Current State of Intraoperative Echocardiography

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Intraoperative use of echocardiography is becoming more prevalent and is now considered an essential part of modern cardiac surgery. Echocardiography can be performed intraoperatively using transesophageal, epicardial or epiaortic, and substernal approaches. These techniques have a variety of applications in evaluating myocardial and valvular function, assessing aortic atheroma, and determining adequacy of various kinds of repair and reconstruction. Future applications will most likely involve more compact equipment, the implementation of epicardial and transesophageal real-time three-dimensional echocardiography, and better use of provocative methods of intraoperative testing. (ECHOCARDIOGRAPHY, Volume 20, November 2003)

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Intraoperative echocardiography has become an integral part of cardiac surgical procedures and has an enormous impact on both the immediate intraoperative course and long-term outcome. The use of echocardiography during open heart surgery dates back over 30 years. Today, intraoperative echocardiography represents its own evolving subspecialty, and utilizes a variety of diagnostic tools and ultrasound modes to assist surgeons, anesthesiologists, and cardiologists in their management of the cardiac patient.

History

Echocardiography came to the operating room in the early 1970s as epicardial M-mode ultrasound to evaluate the results of mitral valve commisurotomy[1] and to assess left ventricular (LV) function in patients undergoing coronary artery bypass surgery. The first publication on intraoperative M-mode transesophageal echocardiography (TEE) was in 1979, when Matsumoto and colleagues[2] used a handmade probe to assess ventricular performance. The electronic phased-array transducer was introduced in 1982 and represented a major technologic breakthrough.[3] In the late 1980s, high frequency biplane TEE probes became available and provided high resolution, color mapping, and continuous-wave Doppler interrogations.[4] In 1992 the dynamic three-dimensional TEE was first described.[5]

Purpose

Modern intraoperative echocardiography serves several purposes. First, it assists the surgeon with planning of the operation by providing precise information about cardiovascular anatomy and function. Second, it allows intraoperative monitoring. Third, it helps minimize the risk and increase the efficiency of the operation by guiding surgical manipulations, especially during minimally invasive and robotic procedures. Finally, it confirms the results of the operation, which is equally important for valve and coronary surgery.

Approach

Intraoperative echocardiography is routinely used in two different approaches: transesophageal, and epicardial or epiaortic.

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Transesophageal Echocardiography

Transesophageal echocardiography has become the most common and convenient way to obtain echocardiographic data during cardiac surgery. TEE does not interfere with the surgical field and provides continues information about cardiovascular anatomy and function. TEE is an integral part of any valve operation, and its use is also becoming routine during coronary artery bypass surgery and aortic procedures.

Safety of TEE

Safety of TEE was documented by Kallmeyer and colleagues,[6] who evaluated 7200 adult cardiac surgery patients and found no mortality and very low morbidity associated with TEE. The most common TEE-associated morbidity was severe odynophagia (0.1%), which resolved with medical treatment. Other complications included dental injury (0.03%), endotracheal tube malpositioning (0.03%), upper gastrointestinal bleeding (0.03%), and esophageal perforation (0.01%). In that study, insertion of TEE probe was unsuccessful in 0.18% and was contraindicated in 0.5% of the patients.

Accuracy of Intraoperative Interpretation

Depending on the institution, intraoperative TEE examinations are performed by either cardiologists or anesthesiologists. Only a few studies have compared the interpretations of intraoperative TEE by cardiologists and anesthesiologists. Based on 154 patients, Mathew et al.[7] reported that agreement between anesthesiologists and cardiologists was reached in 80% of the studies, and experienced anesthesiologists (over 5 years of experience) had higher levels of accuracy. Miller et al.[8] demonstrated that anesthesiologists correctly interpreted 79% of baseline images, whereas 6% were interpreted incorrectly and 15% were not evaluated. To standardize and ensure the quality of intraoperative TEE, official guidelines for performing a comprehensive intraoperative multiplane TEE examination were released in 1999.[9]

Unexpected Findings

A thorough baseline echocardiographic examination at the beginning of surgery is essential. New unexpected findings such as patent foramen ovale (PFO), intracardiac masses (Fig. 1), valvular abnormalities (Fig. 2), and aortic atherosclerosis can alter the course of the operation. Click and coworkers[10] evaluated the impact of routine intraoperative TEE on surgical decisions made perioperatively in 3245 adult patients undergoing cardiac surgery. They demonstrated that new findings were identified in 15% of the patients, directly affecting surgery in 14%. The most common finding was PFO, which resulted in closure in the majority of patients. New information after bypass was found in 6% of patients, changing the operative or hemodynamic management in 4%. In these patients the predominant problem was valvular dysfunction, requiring re-repair or replacement.

Monitoring. General assessment of the size of the cardiac chambers, LV and right ventricular (RV) systolic, and LV diastolic function

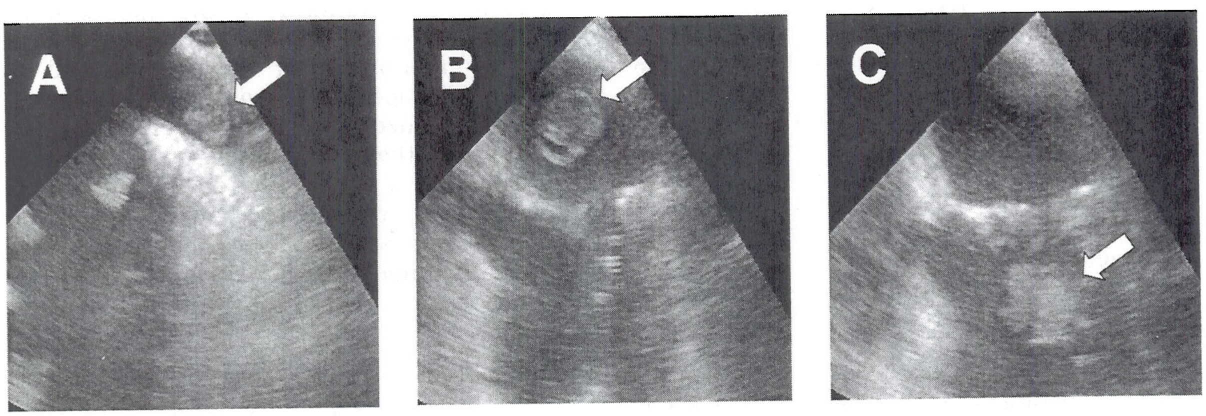

Figure 1. *Transesophageal echocardiographic images selected from a 5-second sequence obtained in a patient undergoing off-pump coronary artery bypass grafting (CABG). Arrows indicate a clot noted in the* **(A)** *left atrial appendage that became mobile during the procedure, which was then seen in the* **(B)** *left atrium, and subsequently in the* **(C)** *left ventricle.*

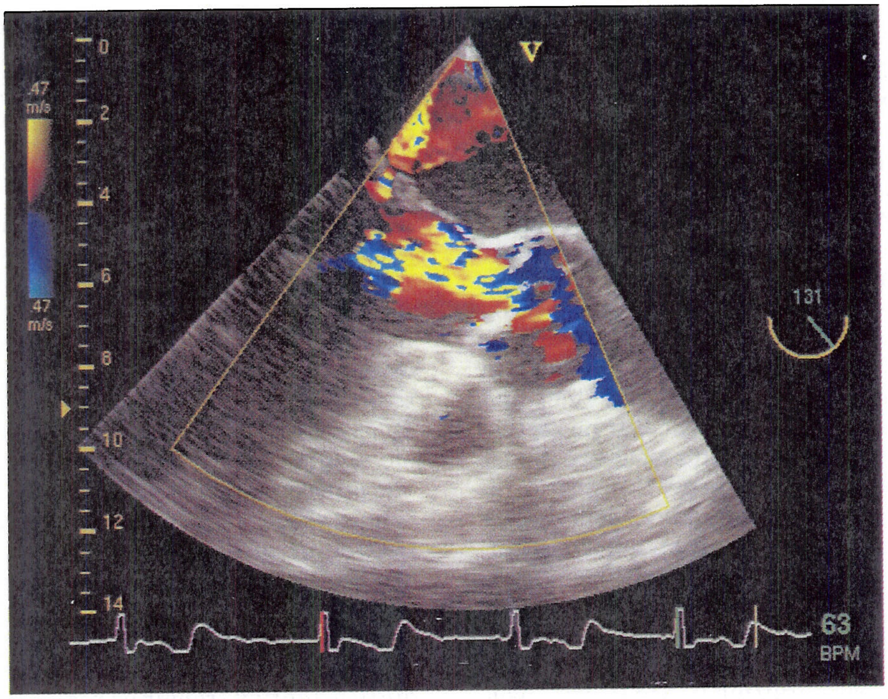

Figure 2. *Transesophageal color Doppler image illustrating unexpected moderate aortic insufficiency that precludes performing coronary artery bypass grafting off-pump and compromises delivery of antegrade cardioplegia in case of performing standard on-pump coronary artery bypass grafting operation.*

can be easily obtained by TEE.[11] Cardiac output can be determined using multiplane TEE with acceptable accuracy when compared with standard thermodilution method.[12,13] Preload, as measured by end-diastolic area, can be determined with great accuracy by TEE. Multiple studies have indicated the benefits of preload determination with TEE over pulmonary catheter data.[14]

Stroke Prevention. During cannulation of the aorta in preparation for cardiopulmonary bypass, TEE provides valuable information about the extent of atherosclerosis in the proximal ascending and descending aorta. Unfortunately, transesophageal views of significant parts of the ascending aorta and the aortic arch are limited by the trachea, and require epicardial (or epiaortic) imaging.

Guiding. TEE can be an excellent guide during cannulation of the aorta, superior vena cavae (SVC), inferior vena cavae (IVC), and coronary sinus during standard and minimally invasive operations.[15–17] The position of the endoaortic clamp in the ascending aorta requires continuous TEE monitoring. The endoaortic clamp is a balloon catheter inserted through femoral artery. It is used to occlude the aorta, deliver cardioplegia, and provide aortic root venting and pressure measurements. The proximal displacement of the endoclamp can be easily detected when it comes closer to aortic valve, and its distal migration can be detected by loss of pulsed-wave Doppler signal from the right carotid artery. This guiding and monitoring function of TEE will likely play an even more important role in developing totally endoscopic robotic cardiac surgery.

Use of TEE in Coronary Revascularization

There is increasing evidence that justifies a routine use of intraoperative TEE in coronary bypass surgery.[18,19] Savage and colleagues[20] reported that intraoperative echocardiography in 82 high-risk patients, undergoing coronary artery bypass grafting, initiated at least one major surgical management alteration in 27 patients (33%), and at least one major anesthetic/hemodynamic change in 42 patients (51%). This study also suggested that intraoperative TEE reduces mortality and the rate of myocardial infarction in this high-risk population compared to a similar group of patients without intraoperative echocardiography

(1.2% versus 3.8%, and 1.2% versus 3.5%, respectively).

It was demonstrated that intraoperative low-dose dobutamine echocardiography is a reliable method to predict myocardial functional reserve and determine functional recovery expected immediately after coronary revascularization.[21,22] Monitoring of LV function and regional wall motion abnormalities is even more important during off-pump coronary artery bypass operations.[23] Hemodynamic deterioration during manipulation of the heart might occur secondary to decrease in preload, changes in right ventricular anatomy and function, and distortion of the heart valves. Real-time assessment of these parameters helps surgeons adjust the position of the heart before making the coronary arteriotomy and, therefore, committing themselves to performing an anastomosis under suboptimal hemodynamic conditions. Intraoperative TEE findings may precipitate the institution of cardiopulmonary bypass in patients originally planned to undergo off-pump coronary artery bypass grafting (CABG). This usually occurs when surgical correction of valvular abnormalities or PFO is necessary, or when proper stabilization for off-pump surgery cannot be achieved. In addition, detection of new wall motion abnormalities during, or immediately following CABG, guides the surgeon to specific grafts for reevaluation.

The management of moderate mitral regurgitation (MR) at the time of coronary revascularization remains controversial and deserves special attention. Aklog et al.[24] described that intraoperative TEE downgrades the severity of preoperatively moderate MR in 89% of patients. The mean grades of preoperative, intraoperative, and postoperative MR in their study were 3.0 ± 0.0, 1.4 ± 1.0, and 2.3 ± 0.8, respectively.[24] Therefore, in patients with a less than expected degree of MR during bypass surgery, intraoperative provocative testing should be used to determine the surgeon's decision about mitral valve correction.

Evaluation of mild to moderate aortic stenosis, a condition common in the aging population of patients undergoing CABG, is also facilitated by perioperative TEE. In cases of intermediate aortic gradients, determination of the calculated valve area indexed to body size as well as the severity of aortic leaflet calcification and leaflet mobility is helpful when deciding whether aortic valve replacement needs to be added to CABG.[25] The above echocardiographic findings should be taken into account along with the etiology of the aortic valve disease, the rate of progression of stenosis, and the patient's life expectancy and general medical condition.

Use of TEE in Valve Surgery

The goals of the intraoperative echocardiographic valvular exam are to identify the underlying structural abnormality, propose the mechanism of dysfunction, and then quantify the degree of stenosis or regurgitation. This exam often differs from the routine preoperative exam by its primary focus on mechanism, as opposed to severity. Assessment of severity of valvular lesions in the operating room (without provocative maneuvers) can often underestimate values due to the hemodynamic changes that occur under anesthesia. However, a very thorough exam can be performed in an anesthetized patient to inspect the valves and subvalvular apparatus in their entirety and direct the surgeon to the precise components that require attention (repair or replacement), as well as aid in determining the optimal approach. In addition, cardiac function should be thoroughly evaluated prior to valve surgery. Valve sparing operations and aortic valve replacements with either a stentless valve, homograft, or pulmonary autograft require relatively long ischemic times. If cardiac function is poor or if additional surgery, such as multiple valves or bypass grafting is required, consideration should be given to a shorter procedure such as a replacement with a stented valve.

Aortic Valve Surgery. Intraoperative TEE during valve operations has become a standard of care in most cardiac centers throughout the world. TEE performed during aortic valve surgery allows the surgeon to determine the precise anatomy of the valve, the size of the aortic annulus, the severity of stenosis, and the degree of aortic insufficiency that may compromise antegrade delivery of cardioplegia. Additionally, TEE allows determination of the degree of associated mitral valve pathology, which may also require surgical correction.[26] It is especially important to confirm the absence of aortic insufficiency after subcoronary implantation of an aortic homograft or a stentless valve. These valves can be distorted during placement, unlike their less pliable stented and mechanical valves.[27] Intraoperative echo can help with decisions about valve sizes and whether or not a root enlargement is necessary in case of a small aortic annulus. The sizing and the insertion of a stentless porcine valve, as well as homografts, require a thorough understanding of aortic root anatomy, especially the sinotubular junction. If the sinotubular junction is dilated or if there is a discrepancy of more than one valve size between the aortic diameter and the sinotubular junction diameter, a stentless porcine valve should not be used, it may result in aortic insufficiency. Following separation from bypass, TEE is necessary to confirm the proper positioning and the function of the prosthesis. Careful inspection for paravalvular leaks should also be performed at this time. Intraoperative TEE also plays an important role in the aortic valve repair surgery. It is vital in the assessment of the results of valve-sparing operations, such as Yacoub and David procedures, for remodeling the aortic root.[28,29]

Mitral Valve Surgery. Intraoperative echocardiography is an integral part of mitral valve surgery. The assessment of the mitral valve pathology should include careful analysis of all parts of the mitral valve: anterior and posterior leaflets, submitral apparatus (chords and papillary muscles), mitral valve annulus, and the left ventricle. As with aortic valve surgery, there are two options for surgical treatment of the mitral valve disease: repair or replacement. There are certain situations when the valvular pathology is more suitable for repair, rather than replacement. These conditions include myxomatous disease, especially posterior leaflet prolapse, ischemic mitral valve disease with a restrictive posterior leaflet (with or without annular dilatation), pure mitral stenosis without significant regurgitation, or massive calcifications. Repair of myxomatous anterior leaflet pathology can be more challenging. Rheumatic mitral valve regurgitation is corrected with mitral valve replacement in the vast majority of patients. The role of intraoperative echocardiography in the choice of the operative strategy is described in detail below for each specific etiology.

The choice of the operation for rheumatic heart disease depends on the degree of mitral valve regurgitation and the amount of calcification on the leaflets, annulus, and submitral apparatus. Today, in the United States, many patients with favorable anatomy (no significant MR or calcifications) undergo percutaneous balloon mitral valve commisurotomy. Most surgical patients have unfavorable anatomy, not amenable to repair, and therefore undergo valve replacement with either a mechanical or bioprosthetic valve.

Fibroelastic degenerative or myxomatous mitral valve regurgitation is the most common indication for isolated mitral valve surgery. The modern era of surgical treatment of this pathology started in the 1980s with the contribution of Carpentier, who invented a segmental approach for the evaluation of the mitral valve disease and demonstrated superior long-term results of mitral valve repair over valve replacement.[30] To plan a mitral valve repair, the surgeon needs to know precise details of the anatomy and function of each of three segments of anterior and posterior leaflets. The evaluation of the submitral apparatus includes the chord status (e.g., intact, elongated, restricted, or ruptured), and anatomy and function of the papillary muscles. The presence of annular dilatation and annular calcification are also important, as well as information about LV function, the degree of MR, the size, and the direction of the regurgitant jet (Fig. 3). The annulus should be measured in two dimensions (Fig. 4): the "length" at the mid-esophageal commissural view (~60 degrees) and the "width" at the mid-esophageal long-axis view (~120 degrees). Functional parameters can vary with preload, afterload, and heart rate. Today the surgical risk of the isolated mitral valve repair for myxomatous disease is extremely low, and long-term results are significantly better in surgical as opposed to medical treatment of myxomatous disease.[31–33] Smolens et al.[34] demonstrated that early surgical repair of mildly symptomatic or asymptomatic patients with severe MR under

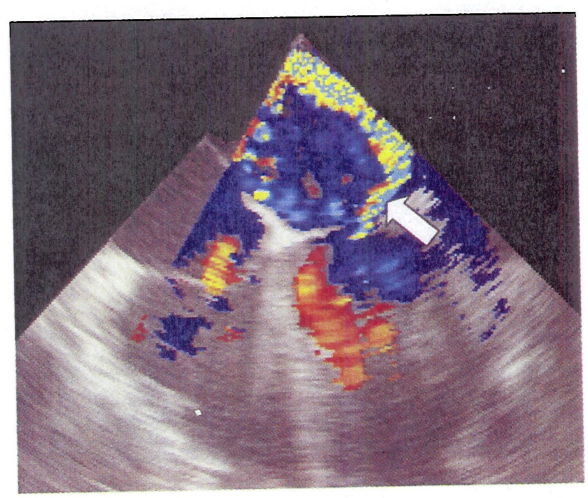

Figure 3. *Transesophageal color Doppler image illustrating an eccentric mitral regurgitant jet (arrow), which suggests anterior leaflet pathology.*

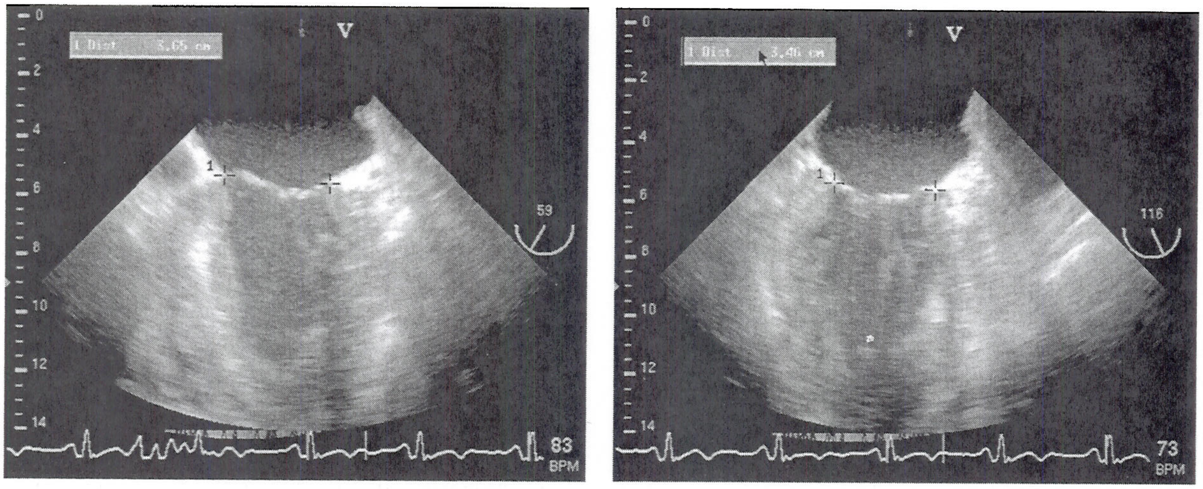

Figure 4. *Transesophageal echocardiographic images used to measure mitral annulus in two planes: the mid-esophageal commissural view (left) and the mid-esophageal long-axis view (right). Note the electronic calipers indicating the measurements of the mitral annulus "length" (left) and "width" (right).*

TEE guidance can be performed with no mortality and low morbidity. Following repair, the LV outflow tract should be inspected for systolic anterior motion (SAM) of the mitral valve (Fig. 5), particularly when the preoperative anterior mitral valve leaflet length exceeds 3.5 cm (measured in the long-axis view).

Ischemic cardiomyopathy with annular dilatation and posterior leaflet retraction is a common mitral pathology. Current literature supports the idea that the repair of moderate MR may decrease mortality.[16] The degree of MR

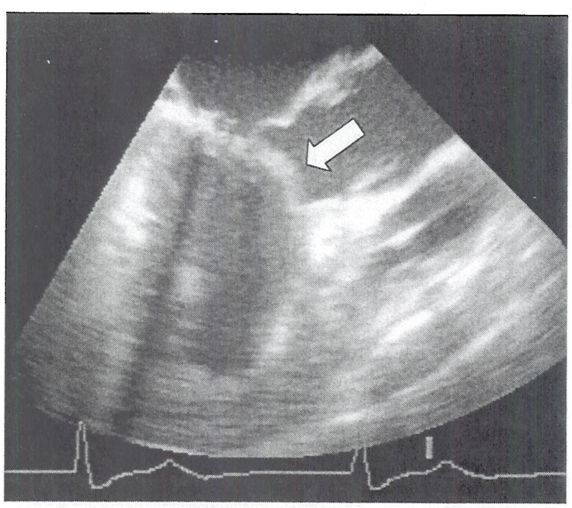

Figure 5. *Transesophageal echocardiographic image illustrating systolic anterior movement after mitral valve repair. Note the anterior leaflet obstructing the left ventricular outflow tract (arrow).*

in anesthetized patients may be significantly less than in awake patient. Therefore, intraoperative TEE evaluation of MR under changing hemodynamic conditions (increased preload and afterload) should be performed.

Intraoperative TEE is very accurate in detecting the mechanism of mitral regurgitation resulting from infective endocarditis, and therefore has a high predictive value as to whether repair is possible or the valve needs to be replaced. Most common repairs involve the removal of vegetations, patching a hole in a leaflet, and resection of a destroyed leaflet.[35,36]

Information obtained from TEE also helps the surgeon choose the most efficient approach to the mitral valve. In patients with nonsignificant tricuspid valve pathology and an enlarged left atrium, most surgeons choose to approach the mitral valve by left atriotomy made in the interatrial groove. In patients where left atrial size is normal, and especially where significant tricuspid regurgitation is present, most surgeons choose to approach the mitral valve by opening the right atrium and interatrial septum. This is known as the trans-septal approach.

Use of TEE for LV Reconstruction

In the last two decades the incidence of the heart failure has been steadily increasing.[37] Despite the advances in medical therapy, the mortality among the patients with end-stage heart failure remains high. In the past few years there has been increasing interest in the LV reconstruction procedure, which has been found to be an effective surgical treatment of patients with end-stage ischemic heart failure. This operation has also been referred to as Dor procedure, surgical ventricular restoration, infarction excision surgery, and endoventricular circular patch-plasty. Shiota and colleagues[38] emphasized the importance of communication between cardiac surgeons and echocardiographers for successful outcomes of these procedures, because echocardiography provides information about anatomy, absolute LV volume, ejection fraction (EF), and the severity of MR. The precision required in measuring the amount of myocardium to be resected has prompted those authors to suggest that three-dimensional echocardiography may become a preferred method for preoperative evaluation of these patients.

Based on the analysis of 950 endoventricular patch repair operations with hospital mortality of 7%, Dor[39] indicated that there are two preoperative echocardiographic predictors of long-term survival: LV ejection fraction (LVEF) and end-systolic volume index (ESVI). Life expectancy at 10 years reaches 80% for preoperative LVEF > 30% and ESVI < 90 ml, and only 60% for LVEF < 30% and ESVI > 90 ml.[39]

Preoperative evaluation of MR in these patients is very important as well. In patient with significant MR, the surgical correction of the mitral regurgitation may be considered. There are several surgical options to repair ischemic MR, which are routinely guided by echocardiography. The standard approach is annuloplasty from the left atrium with a C-shape or full ring. It has been recently reported that Alfieri repair, which includes suturing of mid points of two mitral valve leaflets thus creating a double orifice valve, can be performed from inside of the LV as well. Postoperative echocardiographic evaluation of the mitral valve function should always be performed after the Dor procedure with or without mitral valve repair.[40]

Epiaortic/Epicardial Echocardiography

There is wide recognition of aortic atherosclerosis as a major cause of intraoperative stroke.[41,42] Echocardiography is clearly superior to manual palpation of the aorta to detect atherosclerotic disease. Unfortunately, TEE cannot visualize much of the ascending aorta and proximal aortic arch because of their relation to the trachea. Therefore, direct epicardial or epiaortic echocardiography is the tool of choice to diagnose aortic atherosclerosis when manipulations of the aorta are planned.[43]

There are several classifications of the atherosclerotic aortic disease. According to Katz, grade I represents no disease or minimal thickening, grade II is extensive intimal thickening, grade III is sessile atheroma, grade IV is protruding atheroma, and grade V is mobile atheroma.[44] Wareing[45] suggested a simpler classification where mild disease is described as only localized thickening of <3 mm, moderate to intimal thickening of 3 to 5 mm, and severe atherosclerotic disease represents all the rest (thickening > 5 mm, calcifications, ulcerated plaque, protruding, or mobile atheroma). Baribeau and colleagues[46] reported that in over 1500 patients who underwent epiaortic ultrasound, the incidence of severe atherosclerotic disease was 8%, moderate disease was present in 19%, mild disease in 57%, and no disease in only 16%. The stroke and mortality rates were: 1.2% and 2.8%, respectively, for normal aorta; 2.5% and 3.6% for mild disease; 3.5% and 6% for moderate; and 10% and 8% for severe aortic atherosclerosis.

There are several strategies that can be used to minimize the risks of intraoperative stroke when epiaortic imaging reveals atherosclerotic disease in the ascending aorta. First, in patients undergoing coronary bypass surgery, it is better to avoid aortic manipulations by performing the operation off-pump and using internal mammary arteries in situ as conduits. If necessary, other conduits can be connected to the mammary arteries. When the institution of cardiopulmonary bypass is necessary and aortic cannulation is unavoidable, other aortic cannulation sites, including femoral or axillary arteries, may be considered.[47] To avoid applying the aortic cross clamp, many surgeons carry out bypass operations on a beating or fibrillating heart without performing proximal aortic anastomosis. Some surgeons perform proximal anastomoses using a very short time of total hypothermic circulatory arrest. Acceptance and availability of an automatic proximal anastomotic device has facilitated proximal vein to aorta anastomosis without clamping the aorta, thereby decreasing the risk of stroke.

When atherosclerotic disease of the ascending aorta is noted by epiaortic echocardiography at the beginning of valve surgery, the strategy of the procedure needs to be adjusted. Mitral valve operations can be performed on cold fibrillatory arrest without cross-clamping the aorta, through either median sternotomy or right thoracotomy. Aortic valve surgery can be performed using a short period of total circulatory arrest to replace a portion of the ascending aorta with a tube graft, which can be cross-clamped when the circulation is restarted.

Kouchoukos and his group have used epiaortic echocardiography extensively in the early 1990s, and advocated a replacement of severely atheromatous ascending aorta in patients undergoing CABG operations. They reported early mortality and stroke rates of 8.6% and 7.4% respectively, and 3-year survival was only 40%.[48] Byrne and colleagues[49] reported a few cases of successful aortic valve replacement using "no cross-clamp" technique on total circulatory arrest that lasted less then one hour.

Epicardial Doppler echocardiography with high frequency probes (typically 15 MHz) has been used effectively to evaluate flow in arterial grafts, which are prone to spasm. This allows avoiding undue manipulation of the grafts, which is often required when using transit time flow probes.[50] This technique has also been used to evaluate LV size and volume.

A new technique, known as substernal echocardiography, utilizes a specially constructed mediastinal chest tube that allows access of a pediatric echo probe to evaluate myocardial performance and graft flow, as well as to rule out tamponade after chest closure.[51]

Echocardiographic Assessment of Aortic Dissection

Transesophageal echocardiography is an important tool for quick diagnoses and early initiation of treatment of aortic dissection. Rizzo and colleagues[52] reported that rapid noninvasive diagnosis of aortic dissection and avoidance of routine angiography improves survival by expediting surgical intervention and thus decreasing the risk of aortic rupture. Multiple studies have compared sensitivity and specificity of computer tomography (CT), magnetic resonance imaging (MRI) and TEE in the diagnosis of acute dissection. The sensitivity and specificity of multiplane TEE were 99% and 98%, respectively.[53,54] Compared with MRI and CT, TEE is superior in identifying intimal flap with an entry and sometimes exit sites. Doppler imaging also reveals flow differences between the true and false lumens. Echocardiographic images provide information about presence and severity of aortic insufficiency as well as pericardial effusion, which may be caused by aortic dissection. Pepi et al.[55] compared biplane and multiplane TEE for diagnosis of acute aortic dissection. They found that both techniques have 100% sensitivity and specificity in terms of the presence or absence of aortic dissection or intramural hematoma. Multiplane TEE was found to improve the visualization of coronary arteries, aortic arch and entry tears. Thus, this would be a good way to diagnose type A aortic dissections, either prior to surgery or intraoperatively.[55]

Pediatric and Congenital Applications

Intraoperative TEE is now routine during pediatric cardiac surgery. The few contraindications include small weight (most centers use 2.5 kg as a cutoff) or the presence of esophageal disease, such as a tracheo-esophageal fistula. Epicardial echocardiography can supplement or replace TEE. Intracardiac echo probes have been used as transesophageal echo probes in very small babies. In addition to the information described above, specific data that is gained during pediatric and congenital heart disease operations include adequacy of repair of septal defects, shunt direction across patent foramen ovale or ventricular septal defects, patency of fenestration after Fontan procedures, Blalock-Taussig shunt flow disturbances, aortic arch flow patterns, right ventricular pressures, and septal motion during biventricular pacing. In addition, TEE provides guidance during intraoperative occluder device placement.

Conclusions

Echocardiography is an easily accessible modality in the operating room. It has great utility in monitoring cardiac function in patients undergoing cardiac surgical procedures. It is also a useful tool in monitoring the cardiac status of high-risk patients and ensuring satisfactory outcomes following valve repairs. It is of great value in detecting aortic dissections as well as helping to achieve technical excellence in aortic surgery. Intraoperative echocardiography may be utilized through transesophageal, epicardial or epiaortic, and substernal approaches. Echocardiography is safe and can be adapted to the entire spectrum of cardiac surgical procedures. Newer techniques utilizing real-time three-dimensional imaging and smaller probes may expand the applicability of this promising technique in the operating room.

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