulmonary valve anatomy  
Determine size of pulmonary arteries  
Evaluate for intracardiac shunts  
Assess for ventricular hypertrophy and function |
| Pulmonary/conduit regurgitation   | Evaluate severity of regurgitation and possible obstruction  
Interrogate atrial and ventricular septum for shunts  
Assess ventricular sizes and function |
| Tetralogy of Fallot               | Define size and location of septal defects  
Evaluate right ventricular outflow tract (subvalvar, valvar and supravalvar regions)  
Define morphology, obstruction, gradients  
Determine size of pulmonary arteries  
Evaluate aortic valve competence/aortic override  
Evaluate origin and course of coronary arteries  
Baseline determination of ventricular function |
| d-Transposition of the great arteries | Evaluate ventriculoarterial relationships and intracardiac shunts (location, size, flow direction, relation to outflows)  
Assessment of outflow tract obstruction  
Evaluate atrioventricular and semilunar valves  
Evaluate origin and course of coronary arteries  
Assessment of septal geometry (as an indicator of ventricular pressures)  
Evaluate ventricular sizes and function |
| Double outlet right ventricle     | Evaluate septal defects (size, shunt direction, location, relation of ventricular septal defect to great arteries)  
Assess physiology based on anatomic findings (i.e. ventricular septal defect, transposition or Taussig–Bing, tetralogy type)  
Evaluate great artery relationship (normal, malposed, side by side)  
Evaluate for outflow obstruction  
Assess ventricular sizes and function |
| Truncus arteriosus                | Evaluate septal defects (size, location)  
Evaluate truncal valve (for stenosis/regurgitation)  
Assess origin of the pulmonary arteries (type of truncus), pulmonary blood flow  
Assess ventricular function |
| Single ventricle                  | Evaluate morphologic type  
Assess atrioventricular and semilunar valves, inflows and outflows  
Interrogate for adequacy of interatrial communication if indicated  
Evaluate prior surgical interventions  
Assess ventricular function |
Fig. 9.8 Echocardiographic images of obstructive lesions. (a) Bicuspid (bicommissural) aortic valve. Left panel showing diastolic frame of bicuspid aortic valve in the short axis view (arrow points to the coaptation site). Right panel depicting typical “fish mouth” appearance of bicuspid aortic valve in systolic frame. The region of commissural fusion is noted by the arrow. (b) Supravalvar aortic stenosis. Aortic long axis view demonstrating the typical hourglass deformity that accounts for narrowing of the sinotubular region (arrows) in a patient with supravalvar aortic stenosis. (c) Double chamber right ventricle. Long axis view of pulmonary outflow tract in a patient with right ventricular obstruction displaying severe hypertrophy of muscle bundles located below the level of the pulmonary valve. (d) Subaortic stenosis. Two-dimensional echocardiographic appearance of complex subaortic obstruction. A fibromuscular narrow tunnel (arrows) is noted accounting for the left ventricular outflow tract obstruction. (e) Cor triatriatum. The classic membrane (arrows) that partitions the atrium into separate compartments in the cor triatriatum is highlighted in this mid-esophageal four-chamber view. (f) Mitral stenosis. Spectral Doppler interrogation in a patient with moderate to severe mitral valve obstruction demonstrating an estimated mean transmural gradient of 10.8 mmHg by continuous wave Doppler. Also reproduced in color, facing p. 146. AO, aorta; LA, left atrium; LV, left ventricle; LVOT, left ventricular outflow tract; MPA, main pulmonary artery; PV, pulmonary valve; RA, right atrium; RV, right ventricle.
and functional evaluation of CHD. Over the last two decades, interventional procedures have become increasingly employed in the non-surgical management of congenital cardiac anomalies. Transesophageal echocardiography allows for a safer and more effective application of catheter-based approaches and may reduce fluoroscopic exposure, amount of contrast material administered, and duration of the interventional procedure.  

Studies addressing the role of this imaging modality confirm major contributions. These include: (i) acquisition of detailed anatomic and hemodynamic data prior to and during the procedure; (ii) real time evaluation of catheter placement across valves and vessels; (iii) immediate assessment of the results; and (iv) monitoring of complications associated with interventions. The refinement in interventional cardiac catheterization techniques coupled with advances in TEE now allow for the high
### Table 9.3 Post-bypass echocardiographic data by type of congenital heart defect repair or surgical procedure.

<table>
<thead>
<tr>
<th>Cardiac pathology</th>
<th>Evaluate for the following in the post-surgical echocardiographic exam</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atrial septal defect</strong></td>
<td></td>
</tr>
<tr>
<td>Secundum</td>
<td>Residual shunt</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular valve regurgitation</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Sinus venosus</td>
<td>Residual shunt</td>
</tr>
<tr>
<td></td>
<td>Superior vena cava obstruction</td>
</tr>
<tr>
<td></td>
<td>Pulmonary venous obstruction (if associated anomalous pulmonary venous return)</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td><strong>Ventricular septal defect</strong></td>
<td></td>
</tr>
<tr>
<td>Perimembranous</td>
<td>Residual shunt (tiny leaks may be acceptable at the edges of the patch)</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular valve regurgitation, aortic insufficiency</td>
</tr>
<tr>
<td></td>
<td>Right ventricular pressure can be calculated by using the tricuspid regurgitant jet or residual ventricular septal defect peak velocity</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Supracristal, subarterial (doubly committed)</td>
<td>Residual shunt (as above)</td>
</tr>
<tr>
<td></td>
<td>Residual or new aortic/pulmonary insufficiency compared to pre-bypass exam</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Muscular or inlet</td>
<td>Residual shunt (as above, tiny/small residual muscular ventricular septal defect may be acceptable)</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular valve regurgitation</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td><strong>Atrioventricular septal defect (ASD)</strong></td>
<td></td>
</tr>
<tr>
<td>Partial or ostium primum ASD/cleft mitral valve</td>
<td>Residual shunts</td>
</tr>
<tr>
<td></td>
<td>Residual/new atrioventricular valve regurgitation (mild regurgitation may be acceptable)</td>
</tr>
<tr>
<td></td>
<td>Mitral inflow obstruction (if mitral cleft closed)</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Complete atroventricular septal defect</td>
<td>Residual atrial or ventricular level shunts</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular valve stenosis (particularly if annuloplasty or left-sided cleft closure performed)</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular valve regurgitation</td>
</tr>
<tr>
<td></td>
<td>Left ventricular outflow tract obstruction</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Aortic stenosis (subvalvar, valvar, supravalvar)</td>
<td>Residual outflow obstruction or aortic insufficiency</td>
</tr>
<tr>
<td></td>
<td>New ventricular septal defect</td>
</tr>
<tr>
<td></td>
<td>Mitral regurgitation</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Ross procedure</td>
<td>Aortic stenosis or insufficiency</td>
</tr>
<tr>
<td></td>
<td>Right ventricular outflow tract conduit (for stenosis/regurgitation)</td>
</tr>
<tr>
<td></td>
<td>Global and segmental left ventricular function</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>Residual ventricular septal defect or unmasked defects</td>
</tr>
<tr>
<td></td>
<td>Residual right ventricular outflow tract obstruction</td>
</tr>
<tr>
<td></td>
<td>Pulmonary regurgitation</td>
</tr>
<tr>
<td></td>
<td>Right ventricular systolic pressure can be assessed by using the tricuspid regurgitant jet</td>
</tr>
<tr>
<td></td>
<td>Right and left ventricular function</td>
</tr>
<tr>
<td>Right ventricular conduit operation</td>
<td>Conduit stenosis or insufficiency</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular valve competence</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Arterial switch operation (Jatene procedure)</td>
<td>Neo-aortic and pulmonic anastomoses (for stenosis)</td>
</tr>
<tr>
<td></td>
<td>Semilunar valve competence</td>
</tr>
<tr>
<td></td>
<td>Outflow tracts (for obstruction)</td>
</tr>
</tbody>
</table>

Continued p. 150
**Table 9.3 (cont’d)**

<table>
<thead>
<tr>
<th>Cardiac pathology</th>
<th>Evaluate for the following in the post-surgical echocardiographic exam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Atroventricular valve regurgitation</td>
</tr>
<tr>
<td></td>
<td>Residual intracardiac shunts</td>
</tr>
<tr>
<td></td>
<td>Coronary flow</td>
</tr>
<tr>
<td></td>
<td>Global and segmental left ventricular function</td>
</tr>
<tr>
<td>Double outlet right ventricle</td>
<td>Residual intracardiac shunts</td>
</tr>
<tr>
<td></td>
<td>Outflow tract obstruction</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular/semilunar valve regurgitation</td>
</tr>
<tr>
<td></td>
<td>Right ventricular to pulmonary artery conduit function (if applicable)</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Truncus arteriosus</td>
<td>Truncal valve (aortic) stenosis and insufficiency</td>
</tr>
<tr>
<td></td>
<td>Right ventricular to pulmonary conduit (for stenosis or insufficiency)</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular valve regurgitation</td>
</tr>
<tr>
<td></td>
<td>Residual ventricular level shunt</td>
</tr>
<tr>
<td>Fontan or Glenn procedure</td>
<td>Estimate right ventricular/pulmonary artery pressures</td>
</tr>
<tr>
<td></td>
<td>Ventricular function</td>
</tr>
<tr>
<td>Total anomalous pulmonary venous return</td>
<td>Adequacy of pulmonary venous anastomosis</td>
</tr>
<tr>
<td></td>
<td>Residual atrial level shunt</td>
</tr>
<tr>
<td></td>
<td>Atrioventricular valve regurgitation</td>
</tr>
<tr>
<td></td>
<td>Right ventricular/pulmonary artery pressure (can be estimated from tricuspid or pulmonary regurgitant jets)</td>
</tr>
<tr>
<td></td>
<td>Right and left ventricular function</td>
</tr>
</tbody>
</table>

**Fig. 9.10** Continuous wave Doppler interrogation of left ventricular outflow tract in patient with subaortic obstruction demonstrating gradient estimation peak velocity across outflow measures 2.89 m/second, predicting a peak gradient of 33.4 mmHg (obtained by application of the modified Bernoulli equation or $4(V^2)$). Also reproduced in color, facing p. 146.
success rate of these procedures and their low incidence of complications.

### Training and certification in pediatric transesophageal echocardiography

Guidelines for physician training in TEE were published by the ASE Committee for Physician Training in 1992. Regarding pediatric TEE, recommendations were as follows:

One should have a thorough knowledge of cardiac disease, and the hemodynamic alterations associated with acquired and congenital disorders, understanding of ultrasonic image formation and Doppler assessment of intracardiac blood flow, the range of normal structural findings and echocardiographic manifestations of a large number of cardiac disorders. Physicians performing and interpreting diagnostic TEE studies should first develop experience with general echocardiographic techniques consistent with at least level II training in echocardiography. This training involves the performance and primary interpretation (with supervision) of approximately 300 general echocardiographic studies over a period of 6 months or achievement of the equivalent level of experience. Training in the TEE examination needs to include development of cognitive and technical skills. Recommended practical experience includes introduction of the TEE probe and manipulation, optimization of instrument controls, and interpretation of the findings.

Training and certification in intraoperative echocardiography has received considerable attention in recent years. Most guidelines, however, have focused on the adult with little emphasis on pediatric TEE or congenital pathology. Prior recommendations by the Committee on Standards for Pediatric Transesophageal Echocardiography have suggested that the guidelines for training of non-pediatric cardiologists in pediatric TEE be consistent with those required for pediatric cardiology trainees, and should be individualized to include the existing level of familiarity a physician may have with children and their heart disease. It is strongly recommended that a pediatric cardiologist knowledgeable in TEE participate in the performance and interpretation in studies in infants and young children and those with complex heart disease.

A pediatric task force appointed by the Pediatric Echocardiography Council of American Society of Echocardiography is currently addressing revised practice guidelines for TEE in children.

A joined task force of the ASE and Society of Cardiovascular Anesthesiologists has recently published revised guidelines for training in perioperative echocardiography. Echocardiographic evaluation of CHD is included under the section on advanced training. The task force recommends that for those seeking advanced training in perioperative echocardiography cognitive skills should include:

1. Knowledge of CHD (if congenital practice is planned then this knowledge must be detailed).
2. Detailed knowledge of all other diseases of the heart and great vessels that is relevant in the perioperative period (if pediatric practice is planned then this knowledge may be more general than detailed).
3. Detailed knowledge of the techniques, advantages, disadvantages, and potential complications of commonly used cardiac surgical procedures for treatment of acquired and CHD.

The guidelines propose that skills should include knowledge of CHD and of the techniques, advantages, disadvantages, and potential complications of commonly used procedures in congenital heart surgery.

Given these recommendations and training requirements, it has been asked how one should proceed as an anesthesiologist interested in pediatric TEE. With increasing experience by those involved in pediatric intraoperative TEE, the issue has also been raised of who is responsible for the intraoperative interpretation of TEE and the role of the anesthesiologist. Recent publications indicate that properly trained cardiac anesthesiologists are able to utilize this technology competently resulting in changes in medical and surgical management in a significant number of patients. We believe that one should follow the general guidelines established by the American Society of Anesthesiologists and the Society of Cardiovascular Anesthesiologists: “Anesthesiologists with advanced training in perioperative TEE should be able to exploit the full diagnostic potential of TEE in the perioperative period.” Because it is essential in many intraoperative applications to obtain a definitive interpretation of the TEE examination at the time of surgery, the task force strongly recommends that anesthesiologists actively pursue collaboration with surgeons, cardiologists, or other physicians involved in a patient’s care as a team approach. This would propose a core of interested individuals (anesthesiologists, pediatric cardiologists, and cardiothoracic surgeons) who collaborate as the guidelines have suggested.

In 1996 the Society of Cardiovascular Anesthesiologists appointed a task force to develop a certification process to recognize knowledge and proficiency in the interpretation of perioperative TEE. The inaugural formal examination was given in 1998. This examination is currently administered by the National Board of Echocardiography. The test focuses on adult heart disease with a small component of CHD in the adult; pediatric TEE has not been formally addressed.

### Quality assurance

All quality assurance programs for echocardiography should include the following elements: indications for the study,
technical aspects of performing and recording the examination, application of examination findings to physiologic conditions, documentation, equipment, care of equipment, professional communication, education, and billing. At most institutions, the pediatric TEE examinations are viewed and interpreted immediately and reports for the pre- and post-bypass examinations are generated. In consideration of the educational value, some centers highly encourage the retrospective review of the echocardiographic data when significant discrepancies are identified between these and the intraoperative surgical findings.

Limitations

The literature extensively documents the utility of TEE in congenital heart surgery and in the detection of residual abnormalities that may require immediate revision. Despite the significant contributions of TEE to intraoperative care some limitations are recognized. Thus, decisions regarding return to bypass to address residual pathology should consider that a variety of factors (the level of inotropic support, high catecholamine state during the immediate bypass period, loading conditions, and functional state of the myocardium) may influence the echocardiographic findings and may under- or overestimate the hemodynamic severity of the condition in question. This implies that the optimal setting for hemodynamic assessment in most patients requires conditions that reflect the patient’s baseline steady state, a potential challenge in the operating room. Decisions regarding return to bypass to address suboptimal repairs require assessment of the overall risk–benefit ratio, and in many instances this is a clinical judgment not exclusively based on the echocardiographic information but also influenced by numerous other factors.

Contraindications

Conditions associated with increased risk of complications such as esophageal pathology, recent esophageal surgery, severe respiratory decompensation, or inadequate control of the airway are generally considered contraindications to TEE. Additional clinical scenarios that require assessment of the risk–benefit ratio for TEE include cervical spine injury or deformity and severe coagulopathy. In the presence of a gastrostomy feeding tube the TEE examination is still feasible; however, we defer the transgastric examination. In patients with a known aberrant (retroesophageal) subclavian artery we suggest placement of the catheter for arterial blood pressure monitoring in an extremity not being supplied by the anomalous vessel, since loss of the arterial pressure tracing may be seen upon esophageal intubation or probe manipulation. Pulse oximetry monitoring in the extremity supplied by the aberrant vessel may be useful as an indicator of adequate distal bed perfusion. Surgical interventions to address isolated vascular anomalies, such as vascular rings, generally do not benefit significantly from TEE. In these cases, TEE probe insertion can lead to respiratory compromise as the trachea and esophagus are restricted to a confined space by the surrounding vascular structures. In infants with anomalous pulmonary venous connections, consideration should be given to potential compression of the posterior pulmonary venous confluence by the transesophageal probe resulting in detrimental hemodynamic effects (see Fig. 9.2). Potential alternatives in this clinical scenario are the introduction of the probe after sternotomy or during the bypass period.

Complications

Serious complications during pediatric TEE are rare. Most children, including infants, tolerate transesophageal examination well; however, hemodynamics and respiratory parameters must be closely monitored. Blood pressure generally remains stable but can drop precipitously if probe flexion compresses the aorta. Accordingly, placement of the TEE probe is recommended following arterial line placement. Changes in blood pressure resulting from aortic compression during probe manipulation may or may not be evident depending on the location of the arterial catheter or pulse-oximeter sampling probe. A recent case report also noted life-threatening hemodynamic deterioration as a result of acute decreases in pulmonary blood flow presumably related to compression of the pulmonary artery and related structures. Respiratory compromise can occur in association with probe manipulation, peak inspiratory pressures can increase, and systemic arterial desaturation can be seen. In addition, movement of the endotracheal tube may occur during the examination, resulting in displacement into the mainstem bronchi or tracheal extubation. Capnography may be particularly helpful in the recognition of these complications. If desaturation acutely occurs correct position of the endotracheal tube must be confirmed and occasionally the TEE probe must be immediately withdrawn. For all of the above reasons, we recommend frequent monitoring of the peak inspiratory pressures throughout the TEE examinations. While the probe is being withdrawn the endotracheal tube should be firmly held to prevent inadvertent extubation. Although hemodynamic or respiratory alterations can occur in small infants, these are relatively infrequent and fear of compromise should not prevent use of intraoperative TEE in patients when otherwise indicated. Esophageal injury can occur related to intraoperative TEE. A study where flexible esophagoscopy was performed following TEE in infants and children demonstrated frequent mild mucosal injury. A recent study has documented an 18% incidence of dysphagia among pediatric patients under-
going cardiac operations where TEE was used. Although the lack of a control group did not allow for the assessment of the direct effects of TEE, the study suggested that the presence of the probe was a risk factor in this cohort of patients. A case report of an unrecognized esophageal perforation in a small infant during intraoperative TEE underscores the fact that meticulous care must be exercised in the insertion and manipulation of these probes in all patients, in particular in the critically ill neonate. This report raises the concern that manipulation of these probes in all patients, in particular in infant during intraoperative TEE underscores the fact that report of an unrecognized esophageal perforation in a small pneumomediastinum, or retropharyngeal gas. presence of crepitus in the neck, subcutaneous emphysema, revised if necessary. Contributions to anesthetic care include real time monitoring of ventricular filling, cardiac function, ensuring adequate cardiac de-airing, in addition to optimization of hemodynamic management strategies. Furthermore, the intraoperative transesophageal findings assist in the formulation of plans for postoperative care. Although the data thus far regarding the contributions of TEE to pediatric cardiac surgery is quite compelling, further studies are needed to address the impact of this technology on clinical outcomes.

Endocarditis prophylaxis

Endocarditis after TEE examination has been reported in the literature but is considered an unlikely event. The most recent guidelines of the AHA have stated that endocarditis prophylaxis is not routinely recommended for TEE but should be considered optional in high-risk patients.

Conclusion

In many centers TEE is considered the standard of care for intraoperative assessment of most congenital heart repairs prior to removal of the bypass hardware and closure of the sternotomy. This technology has become a valuable adjunct to surgical and anesthetic management. The literature documents the significant perioperative benefits of TEE in the care of infants/children undergoing surgical interventions for congenital/acquired heart disease and the impact in clinical decision-making. Diagnoses can be confirmed or altered preoperatively, the surgical plan can be modified, and the operative procedures can be immediately evaluated and revised if necessary. Contributions to anesthetic care include real time monitoring of ventricular filling, cardiac function, ensuring adequate cardiac de-airing, in addition to optimization of hemodynamic management strategies. Furthermore, the intraoperative transesophageal findings assist in the formulation of plans for postoperative care. Although the data thus far regarding the contributions of TEE to pediatric cardiac surgery is quite compelling, further studies are needed to address the impact of this technology on clinical outcomes.

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