Intraoperative transesophageal echocardiography during surgery for congenital heart defects

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Objective: This study was undertaken to further define the impact of intraoperative transesophageal echocardiography during surgery for congenital heart disease and to determine appropriate indications.

Methods: The impact of transesophageal echocardiography on patient care was assessed in 1002 patients who underwent this procedure during surgery for congenital heart defects. It had major impact when new information altered the planned procedure or led to a revision of the initial repair. The safety of intraoperative transesophageal echocardiography was evaluated by review of the prospective data sheets and the medical record. A simple relative cost analysis was also performed.

Results: Patient median age was 9.9 years (range 2 days to 85 years). Transesophageal echocardiography had prebypass or postbypass major impact in 13.8% of cases (n = 138/1002). Major impact was more frequent during reoperations ($P < .03$). Procedures that benefited most from the additional information were valve repairs (aortic or atrioventricular) and complex outflow tract reconstructions. Partial anomalous pulmonary venous connection, tricuspid valve repair (other than of Ebstein anomaly), simple atrioventricular discordance, aortic arch anomalies, and secundum atrial septal defects had major impact rates less than 5%. No major complications occurred. Minor complications occurred in 1% of patients and were most often observed in infants smaller than 4 kg. Routine use of transesophageal echocardiography for all patients with congenital heart defects proved cost-effective.

Conclusions: On the combined basis of the observed rates of major impact, the minimal complications, and the relative cost advantage, we believe that routine use of transesophageal echocardiography during most intracardiac repairs of congenital heart defects is justified, particularly for patients undergoing repeat operations for congenital cardiac malformations.

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Intraoperative transesophageal echocardiography (ITEE) has been used in the care of patients with congenital heart defects since the late 1980s. Previous reports have suggested that ITEE can provide important additional information during intracardiac repair of congenital heart defects.[1-8] Recommendations for the use of ITEE have been broad, in part because of the small sample size in previous studies. The preliminary experience with ITEE during surgery for congenital heart defects at the Mayo Clinic confirmed the accuracy of ITEE and identified selected patients who would benefit from ITEE on

the basis of a small study population of 104 patients.[9] Bezold and colleagues[10] at Texas Children's Hospital reported a larger experience with ITEE in 341 patients. They concluded that biplanar imaging was far superior to monoplanar imaging. ITEE also seemed to be most beneficial for selected diagnoses and surgical procedures in this series. On the basis of a study of more than 1500 cases, Stevenson[11] concluded that ITEE had a low complication rate (about 3%), but he did not expand on the clinical utility of ITEE in that recent report.

The largest experience specifically evaluating the utility of intraoperative echocardiography, involving more than 1000 cases, was published by Ungerleider and associates.[12] Their study evaluated both epicardial and transesophageal echocardiography. Disadvantages of epicardial imaging include invasion of the surgical field, limited windows, possible induction of ventricular ectopic beats, and possible transient hypotension.[9] ITEE has therefore become the preferred modality of imaging during surgery for congenital heart defects.

Arguments pertaining to the use of ITEE focus on the cost and the risk of complications related to the procedure versus the benefit to the patient.[13] Ungerleider and associates[12] reported, "The average cost for patients who return to the operating room during their hospitalization for revision of a repair is significantly greater than for those whose repairs are revised before they leave the operating room ($94,180.28 ± $33,881.63 versus $21,415.79 ± $8215.74)." Subsequent cost analysis by Stevenson[14] from Seattle focused on a series of ITEE use in which a 2.8% rate of immediate surgical revision was found to be cost-effective.

As a continuation of the previous Mayo experience with ITEE, we are reporting this series involving only biplanar or multiplanar ITEE during surgical repair for congenital heart defects. This was a collaborative study involving pediatric cardiovascular surgeons, congenital cardiologists, and anesthesiologists. The first objective of this study was to better define the impact of ITEE in a larger group of patients. The second objective was to determine specifically the appropriate indications for ITEE during surgery for congenital heart defects.

Methods

Overview

ITEE was performed in 1002 patients during surgery for congenital heart defects at the request of the clinicians involved in each patient's care. Impact of ITEE was assigned prospectively, while the patient was still in the operating suite, by the surgeon and by the cardiologist who performed the ITEE. Data were initially recorded by hand and then converted to a computer database. Subsequent review of medical records was performed at the end of the study period and before statistical analysis to confirm the initial assessment of impact, expand on pertinent clinical information, and detect any late complications. All patients consented to participation in the research study, and the protocol was approved by the Mayo Clinic institutional review board.

Study Design

Biplanar or multiplanar ITEE was performed and interpreted by a cardiologist at the request of the surgeon for most intracardiac procedures. Epicardial echocardiograms were excluded from this study. ITEE was not routinely performed for simple extracardiac procedures such as pulmonary artery banding, systemic-pulmonary arterial shunts, or isolated coarctation repairs. All ITEE procedures were performed with commercially available echocardiographic systems (Hewlett Packard Sonos 1000-2500; Hewlett-Packard Company, Palo Alto, Calif; or Acuson XP-10; Acuson Corporation, Mountain View, Calif). All ITEE probes had either biplanar or multiplanar capability. Pediatric probes with a tip diameter of 10 mm were usually used in patients weighing less than 15 kg. Adult ITEE probes with a tip diameter of 12 to 13 mm were used in patients weighing more than 15 kg.

Impact was defined by the cardiologist and surgeon at the time of the procedure and was described as one of five distinct impact categories. The four positive impact categories were prebypass major impact, prebypass minor impact, postbypass major impact, and postbypass minor impact. If no new information was revealed on either the prebypass or the postbypass scan, the fifth category, no impact, was recorded for that patient.

The first major impact category was defined as unique prebypass information obtained by ITEE that altered the planned surgical procedure. An example would be the identification of an atrial septal defect (ASD) not previously known to be present in a patient undergoing a reoperation in which atrial exposure was not planned (for example, a right ventricle–pulmonary artery conduit replacement). The second major impact category was defined as unique postbypass information that described clinically significant residual findings that would not have been found by routine surgical pressure measurements. To be considered major impact, these findings required a return to bypass for surgical revision of the initial repair. An example would be an iatrogenic ventricular septal defect (VSD) after subaortic resection that required bypass again for surgical closure. Combined major impact rates refer to the percentage of patients in a group who had either prebypass or postbypass major impact. If a patient had impact in both categories during a single surgical procedure, that patient was counted only once in the calculation of the combined impact rate.

The first of two minor impact categories was described as new prebypass information that did not alter the surgical plan but did refine the diagnosis. An example would be a previously undetected ASD in a patient with Ebstein anomaly that would have been visualized by the surgeon during routine inspection of the atrium before tricuspid valve repair and thus did not change the surgery. The second minor impact category was new postbypass information that did not lead to surgical intervention. An example would be moderate mitral valve regurgitation after attempted valve repair in which this result was accepted and not revised.

Statistical Methods

Statistical analysis was performed for each of five categories: (1) prebypass major impact, (2) postbypass major impact, (3) combined prebypass and postbypass major impact, (4) prebypass minor

TABLE 1. Findings associated with preoperative major impact

	No.
Undetected residual shunts	22
ASD	12
VSD	3
Patent ductus arteriosus	4
Other	3
Influenced atrioventricular valve repair or replacement	20
Influenced ventricular outflow tract enlargement	14
Left	9
Right	5
Undetected obstructive atrial membranes	5
Undetected restrictive ASDs in univentricular heart	5
Undetected pulmonary artery stenoses	4
Undetected anomalous pulmonary veins	3
Undetected anomalous systemic veins	3
Other	15

TABLE 2. Findings associated with postoperative major impact

	No.
Residual shunts	14
VSD	7
ASD	2
Other	5
Valvular dysfunction after repair	11
Redirect intracardiac baffle	9
Intra-atrial	5
Intraventricular	4
Atrioventricular valve dysfunction after surgery other than atrioventricular valve repair	5
Residual outflow tract stenosis	4
Left ventricle	2
Right ventricle	2
Ventricular dysfunction (intracardiac/vascular air)	4
Fontan pathway stenosis	3
Other	6

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impact, and (5) postbypass minor impact. The four parameters used for analysis within each category were age, surgical history (first operation vs reoperation), primary diagnosis, and surgical procedure performed. In analyzing surgical history, only the first operation performed during the study period was included. Statistical analysis included the use of logistic regression models in establishing associations between echocardiographic benefits and patient characteristics. Generalized estimating equations were used within these logistic regression models.[15] This made it possible to use data from patients who had more than one operation by accounting for within-patient correlations. It was computationally impossible to evaluate two of the variables of interest—diagnosis and surgical plan—with generalized estimating equations because of the large number of diagnostic and surgical categories and the sparseness of observations in several of the categories. For these variables, the significance of their association with the benefit questions was assessed with the Fisher exact test.

Cost Analysis

Cost analysis was performed by comparing the 1999 charges for the 1002 ITEEs with the cost saving of avoiding late reoperations in the postbypass major impact cases. No attempt was made to assign a monetary value to the prebypass information supplied by ITEE. Four of the 56 patients required bypass again because of regional wall motion abnormalities caused by air in the coronary arteries. Ventricular function for these patients improved after this second bypass without surgical revision. Because no additional surgery was performed, these 4 patients were excluded from the total reoperation cost analysis.

Total estimated hospital charges for reoperation in the patients with postbypass major impact were calculated with the assumption that the reoperation occurred during the same hospitalization as the initial surgery. All monetary figures were based on 1999 charges. According to the surgical indication for revision of the initial operation, a surgical base charge was established for each patient. The total time in the operating room for the hypothetic late reoperation was assumed to be 4 hours (to calculate the incremental operating room charges). The charge for cardiovascular anesthesia with standard supplies was based on the average cost for 20 patients with similar diagnoses.

Each patient undergoing late reoperation was assumed to require 3 additional days in the intensive care unit. A charge for one transthoracic echocardiogram was added to the operating room and intensive care charges to derive the total estimated cost for a late reoperation. Charges for consulting medical services, laboratory and radiology tests, and additional days in the hospital but not in the intensive care unit were not included in the cost analysis because of the high variability for each individual patient.

Our analysis compared the total estimated cost of late reoperation in the 52 patients with postbypass major impact with 1999 charges for 1002 ITEE studies in patients with congenital heart defects. The cost for the ITEE included the equipment charge, prebypass and postbypass pediatric cardiology interpretation, and the charge for probe insertion.

Results

Data from a total of 1002 patients were analyzed. There was no significant gender predilection, with 475 female (47.4%) and 527 male (52.6%) patients. The median age was 9.9 years, with a wide age range from the neonatal period through late adulthood (2 days to 85 years). The mean age was 16.7 years. The median weight was 28.2 kg (range 2.3-149 kg). The median height was 134 cm (range 33-196 cm). No statistical difference was present between male and female patients with regard to height and weight according to the Wilcoxon rank sum test.

Major Impact

The combined major impact rate for the series was 13.8% (n = 138/1002). Separate rates of preoperative and postoperative major impact were 9.1% (n = 91/1002) and 5.6% (n = 56/1002), respectively. Findings associated with major impact are summarized in Tables 1 and 2.

TABLE 3. Major impact by age (either before or after bypass)

Age (y)	Total patients	Major impact	
		No.	%
<6	377	59	15.6
≥6 to <18	289	44	15.2
≥18	336	37	11.0*

*P = .018 versus patients younger than 18 years at the time of the operation.

TABLE 4. Major impact by operative history (either before or after bypass)

	Before bypass (%)	After bypass (%)	Combined (%)
All patients	8.9	5.6	13.8
First operation	6.7	4.8	11.3
Reoperation	10.9*	6.5†	16.1‡

*P = .026 versus those undergoing their first cardiac operation.
†P not significant versus those undergoing their first cardiac operation.
‡P = .033 versus those undergoing their first cardiac operation.

Predictors of Major Impact

Age. The patients were divided into three age groups: those younger than 6 years, those from 6 to 18 years old, and adults (>18 years old; Table 3). The combined major impact rate was 15.4% when the patient's age was younger than 18 years. The combined major impact rate of 11% in patients older than 18 years was slightly less than this (Table 3). As a result, younger age was statistically significant as a predictor of major impact, with a P value of .018.

Operative history. A total of 920 of the 1002 procedures were included in the analysis of surgical history. The other 82 procedures were performed on patients who had undergone a surgical procedure performed earlier in this series and were therefore excluded to avoid bias.

Forty-six percent of patients had no previous history of cardiac surgery and 54% had a history of at least one previous intracardiac or extracardiac operation. Table 2 describes the rates of major impact observed according to surgical history. Patients with previous cardiac surgery had a higher incidence of combined major impact than did those patients with no previous surgery (16.1% vs 11.3%, P = .028). According to generalized estimating equations logistic regression models, the odds of having major impact from either the prebypass or the postbypass scan in the combined category were 1.52 times higher for patients with previous surgery than for those undergoing their first cardiac procedure. Patients with previous cardiac surgery also had a greater incidence of prebypass major impact (10.9% vs 6.7%, P = .026). Rates of postbypass major impact were similar in the two groups (Table 4).

Primary diagnosis. All 1002 patients were divided into 1 of 22 primary diagnostic categories (Table 5). The largest categories were univentricular heart (representing 17.8% of the study group), pulmonary atresia with a VSD or truncus arteriosus (representing 13.8%), and Ebstein anomaly (representing 11.9%).

Of the 22 primary diagnostic categories analyzed, complex right ventricular outflow tract obstruction, defined as lesions requiring more than a valvotomy or transannular patch, had the highest combined impact rate (48%; Table 6). This group of patients was 6 times more likely than the overall average to have impact. Other diagnostic categories with high rates of impact were double-outlet right ventricle, transposition of the great arteries (with or without a VSD), complex atrioventricular discordance (associated with pulmonary valve stenosis or atresia and VSD), subaortic stenosis, and partial atrioventricular canal. Impact frequency ranged from 20% to 31% in these groups. The odds ratios ranged from 1.6 to 2.9 for these last five groups.

Surgical plan. All patients were divided into 1 of 22 primary surgical categories according to the primary planned procedure (Table 7). The three most common surgical procedure categories were tricuspid valve repair or replacement for Ebstein anomaly (11.4%, n = 114), VSD closure combined with right ventricular outflow tract repair (10.5%, n = 105), and the modified Fontan procedure for single-ventricle physiology (9.8%, n = 98).

Of the 22 surgical categories analyzed, the Rastelli procedure and complex right ventricular outflow tract obstructions had the highest rates of combined major impact. These two surgical categories were about 5 times more likely to have impact (Table 8). Other surgical categories with high rates of major impact were complete atrioventricular canal, aortic valve repair, and subaortic stenosis or left ventricular outflow tract repair. Combined major impact frequencies ranged from 20% to 24% in these groups. The odds ratio ranged from 1.6 to 2.0 for these three categories. Each of the groups can be described as malformations requiring repair of aortic or atrioventricular valves or complex outflow tract reconstructions.

Low Rates of Major Impact

The following five categories had combined major impact rates less than 5%: (1) partial anomalous pulmonary venous connection, (2) tricuspid valve repair (other than for Ebstein anomaly), (3) simple atrioventricular discordance, (4) aortic arch anomalies, and (5) secundum ASD. Only secundum ASD had a statistically significant lower than average impact rate (P < .01). Although no impact was recorded for secundum ASD as the primary diagnosis or primary surgical plan, 2 patients classified in other primary categories required bypass again for revision of secundum ASD repairs. The first patient was a 4-month-old infant with Down syndrome, a large VSD, and a large secundum ASD. The suture

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TABLE 5. Primary diagnoses

Diagnosis	No. of patients
Univentricular heart	178
Pulmonary atresia, VSD, and truncus arteriosus	138
Ebstein anomaly	119
ASD	66
Tetralogy of Fallot	58
Subaortic stenosis	57
Partial atrioventricular canal	55
Complete atrioventricular canal	44
Transposition of the great arteries with or without VSD	44
Aortic stenosis or regurgitation	34
Complex atrioventricular discordance	33
Double-outlet right ventricle	29
Complex VSD	28
Complex right ventricular outflow tract obstruction	23
Simple VSD	22
Partial anomalous pulmonary venous connection with an ASD	18
Tricuspid atresia	17
Partial anomalous pulmonary venous connection with no ASD	11
Simple atrioventricular discordance	7
Total anomalous pulmonary venous connection	4
Aortic arch anomalies	4
Other	13

TABLE 6. Major impact by primary diagnosis (either before or after bypass)

Primary diagnosis	Patients (No.)	Impact (%)	Odds ratio
Complex right ventricular outflow tract obstruction	23	47.8	6.040
Double-outlet right ventricle	29	31.0	2.892
Transposition of the great arteries with or without VSD	44	27.3	2.432
Complex atrioventricular discordance	33	24.2	2.029
Subaortic stenosis	57	21.1	1.702
Partial atrioventricular canal	55	20.0	1.585

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closure of the ASD caused mitral valve distortion and significant mitral valve regurgitation. Because no surgery had been performed on the mitral valve, routine pressure measurements of the left atrium were not performed. The patient was returned to bypass for revision of the ASD closure (converted to a patch), which relieved the mitral distortion. The second patient was a 3-year-old with pulmonary valve stenosis and a patent ductus arteriosus who also had an ASD and underwent surgical repair of all three defects. A pericardial patch was used to close the ASD. After cardiopulmonary bypass, the patient had reduced oxygen saturation. This was presumed to be due to ventilation problems. ITEE revealed that the pericardial patch had been attached to the eustachian valve, creating an inferior vena cava–left atrial shunt. The patient was returned to bypass, and the atrial patch was revised.

Minor Impact

Overall, the minor impact rate for the pre-bypass ITEE was 12.3% (n = 123/1002) and that for the postbypass ITEE was 10% (n = 100/1002). A slightly higher prebypass minor impact rate was observed in the reoperation group (13.7% vs 10.6%). However, neither age nor operative status was statistically significant as a predictor of minor impact.

Complications

Complications were reported by the cardiologist, surgeon, and anesthesiologist. No major complications, defined as death, esophageal or gastric perforations, accidental extubations, upper gastrointestinal bleeding, or endocarditis, occurred as a result of ITEE during the study period. Minor complications, defined as transient airway compression, problems with ventilation, or compression of the descending aorta by the probe, were observed in 10 patients, or 1% of the study population. Minor complications were most common in patients weighing less than 4 kg. ITEE was performed in 51 patients weighing less than 4 kg. Minor complications occurred in 6 of these infants, representing a minor complication rate of 11.8% in this subset of patients.

Cost Analysis

Fifty-two patients had revision of their initial surgical repair before leaving the operating room on the basis of ITEE findings. The total estimated cost for these 52 late reoperations (performed at a later time during the same hospital stay) would have been $895,664, or $15,994 per operation. Reoperation costs included charges for the procedure performed, incremental operating room fees, anesthesia and supplies, 3 nights in the intensive care unit, and one transthoracic echocardiogram. The total 1999 charges for 1002 ITEE studies would have been $746,490, or $745 per ITEE. Thus this model predicts that ITEE produced an overall saving of $149,174 by avoiding the costs of late reoperation in this patient group. These data suggest that if ITEE prompted an immediate surgical revision in 5% of patients studied, the ITEE service would pay for itself, even without considering any benefits derived from the preoperative scan.

Discussion

The use of ITEE in our study population yielded valuable new information in 13.8% of cases, either changing the preoperative surgical plan (9.1%) or prompting immediate revision of hemodynamically significant defects (5.6%). Patients who benefited the most from ITEE were those undergoing reoperations of any kind and those in diagnostic and surgical categories involving valve repair (aortic or atrioventricular) or complex ventricular outflow tract recon-

TABLE 7. Surgical plan

Plan	No. of patients
Ebstein anomaly	114
VSD and right ventricular outflow tract repair	105
Fontan procedure	98
Palliation of univentricular heart	90
Secundum ASD	67
Subaortic and left ventricular outflow tract repair	66
Mitral valve repair	59
Aortic valve repair	58
Complex conduit	54
Simple conduit	46
Partial atrioventricular canal	37
VSD, other	34
Complex right ventricular outflow tract obstruction	26
Complete atrioventricular canal	25
Rastelli procedure	23
VSD, membranous	22
Other	26
Partial anomalous pulmonary venous connection with ASD	18
Arterial switch	15
Partial anomalous pulmonary venous connection with no ASD	10
Tricuspid repair (not Ebstein)	5
Total anomalous pulmonary venous connection	4

TABLE 8. Major impact by surgical plan (either before or after bypass)

Surgical plan	Patients (No.)	Impact (%)	Odds ratio
Rastelli procedure	23	43.5	5.024
Complex right ventricular outflow tract obstruction	26	42.3	4.815
Complete atrioventricular canal	25	24.0	1.987
Aortic valve repair	58	20.7	1.663
Subaortic and left ventricular outflow tract repair	66	19.7	1.562

structions. We therefore strongly recommend the routine use of ITEE for all such patients during intracardiac operations.

Although relatively low impact rates were observed for some diagnostic categories (partial anomalous pulmonary venous connection, tricuspid valve repair other than for Ebstein anomaly, simple atrioventricular discordance, aortic arch anomalies, and secundum ASDs), instances of major impact did occur among these patients. One could reasonably ask whether the routine use of ITEE is truly indicated for these low-impact categories. In our study population, no major complications occurred. Only 1% of patients had minor complications, which occurred primarily in neonates weighing less than 4 kg. As technology continues to advance, the introduction of smaller ITEE probes should minimize such minor complications in the future. Previous studies also support the conclusion that ITEE in pediatric and adult patients is a safe procedure.[16-18] Therefore the low risk of complications does not detract from considering routine use of ITEE.

If adequate medical resources are available, then the final question involves the cost-benefit profile of routine use of ITEE for all patients with congenital heart defects. Stevenson[14] reported a series of operations with ITEE in which a 2.8% rate of immediate surgical revision was found to be cost-effective. The total cost for reoperation in 11 patients was $418,447, or $38,040 per operation. The total cost of performing 400 ITEEs was $259,670, or $650 per ITEE. Thus in this particular patient group the overall savings were $158,777.[14] One may therefore extrapolate from these data that the break-even point is a postbypass major impact rate of 1.8% (n = 7/400). The cost analysis performed for our patient population also supports the conclusion that ITEE is cost-effective. We found an immediate revision rate of 5% to be cost-effective for routine application of ITEE. The major difference in cost analysis between the two studies was the charge for reoperation ($38,040 for Stevenson[14] versus $15,994 in our study). Our cost analysis was based on a minimalist strategy and included only essential charges for the reoperation. Miscellaneous charges for consulting medical services, laboratory and radiologic tests, and additional days in the hospital on the ward were not included in the cost analysis because of the high variability for each individual patient.

Although the exact costs of reoperation can be debated, the data still indicate that routine use of ITEE during surgery for congenital heart defects is cost-effective. It is important to note that this conclusion is based only on postoperative major impact. There are clearly additional benefits derived from ITEE, including new information acquired on the preoperative scans that may lead to changes in the planned surgery. The preoperative benefits of ITEE are difficult to quantitate. Preoperative impact would certainly be reduced if all or most patients had transesophageal echocardiography as part of their outpatient evaluation. We believe that this approach is usually unnecessary. Instead, we have reserved outpatient transesophageal echocardiographic evaluation for those situations in which there is a question of whether to proceed to surgery. When a patient clearly needs an operation on the basis of routine evaluations, we prefer to perform ITEE in the operating room. This is true even if there are some questions that have not been completely addressed by the preceding evaluation. ITEE allows both the cardiologist and the surgeon to be present during the evaluation and to review the data together before formulating a final surgical plan. We recognize that this preference has probably influenced the frequency with

which ITEE was found to have major preoperative impact in our series. However, we believe that this approach is the most efficient method, particularly for pediatric patients, who would generally require an additional general anesthetic if transesophageal echocardiography were performed outside the operating room.

Limitations of the Study

Because of the referral pattern at the Mayo Clinic, our study population has a larger proportion of adults with congenital heart defects than most previous reports. In addition, ITEE was not performed during all neonatal intracardiac procedures. For example, repair of total anomalous pulmonary venous connections frequently was not evaluated with ITEE because the probe would possibly compromise surgical exposure in the posterior mediastinum. Also, in some cases ITEE was not requested if the weight of the neonate was so low that ventilation problems could occur. Therefore our conclusions may not be easily generalized to a broad neonatal population. However, they should apply to the vast majority of patients requiring repair of congenital heart defects, namely those weighing more than 4 kg.

Conclusions

Major impact was observed in almost all diagnostic and surgical categories and was more common among patients who had previous cardiac surgery. There were no major complications, and minor complications were rare. Even though some diagnostic and surgical groups had relatively low rates of major impact, observed overall frequencies of major impact and immediate revision support the premise that routine use of ITEE would be cost-effective. We therefore believe that routine use of ITEE during intracardiac surgery for all congenital heart defects is justified.

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