Update on Cardiovascular Imaging

Intraoperative Transesophageal Echocardiography in Congenital Heart Surgery

The Texas Children's Hospital Experience

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Echocardiography was 1st applied to the intraoperative management of congenital heart disease in the 1980s with the development of epicardial imaging. This method contributed to improved postoperative outcome by making it possible to identify residual lesions, thus allowing immediate intervention in the operating room.[1,2] Currently, intraoperative transesophageal echocardiography (TEE) is becoming the preferred technique for perioperative evaluation of congenital heart disease. The transesophageal approach overcomes most of the disadvantages of epicardial echocardiography, including limited imaging windows, the potential for contamination of the surgical field, and interruption of the surgical procedure. Additionally, deleterious effects from direct application of the probe to the epicardium, such as ventricular arrhythmias or decreases in cardiac output, are avoided.

Initially, intraoperative TEE in pediatric patients was restricted to the use of monoplane probes due to size constraints of the endoscope and transducer tip. Monoplane probes provide only transverse plane imaging, which is useful, but does not enable complete evaluation of cardiac anatomy in many complex congenital heart lesions.[3-10] More recently, the development of small pediatric biplane TEE probes has added longitudinal plane imaging capability, substantially improving the degree of anatomic definition possible intraoperatively.[5,11-14] Most TEE probes are now mounted on flexible endoscopes and provide high-resolution 2-dimensional imaging combined with pulsed, continuous-wave, and color-flow Doppler imaging. With these newer pediatric probes, TEE is possible even in small infants.

Although its role in complex congenital heart disease is still under evaluation, TEE is becoming standard practice for the intraoperative monitoring of ventricular function and for evaluation of surgical repair. This paper discusses the utility of TEE for perioperative management of congenital heart disease, with an emphasis on biplane imaging. In addition, we report the results of a retrospective review of the first 341 intraoperative transesophageal studies (primarily with biplane probes) performed at Texas Children's Hospital.

Equipment and Imaging Techniques

Transesophageal Probes. Today's standard TEE probes consist of multi-element phased array transducers for transmission and reception of ultrasonic signals. These transducers are mounted at the end of a flexible, steerable endoscope providing anterior, posterior, and lateral flexion. Adult or pediatric monoplane and biplane probes that vary accordingly in the size and length of both the endoscope and transducer (Table I) are commercially available. The transducer diameter is slightly larger than the endoscope shaft. Biplane transducers require more phased array elements, resulting in longer transducer components than those in monoplane transducers. Because the transducer itself is not flexible, the length of the transducer is a major factor that often limits negotiation of the oropharynx in small children. In our experience, biplane TEE probes sized for adults can be used rou-

TABLE I. Specifications of Probes Used for Intraoperative TEE in Pediatric Patients

	Pediatric		Adult	
Probe Component	**Monoplane**	**Biplane**	**Monoplane**	**Biplane**
Endoscope length (cm)	60-80	60-80	100-110	100-110
Endoscope diameter (mm)	4-7	4-7	8-11	8-11
Transducer diameter (mm)	6-10	9-13	11-13	12-14
Flexion	4-way movable tip		4-way movable tip	
Frequency	5 MHz, 7 MHz*		3.5 MHz, 5 MHz*	
Doppler capability	Pulsed, continuous wave, color		Pulsed, continuous wave, color	

*Multifrequency transducers

tinely and safely in children who weigh 15 kg or more; pediatric biplane probes are used in infants starting at 2.5 kg.

Monoplane probes limit imaging to transverse-oriented planes. Biplane probes increase the value of TEE in the operating room, because they have an additional transducer that allows imaging parallel to the various longitudinal axes of the heart. In contrast to early pediatric biplane probes, current multifrequency probes are small enough to be used in neonates, providing high-resolution near-field imaging in addition to Doppler imaging. Prototypes are being developed for a pediatric-sized version of the multiplane TEE probes that are already used in adults. The additional imaging planes provided by these probes are likely to be exceptionally beneficial in providing extra imaging dimensions for complex congenital cardiac anomalies.[14] Multiplane TEE will likely prove to be of even greater benefit in pediatric patients than it has been in adults.[14-17]

The transesophageal approach is effective because the proximity of the esophagus to the heart optimizes a basic physical property of ultrasound: the image resolution improves with increasing frequency of ultrasound, but the depth of ultrasound penetration decreases. From the esophagus, high-resolution imaging of most intracardiac structures is possible with the use of high-frequency multifrequency transducers (5 to 7.5 MHz). In addition to 2-dimensional and M-mode imaging, standard TEE probes also have pulsed, high-pulse-repetition frequency, continuous wave, and color-flow Doppler capabilities. Doppler echocardiography allows preoperative detection of unrecognized defects, postoperative detection of residual stenoses and small ventricular septal defects, and improved detection and quantitation of valvar insufficiency.

Imaging Planes. Standard tomographic planes have been defined for both horizontal and longitudinal imaging.[18-21] Figures 1 through 6 illustrate several of these standard planes using patients from our

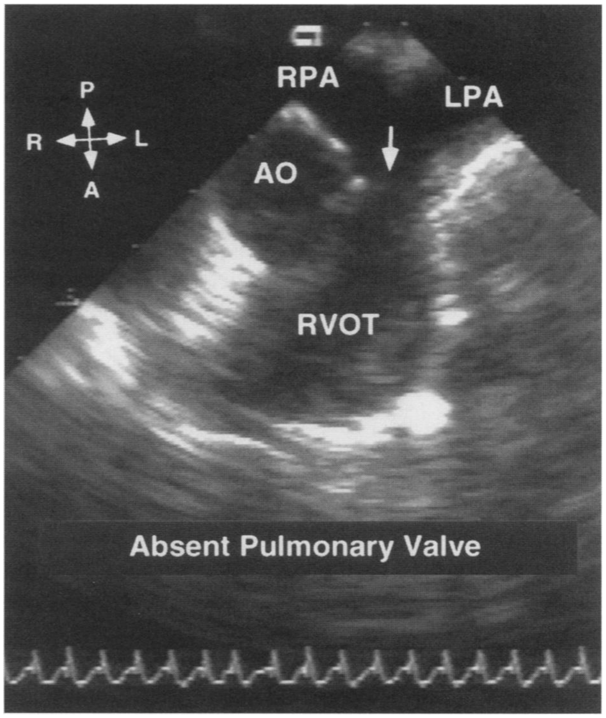

Fig. 1 *Transverse basal short-axis view in a patient with absent pulmonary valve syndrome, showing a narrow right ventricular outflow tract with dilated branch pulmonary arteries. Rudimentary valve tissue is also noted (arrow). This plane is ideal for pre- and postoperative Doppler evaluation of the pulmonary outflow tract and pulmonary arteries.*

A = anterior; AO = aorta; L= left; LPA = left pulmonary artery; P = posterior; R = right; RPA = right pulmonary artery; RVOT = right ventricular outflow tract series; they demonstrate many of the orthogonal views required for complete pre- and postoperative TEE evaluation of congenital heart disease. Horizontal primary planes include 1) basal short-axis (Fig. 1), 2) frontal 4-chamber (Fig. 2), and 3) transgastric short-axis (Fig. 3) views. These views are achieved, starting at the cardiac base, by sequentially increasing the probe depth and anterior flexion. Multiple secondary transverse views can be produced by changing anterior–posterior flexion, depth, and to a lesser degree, lateral flexion of the probe tip. Longitudinal primary planes accomplished by left-to-right probe rotation include 1) left ventricular–left atrial 2-chamber (Fig. 4), 2) right ventricular outflow (Figs. 5 and 6), 3) ascending aorta, and 4) venae cavae views. Lateral flexion, rotation, and anterior–posterior flexion result in secondary longitudinal tomographic views, the transgastric long-axis view, and the aortic view.

Intraoperative Techniques. The following protocol for intraoperative TEE is used at our institution.[9] Anesthesia induction, tracheal intubation, and line placement are performed before esophageal intubation. The probe tip is coated with sterile lubricant and carefully introduced (with or without digital guidance), with the transducer facing anteriorly. Esophageal or nasogastric tubes, which may interfere with image quality, are preferably removed prior to probe passage. During probe introduction, the tip should be maintained in the midline and the endoscope should remain unlocked to allow free flexion. Firm but gentle pressure may be required for the tip to traverse the upper esophageal sphincter, but then minimal resistance should be encountered on further probe advancement. Maneuvers such as neck flexion, "jaw-thrusting," or leftward turning of the head may aid insertion. In the event that insertion fails, a smaller probe, if available, may be tried. Rarely, probe insertion fails completely and the study is aborted. In our series, risk factors for insertion failure include weight less than 4 kg and abnormal pharyngeal anatomy (as seen in patients with Down syndrome).

After probe insertion, a complete preoperative survey of anatomy and ventricular function is performed. We routinely include all standard imaging planes with secondary planes as necessary to adequately define the anatomy and features of interest. Pulsed and color-flow Doppler studies are performed as necessary, for evaluation of stenoses,

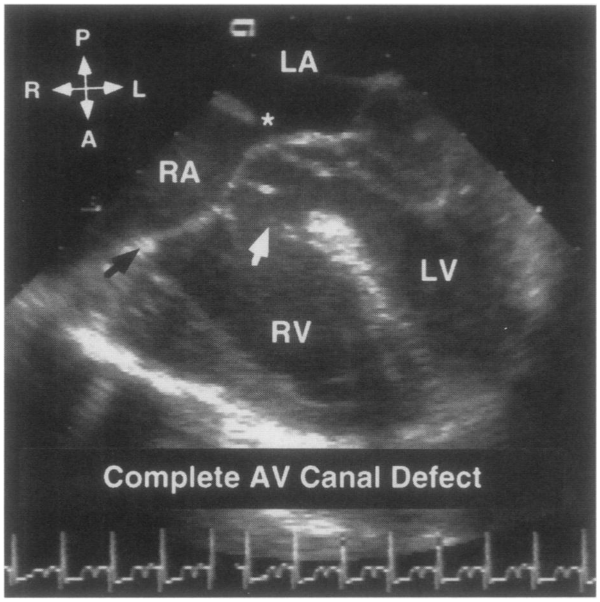

Fig. 2 *Transverse 4-chamber view of a complete atrioventricular canal defect. The primum atrial septal component (*), ventricular septal component (white arrow), and common atrioventricular valve (black arrow) are well delineated. This view is useful for evaluating the inlet ventricular septum, atrioventricular valves, and atrial septum.*

A = anterior; L= left; LA = left atrium; LV = left ventricle; P = posterior; R = right; RA = right atrium; RV = right ventricle

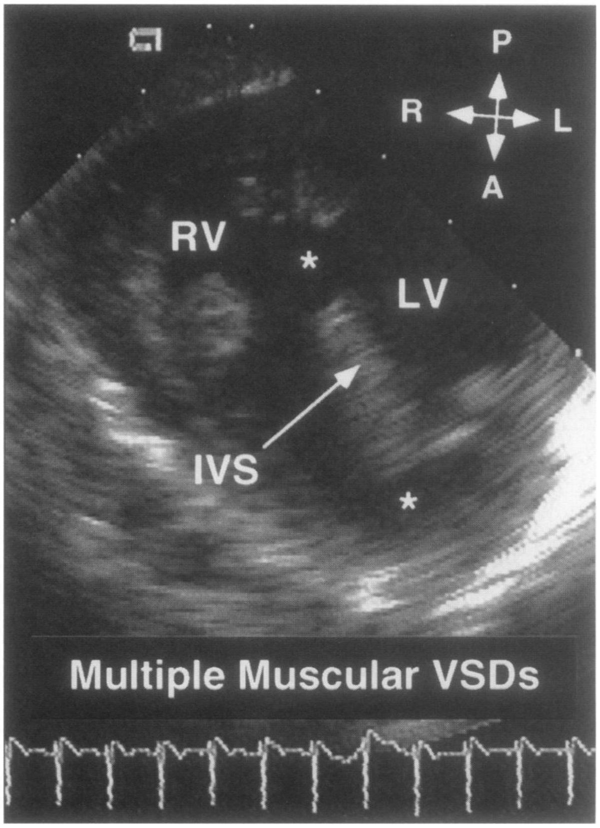

Fig. 3 *Transverse transgastric short-axis view showing multiple muscular ventricular septal defects. This view is useful for evaluating global and regional ventricular function, and for identifying defects of the muscular ventricular septum (*).*

A = anterior; IVS = interventricular septum; L= left; LV = left ventricle; P = posterior; R = right; RV = right ventricle

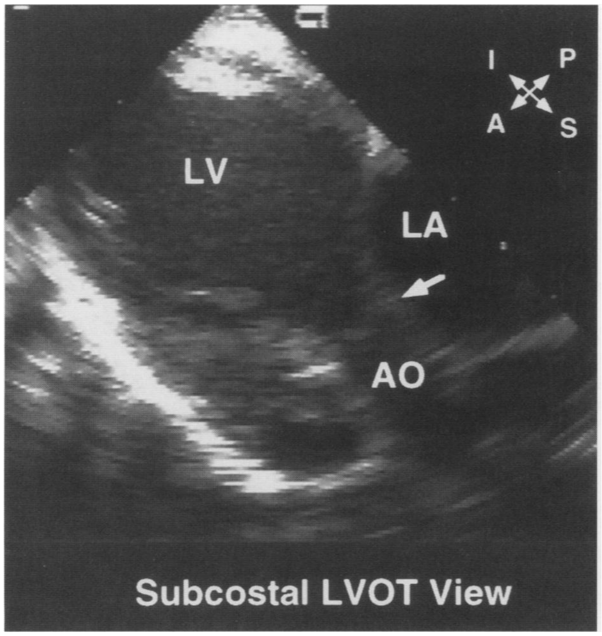

Fig. 4 *Longitudinal transgastric (subcostal) view of a normal left ventricular outflow tract (LVOT). This view shows the benefit of longitudinal imaging for evaluating the LVOT in pediatric patients. This plane provides a favorable angle for Doppler study of the LVOT, aortic valve (arrow), and ascending aorta (AO). The mitral valve can also be evaluated from this view, as well as from the LV–LA 2-chamber longitudinal view (not shown).*

A = anterior; I= inferior; LA = left atrium; LV = left ventricle; P = posterior; S = superior

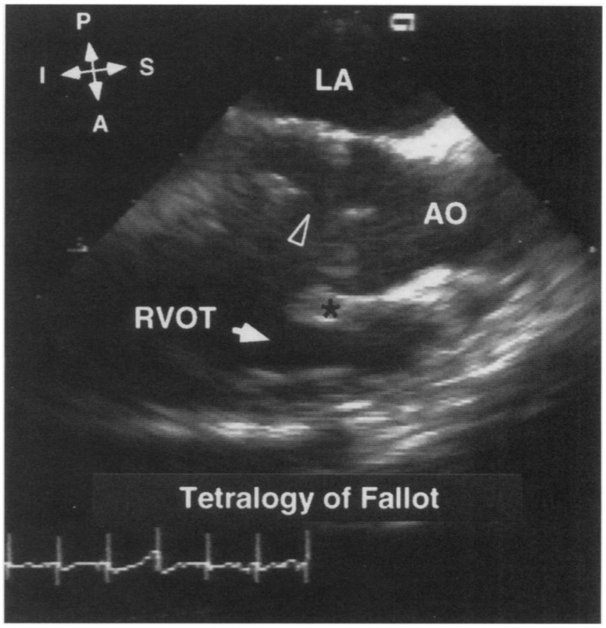

Fig. 5 *Longitudinal view of the right ventricular outflow tract (RVOT) (closed arrow) in a patient with tetralogy of Fallot showing the conoventricular septal defect (open arrow), overriding aorta (AO), and narrowing of the RVOT due to antero-superior deviation of the infundibulum (*). This view is beneficial in evaluating postoperative residual ventricular septal defects and RVOT obstruction.*

A = anterior; I= inferior; LA = left atrium; P = posterior; S = superior

valvar insufficiency, and septal defects. After completion of the preoperative study, the probe is advanced to the stomach and turned off to avoid thermal injury. During weaning and after cardiopulmonary bypass, a more focused study is performed to review the surgical result, monitor ventricular function, and assist in intravascular volume and pharmacologic management. Probes are removed after data collection has been completed, monitoring of function is no longer required, and anticoagulation has been reversed.

Impact on Surgical Management

In view of the decreasing number of diagnostic catheterizations performed, greater emphasis is being placed on intraoperative TEE. Monoplane TEE has proved to be a valuable adjunct in the intraoperative assessment of congenital heart surgery.[3-10,22-24] Although reports describing experience with biplane TEE are somewhat limited in number, it is clear that longitudinal plane imaging has added substantially to the information available for surgical decision-making in the operating room.[5,11-14] Studies are in progress to further define the applications of intraoperative TEE, especially with regard to infants with complex cardiac lesions. Improved patient selection is also important in this era of cost consciousness and limited availability of resources.

We retrospectively reviewed the records and results of the first 341 intraoperative transesophageal echocardiographic studies performed from 1990 through 1995 at Texas Children's Hospital. In order to evaluate the intraoperative impact of TEE, preoperative results (diagnostic changes and alterations of planned procedure) and postoperative results (detection of residual hemodynamically significant lesions, evaluation of function and wall motion, and decisions to return to cardiopulmonary bypass) were analyzed. Complications were also recorded.

Results

At our institution, perioperative TEE is most frequently used for intraoperative evaluation of the surgical procedure, especially in high-risk patients with complex lesions. Less often, intraoperative TEE is performed to disclose conditions that specifically need to be considered before surgery proceeds. Complete studies are performed regardless of the indication for the study.

Patients in our series ranged in age from 2 days to 49 years (mean, 4.0 years) and in weight from 2.5 to

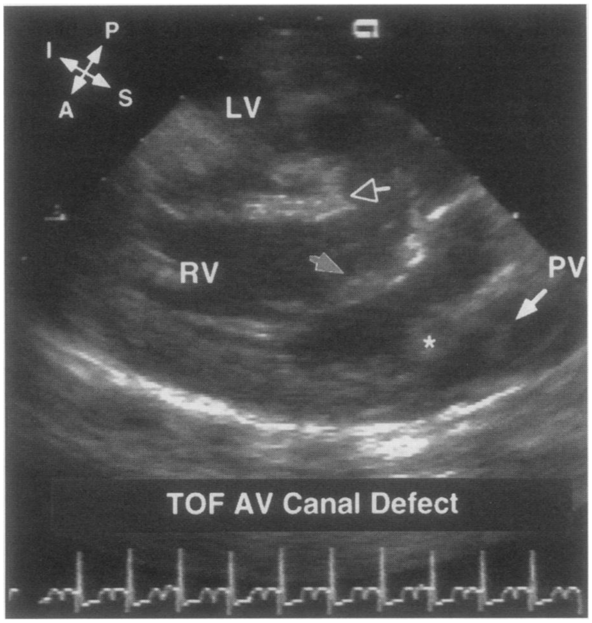

Fig. 6 *Secondary longitudinal view in a patient with tetralogy of Fallot (TOF) and a Rastelli type C atrioventricular canal defect. This view is helpful in defining the atrioventricular valve morphology: both the free-floating anterior bridging leaflet (gray arrow) and the posterior bridging leaflet (open arrow) with its attachments to the ventricular septum are well delineated. As in Fig. 5, infundibular narrowing (*) can be seen. The thickened stenotic pulmonary valve (PV) (solid arrow) is also shown.*

A = anterior; I= inferior; LV = left ventricle; P = posterior; RV = right venticle; S = superior

128 kg (mean, 11.2 kg). Nearly 40% of the patients were infants or small children: 134 (39.3%) weighed less than 10 kg, 52 (15.5%) weighed less than 5 kg, and 28 (8.2%) were infants less than 1 month old. Pediatric probes were used in 208 studies (61%) and biplane probes were used in 313 (92%) (Table II).

TABLE II. Probes Used During Intraoperative TEE

Probe Type	**Number of Studies** (%)	
Pediatric		
Monoplane	10	(3)
Biplane	198	(58)
Total	208	(61)
Adult		
Monoplane	18	(5)
Biplane	115	(34)
Total	133	(39)
Total monoplane	28	(8)
Total biplane	313	(92)
Total studies	341	

TABLE III. Major Diagnostic Categories in Patients Undergoing Intraoperative TEE

Diagnosis	**Number** (%)	
Single ventricle	45	(13.2)
Atrioventricular canal defects (partial or complete)	38	(11.1)
Pulmonary atresia with VSD	27	(7.9)
Tetralogy of Fallot	27	(7.9)
Aortic stenosis or regurgitation, or subaortic stenosis	27	(7.9)
VSD with DCRV or subaortic obstruction	25	(7.3)
Mitral stenosis or regurgitation	21	(6.2)
VSD (isolated)	19	(5.6)
Transposition of the great vessels (neonatal)	16	(4.7)
ASD	13	(3.8)
Pulmonary atresia with intact ventricular septum	11	(3.2)
Total anomalous pulmonary venous return	9	(2.6)
Ebstein's or other tricuspid valve abnormalities	9	(2.6)
VSD and ASD	6	(1.8)
Interrupted aortic arch	5	(1.5)
Double outlet right ventricle	4	(1.2)
Miscellaneous	39	(11.4)

ASD = atrial septal defect; DCRV = double-chambered right ventricle; VSD = ventricular septal defect

Probes designed for use in adults were routinely used in patients weighing 15 kg or more.

The major diagnostic categories of patients undergoing TEE are presented in Table III. Although complex lesions predominated, most of the common forms of congenital heart disease were also represented. Miscellaneous diagnoses included combinations of complex cardiac lesions, Shone and Marfan syndromes, ruptured sinus of Valsalva aneurysm, hypertrophic cardiomyopathy, truncus arteriosus, aorticopulmonary window, coronary aneurysms after Kawasaki disease, and anomalous left coronary artery.

Surgical procedures are summarized in Table IV. Miscellaneous operations consisted mostly of repairs of complex cardiac lesions and combination procedures. In general, only patients undergoing intracardiac repairs requiring cardiopulmonary bypass are

TABLE IV. Surgical Procedures in Patients Undergoing Intraoperative TEE

Surgical Procedure	Number (%)
Atrioventricular canal defect repair*	37 (10.9)
Fontan procedure	35 (10.3)
Rastelli operation or conduit repair	31 (9.1)
Atrioventricular valve repair or replacement	28 (8.2)
Tetralogy of Fallot repair	25 (7.3)
VSD with outflow obstruction repair	25 (7.3)
Isolated VSD repair	19 (5.6)
Glenn procedure	16 (4.7)
Arterial switch procedures (± VSD)	16 (4.7)
Aortic valve repair or replacement	14 (4.1)
Subaortic stenosis resection	13 (3.8)
ASD repair	13 (3.8)
Repair of VSD with associated complex lesions	10 (2.9)
APVR repair (partial or total)	7 (2.1)
Interrupted aortic arch repair	5 (1.5)
Coronary artery procedures	5 (1.5)
Multiple valve repair or replacement	4 (1.2)
Miscellaneous	38 (11.1)

* Includes both partial and complete atrioventricular canal defects.

APVR = anomalous pulmonary venous return; ASD = atrial septal defect; VSD = ventricular septal defect

routinely studied by intraoperative TEE. We do not use TEE for systemic-to-pulmonary artery shunt placements or coarctation repairs unless additional intracardiac procedures are planned. On the basis of our initial experience, which suggested that TEE had limited benefit in simple atrial septal defect repairs, we no longer perform TEE routinely in such cases.

In 45 patients (13.2%), pre-bypass intraoperative TEE studies allowed minor diagnostic refinements that did not affect surgical procedure or outcome. Preoperative findings led to alteration of planned surgical procedures in 32 patients (9.4%). 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 (7/25 patients, 28%), isolated subaortic stenosis (3/13 patients, 23%), atrioventricular valve dysfunction (4/30 patients, 13%), single ventricle (3/45 patients, 7%), and pulmonary atresia with ventricular septal defect (2/27 patients, 7%). In the 32 cases above, TEE was particularly helpful in determining the exact location, anatomic features, and hemodynamic significance of obstructive lesions, and for providing data that were useful in making decisions regarding atrioventricular valve repair versus replacement.

Twenty-eight patients (8.2%) were returned to cardiopulmonary bypass for immediate reoperation based on the results of 2-dimensional and Doppler TEE, along with hemodynamic data. The most common preoperative diagnoses in patients who subsequently required reoperation were ventricular septal defect with associated ventricular outflow obstruction (n = 6), atrioventricular canal defect (n = 4), isolated atrioventricular valve dysfunction (n = 4), and complex single ventricle or heterotaxy syndrome (n = 9). Reasons for reoperation included residual ventricular outflow obstruction (n = 8), moderate-to-severe atrioventricular valve regurgitation (n = 5), Glenn or Fontan procedure failure (n = 4), ventricular pump failure (n = 4), significant residual left-to-right shunt (n = 2), distal pulmonary artery obstruction (n = 2), coronary artery insufficiency due to oversized prosthetic mitral valve (n = 1), and failed Ebstein's anomaly repair (n = 1). The 5 cases of atrioventricular valve regurgitation included 1 patient who had a prosthetic mitral valve perivalvar leak. Intraoperative TEE provided useful information and guidance for all 28 patients who required surgical revisions. Seventeen of these patients (61%) underwent reoperation as a direct result of TEE findings. In the remaining 11 (39%), TEE allowed the identification of structural and functional causes when the patients could not be weaned from cardiopulmonary bypass. In contrast, intraoperative TEE had limited surgical impact in uncomplicated secundum atrial septal defect repair (provided that the pulmonary venous anatomy was defined) and in isolated ventricular septal defect repair.

In the subset of 28 neonatal patients (16 arterial switch procedures for D-transposition of the great arteries, 5 total anomalous pulmonary venous return repairs, and 7 repairs for systemic outflow obstruction), intraoperative TEE provided little new anatomic information and led to no notable changes in the surgical approach; however, it did provide clinically important data regarding ventricular volume, cardiac function, and suspected coronary artery insufficiency during weaning from cardiopulmonary bypass. The data concerning pulmonary artery pressure, pulmonary hypertension, residual outflow gradients, and postoperative myocardial function were also helpful in the early recovery period, providing information that influenced fluid, pharmacologic, and ventilatory management of these infants.

No major complication resulted from the TEE procedure. In 5 (1.5%) small infants (<4 kg), studies were not completed due to transient ventilatory problems, in which the TEE probe was initially considered to be a possible cause of airway compression. In these patients, the probe was removed at either the anesthesiologist's or the surgeon's request in order to eliminate TEE as a potential complicating factor. However, in no case did probe removal substantially change the patient's ventilatory or hemodynamic status. There were no long-term sequelae from esophageal intubation during surgery. Information regarding unsuccessful TEE transducer passage is limited to the last 145 cases, because only recently did collection of these data become routine at our institution. Among those 145 patients, 5 failures occurred (3.4%); all were in neonates or infants, 4 of whom had Down syndrome. The higher failure rate occurred in the Down syndrome patients (with their intrinsic narrow airway), possibly because they required more caution during intubation of the esophagus.

Conclusion

Our series confirms the safety and utility of biplane TEE for the perioperative evaluation of congenital heart disease. Consistent with earlier reports, intraoperative TEE appears to be of most benefit in a limited number of diagnoses and surgical procedures. Monoplane TEE has previously been shown to be of use in atrioventricular canal defect repair, atrioventricular valve replacement or repair, tetralogy of Fallot repair, subaortic and aortic stenosis repair, Fontan procedures, and monitoring of ventricular function during any procedure.[3-14,20-27] The data presented here, as well as the experiences of others,[5,11-14] clearly show that biplane probes provide markedly improved, surgically relevant information compared with that provided by monoplane imaging alone.

Recently, O'Leary and colleagues[13] published their experience at the Mayo Clinic with biplane intraoperative TEE in 104 patients, all over 7 kg in weight. Their results showed that TEE was accurate and safe, and had the most impact on patients undergoing modified Fontan procedures or subaortic resections. Additionally, their research showed that both the transverse and the horizontal imaging planes are needed for complete anatomic evaluation. Because our series included a large number of small infants and children, we believe our results to be complementary to those found by the Mayo Clinic in larger patients (>7 kg). We too found TEE to have a substantial impact on the results of Fontan procedures and left ventricular outflow tract obstruction repairs. In addition, TEE was helpful during repair of ventricular septal defects if there were associated ventricular outflow obstruction (including tetralogy of Fallot), atrioventricular canal defects with atrioventricular valve dysfunction, complex single ventricles, or heterotaxy syndromes. Intraoperative TEE should be performed routinely for all of the above diagnoses and surgical procedures. We agree with the Mayo Clinic findings that biplane TEE is clearly superior to monoplane imaging, particularly for evaluation of the left and right ventricular outflow tracts (Figs. 1, 4 through 6) and for complete assessment of atrioventricular valve function (Fig. 2). We also have shown that TEE is well tolerated in neonates and infants, and provides information on ventricular function and coronary artery supply that is useful both for weaning from cardiopulmonary bypass and for postoperative management. Therefore, we advocate the use of TEE during surgical procedures in infants. Data from this series, however, do not support the routine use of intraoperative TEE in uncomplicated repairs of atrial septal defects, and possibly of isolated ventricular septal defects.

Complications arising from TEE are extremely rare.[4-7,9-14,25] In patients with normal upper-airway anatomy, failed probe passage is also unusual. In our series, Down syndrome patients, with their associated hypotonicity and short hypopharynx, accounted for most failures in passing the pediatric biplane probe.

Future advances in pediatric applications of TEE will likely include further miniaturization of the transducers, allowing studies in smaller children and decreasing the incidence of failed studies. A small multiplane TEE probe may be the most promising new technologic development soon to be available. Experience with multiplane probes in adults has shown notable advantages over biplane TEE.[15-17] Considering the marked complexity of congenital cardiac lesions compared with that of heart disease in adults, the impact of multiplane intraoperative TEE is expected to be even greater in pediatric patients than it has been in adults. Undoubtedly, TEE will continue to be important in the perioperative management of congenital heart defects.

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