

## Echocardiography-Guided Interventions

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**Target Audience:**

Participation should include individuals from the fields of echocardiography, interventional cardiology, electrophysiology, cardiac sonography, and cardiac surgery, as well as medical residents, fellows, and students.

**Learning Objectives:**

After reading this article, participants should be able to: (1) Assess the strengths and weaknesses of each echocardiographic modality (transthoracic echocardiography, transesophageal echocardiography, intracardiac echocardiography, 3-dimensional echocardiography) in guiding interventional cardiologic and electrophysiologic procedures. (2) Use echocardiography to guide interventional procedures. (3) Recognize echocardiographers' role in catheterization and electrophysiology laboratories.

**Author Disclosures:**

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### I. ABSTRACT

A major advantage of echocardiography over other advanced imaging modalities (magnetic resonance imaging, computed tomographic angiography) is that echocardiography is mobile and real time. Echocardiograms can be recorded at the bedside, in the cardiac catheterization laboratory, in the cardiovascular intensive care unit, in the emergency room—indeed, any place that can accommodate a wheeled cart. This tremendous advantage allows for the performance of imaging immediately before, during, and after various procedures involving interventions. The purpose of this report is to review the use of echocardiography to guide interventions. We provide information on the selection of patients for interventions, monitoring during the performance of interventions, and assessing the effects of interventions after their completion.

In this document, we address the use of echocardiography in commonly performed procedures: transatrial septal catheterization, pericardiocentesis, myocardial biopsy, percutaneous transvenous balloon valvuloplasty, catheter closure of atrial septal defects (ASDs) and patent foramen ovale (PFO), alcohol septal ablation for hypertrophic cardiomyopathy, and cardiac electrophysiology. A concluding section addresses interventions that are presently investigational but are likely to enter the realm of practice in the very near future: complex mitral valve repairs, left atrial appendage (LAA) occlusion devices, 3-dimensional (3D) echocardiographic guidance, and percutaneous aortic valve replacement.

The use of echocardiography to select and guide cardiac resynchronization therapy has recently been addressed in a separate document published by the American Society of Echocardiography and is not further discussed in this document.

The use of imaging techniques to guide even well-established procedures enhances the efficiency and safety of these procedures.

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**Table 1** Interventional procedures: use of echocardiography for guidance

Interventional Procedure	TTE	TEE	ICE
Transseptal catheterization	+	++	++ (radial or phased array)
PMBV	++	+++	++
Transcatheter closure of ASD, ventricular septal defect, and PFO	+	++	++ (phased array)
Alcohol septal ablation in HOCM	++	++	—
Percutaneous mitral valve repair	+	+++	+
Percutaneous left ventricular assist device placement	—	++	++
Percutaneous stented aortic valve prosthetic placement	—	+	+
Balloon or blade atrial septostomy	++	++	++
Placement of LAA occlusion devices	—	++	++
Myocardial and intravascular biopsy	++	++	++ (phased array)
Congenital heart disease applications (completion of Fontan procedure, coarctation repair)	+	+	+
Placement of aortic endograft	—	—	++ (radial or phased array)

—, No documented role or benefit in the literature; +, anecdotal reports of use and benefit exist, but further study is needed to delineate; ++, advantages favor use when available; +++, clearly documented benefit or role.

## II. INTRODUCTION

Traditionally, percutaneous cardiovascular interventions have predominantly used angiographic and fluoroscopic guidance, which is limited when interventions involve the myocardium, pericardium, and cardiac valves.

The purposes of this report are to (1) delineate the role of echocardiography in guiding a wide variety of interventional and electrophysiological procedures, (2) discuss the critical echocardiographic aspects of these procedures, and (3) delineate the intraprocedural differences between echocardiographic modalities, comparing transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), and intracardiac echocardiography (ICE) wherever appropriate data are available. We have particularly emphasized the use of ICE where appropriate, because it is the newest of the echocardiographic modalities, and readers may be unaware of some potential applications. [Table 1](#) provides a summary of literature data concerning the use of the different echocardiographic modalities for each of the specific procedures. This report is not intended to provide detailed instructions on “how to” perform these procedures; more specific procedural details are available for review in the referenced documents. Instead, we intend to highlight and illustrate the ways in which echocardiography has had an important impact in the procedures being performed and their outcomes. Summary recommendations are listed in boldface type at the end of each section.

As percutaneous therapy for heart disease continues to advance at a rapid pace, it is inevitable that echocardiographic procedural guidance will continue to evolve rapidly as well. We have sought to keep the material in this report current as of this writing, by adding a section on future directions. Similarly, other modalities, such as magnetic resonance imaging and combined multiple imaging modalities (eg, reconstructed 3D computerized tomography with superimposed real-time echocardiography) will continue to evolve and develop roles in guiding these complex procedures as well.

## III. GENERAL IMAGING CONSIDERATIONS

### A. TTE

TTE is widely available and portable and offers excellent image quality; as such, it has been used widely in guiding percutaneous noncoronary interventional and electrophysiologic procedures. Most currently

available ultrasound systems, including handheld and portable ultrasound systems, offer sufficient 2-dimensional (2D) and Doppler capabilities to guide a variety of interventions, such as echocardiography-guided pericardiocentesis, alcohol septal ablation for hypertrophic cardiomyopathy, percutaneous balloon mitral valvuloplasty (PBMV), and myocardial biopsy. The advent of Doppler tissue imaging has made TTE essential in the optimization of biventricular pacemakers.

### B. TEE

TEE has been widely used as an alternative to TTE in guiding complex procedures. TEE offers superior image resolution to TTE and can be used to monitor a variety of interventions, such as percutaneous transcatheter closure (PTC) of septal defects, PBMV, transseptal catheterization, and many others. Compared with TTE, it excels at assessing intraprocedural anatomy and physiology, monitoring catheter position and contact, and excluding thrombus, pericardial effusion, and other complications.

### C. ICE

A more recent application of cardiac ultrasound, ICE has also demonstrated great potential for monitoring and guiding interventions. Experimental and clinical studies have demonstrated the utility of ICE in monitoring left ventricular and right ventricular function, delineating anatomy, guiding transseptal punctures and therapy, and biopsy of cardiac masses.<sup>1-13</sup>

ICE offers imaging that is comparable with or superior to TEE. ICE has been shown to provide significant benefits when used for radiofrequency ablation of atrial fibrillation (AF) and transcatheter atrial septal closure procedures and has become the imaging standard during these procedures at many centers.<sup>14-28</sup> In the catheterization laboratory during these procedures, an advantage over TEE is that ICE obviates the need for general anesthesia and for additional echocardiography physician support. Compared with guidance using TEE, ICE has been shown to improve patient comfort, shorten both procedure and fluoroscopy times, and offer comparable cost with TEE-guided interventions.<sup>15-17,25,28,29</sup> Additional uses of ICE may include guidance of transseptal catheterization, the placement of LAA occluder devices, the placement of percutaneous left ventricular assist device canulas, the performance of PBMV, and many others.<sup>5,7,30-33</sup> Diagnostic intracardiac imaging may be considered as an alternative to TEE in selected patients with absolute contraindications to TEE (eg, esophagectomy) or to potentially evaluate anatomic regions

**Table 2** Potential risks of ICE

Vascular

- Trauma at catheterization site
- Bleeding
- Hematoma
- Retroperitoneal bleed
- Perforation of venous structures

Cardiac perforation

- Pericardial effusion
- Tamponade

Arrhythmia

- Atrial premature beats
- AF
- Ventricular ectopy and tachycardia
- Heart block

Thromboembolism

- Venous
- Arterial

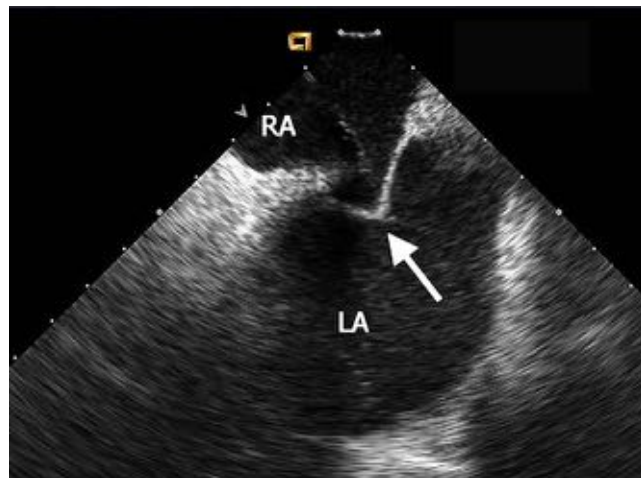
Cutaneous nerve palsy

that TEE may not be able to visualize well because of shadowing from other structures (eg, ascending aortic evaluation, which is not well seen on TEE because of tracheal shadowing in the “TEE blind spot”). The risks of ICE are listed in Table 2.

#### IV. ECHOCARDIOGRAPHY IN TRANSEPTAL CATHETERIZATION

Transseptal catheterization is performed when procedural access to the left atrium is required and is used for PBMV, antegrade aortic balloon valvuloplasty, radiofrequency ablation of AF and other left-sided arrhythmias, transseptal PFO closure, the placement of percutaneous left ventricular assist device cannulas in the left atrium, balloon or blade atrial septostomy, the measurement of complex hemodynamics (such as evaluation of a mechanical aortic valve prosthesis or critical aortic stenosis in which the valve itself cannot be crossed), and, most recently, investigational applications such as the placement of LAA occlusion devices and percutaneous mitral valve repair.<sup>34-40</sup> Traditionally, transseptal catheterization has relied on fluoroscopic guidance, in which anatomic structures are not directly visualized.

Observational studies have suggested that TTE or TEE may be helpful in performing this procedure by allowing direct visualization of the transseptal catheter and its relationship to the fossa ovalis. Although echocardiographic imaging is not invariably required for the successful performance of transseptal catheterization, it offers potential advantages over traditional anatomic and fluoroscopic guidance.<sup>7,30,41-50</sup> Anatomic variability in the position and orientation of the fossa ovalis and its surrounding structures may present specific challenges to even those interventional cardiologists with significant transseptal experience, and imaging offers increased safety, with a lower risk for cannulating other spaces adjacent to the fossa. Inadvertent puncture of the intrapericardial aorta is a serious complication of transseptal catheterization, and echocardiographic imaging reduces this risk. Similarly, imaging may decrease the time required for the transseptal puncture to be performed and minimizes the fluoroscopy time required for the procedure. In patients undergoing PBMV who are pregnant, radiation exposure can be reduced with echocardiographic guidance of the procedure, including the transseptal puncture.<sup>43</sup> Imaging may also assist those operators without significant transseptal experience who are learning the procedure.



**Figure 1** ICE. Phased-array ICE from the right atrium (RA), demonstrating the tenting of the fossa ovalis (arrow) toward the left atrium (LA) before transseptal catheterization. The length of the catheter is seen in the RA.

Early studies of TTE-guided transseptal puncture demonstrated that TTE can delineate the aorta and interatrial septum and the characteristic bulging (or tenting) of the fossa ovalis at a satisfactory location that occurs before transseptal puncture.<sup>49</sup> Saline contrast echocardiography with TTE may help confirm needle position in the right atrium before puncture and in the left atrium after puncture. TTE does not always offer sufficient imaging resolution to guide transseptal catheterization, and as such, TEE and more recently ICE have been used when imaging is required. TEE and ICE also provide the ability to choose the exact site of transseptal puncture, which is important in performing advanced mitral valve interventions for mitral regurgitation (MR) because the catheters are more difficult to manipulate and position if the transseptal crossing point is too close to the plane of the mitral valve orifice. Because ICE can be performed without additional sedation or general anesthesia, as well as with minimal additional patient risk and discomfort, it has become the standard at many centers if imaging is required only for the transseptal catheterization aspect of a procedure.<sup>7,30,42,43,45,48,50,51</sup>

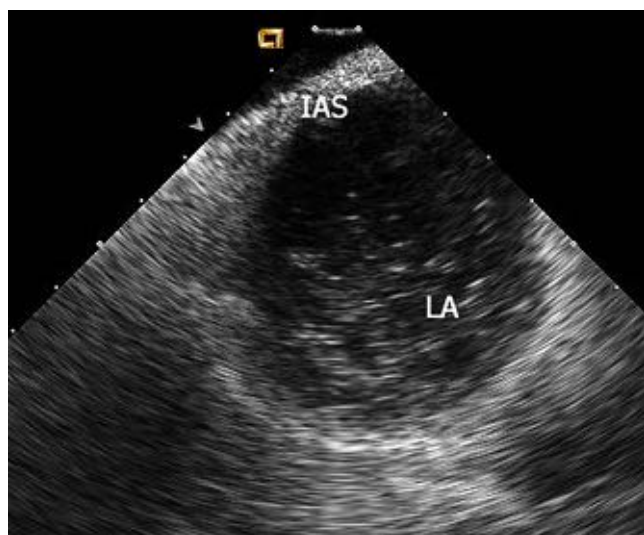
With ICE during a transseptal procedure, recognition of tenting of the interatrial septum identifies the location of the transseptal sheath before puncture (Figure 1). The possibility of perforation of the aorta, pulmonary artery, and atrial wall exists during transseptal catheterization. The injection of a small amount of microbubbles or contrast into the left atrium after the needle has crossed the septum is used to confirm left atrial access (Figure 2). Finally, a guidewire is passed into the left atrium under guidance with ICE to establish stable left atrial access (Figure 3).

**Echocardiography offers the potential for improved safety in performing transseptal catheterization, and although it is not invariably required in all procedures, its use is recommended. ICE offers the advantage of not requiring echocardiographic support when performing transseptal catheterization.**

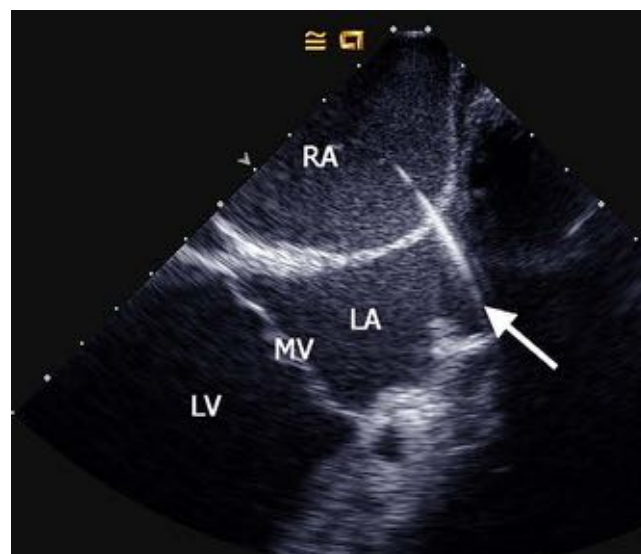
#### V. ECHOCARDIOGRAPHY-GUIDED PERICARDIOCENTESIS

Fluoroscopic guidance and electrocardiographic needle monitoring have been used to improve the safety of pericardiocentesis,<sup>52,53</sup> but





**Figure 2** ICE. Injection of a small amount of saline microbubbles confirms access in the left atrium (LA). The intracardiac echocardiographic catheter is resting on the interatrial septum (IAS).



**Figure 3** ICE. The length of the guidewire (arrow) is seen in the right atrium (RA) and the left atrium (LA) as it enters a left pulmonary vein. The mitral valve (MV) and left ventricle (LV) are seen in the far field.

complications, including damage to the liver, myocardium, coronary arteries, and lungs, have been reported.<sup>54</sup>

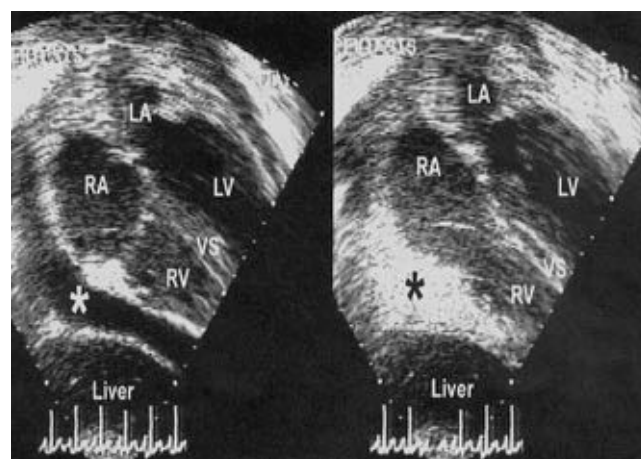
#### A. Safety and Efficacy of Echocardiography-Guided Pericardiocentesis

In a Mayo Clinic series, echocardiography-guided pericardiocentesis was successful in withdrawing pericardial fluid or relieving tamponade in 97% of the procedures.<sup>55</sup> Major complications (including chamber laceration, intercostal vessel injury, pneumothorax requiring a chest tube, sustained ventricular tachycardia (VT), bacteremia, and death) occurred in 1.2% of patients, and minor complications (including transient cardiac chamber entry, transient arrhythmia, minor pneumothorax, and vasovagal reactions) were noted in 3.2%.<sup>55</sup> The safety and efficacy of echocardiography-guided pericardiocentesis had been shown in various subgroups, including pediatric patients,<sup>56</sup> patients who were hemodynamically very unstable after cardiac perforation secondary to invasive percutaneous procedures,<sup>57</sup> postoperative patients,<sup>58</sup> and patients with malignancies<sup>59</sup> or connective tissue diseases.<sup>60</sup>

#### B. Technique of Echocardiography-Guided Pericardiocentesis

The following is a guide to only the critical aspects of echocardiography-guided pericardiocentesis. Additional procedural details are documented in the references. Two-dimensional and Doppler studies are performed to assess the size, distribution, and hemodynamic impact of the effusion and to identify the ideal entry site and needle trajectory for pericardiocentesis. The ideal site of needle entry is the point at which the largest fluid collection is closest to the body surface and from which a straight needle trajectory avoids vital structures. Because ultrasound does not penetrate air, the lungs are effectively avoided. Safety is ensured by using sheathed needles and withdrawing the steel needle upon entering the fluid space.

The left chest wall is often the location selected for entry.<sup>55</sup> The subcostal route involves a longer path to reach the fluid, passes anterior to the liver capsule, and is directed toward the right chambers of the heart.



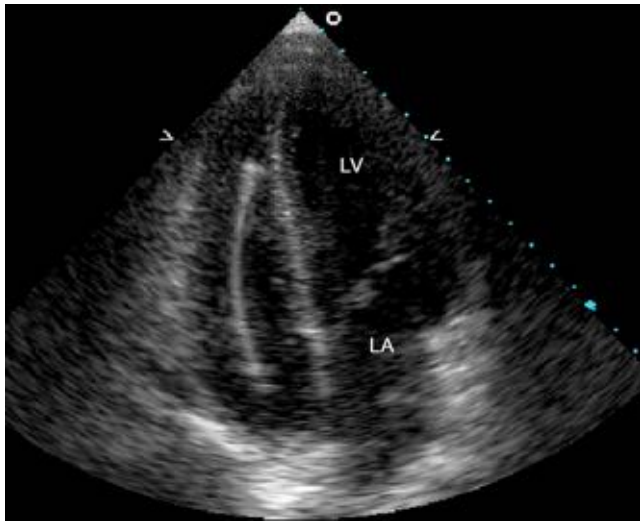
**Figure 4** TTE. Agitated saline contrast injection for assessment of position of Teflon-sheathed needle during pericardiocentesis with opacification of the pericardial space (asterisk) after saline contrast injection. LA, Left atrium; LV, left ventricle; RV, right ventricle; RA, right atrium; VS, ventricular septum.

The position of a catheter introduced into the pericardial space can be confirmed by the injection of agitated saline, and this is performed if bloody fluid has been aspirated or if the catheter position is in question. The appearance of contrast in the pericardial sac confirms its position (Figure 4). If the catheter is not in the pericardial space, it should be repositioned, or another needle passage should be attempted.

The indwelling catheter is removed once the drainage has decreased (typically to <25 mL in 24 hours) and follow-up echocardiography reveals no significant residual effusion.

#### C. Precautions and Contraindications

The contraindications to echocardiography-guided pericardiocentesis are few, and even these should be evaluated on a case-by-case basis.



**Figure 5** TTE. Apical 4-chamber view demonstrating a biptome in the right ventricle positioned along the interventricular septum before biopsy. LA, Left atrium; LV, left ventricle.

In theory, pericardiocentesis is contraindicated in the setting of myocardial rupture or aortic dissection because of the potential risk for extending the rupture or dissection with decompression.<sup>61</sup>

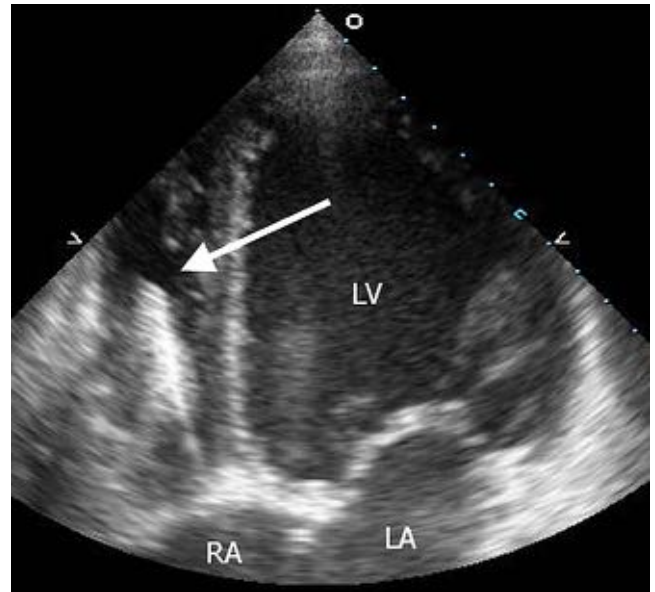
**Echocardiography-guided pericardiocentesis with extended catheter drainage can be performed safely and with efficacy at centers with staff members experienced in this technique. Using echocardiography to guide the procedure avoids the radiation associated with fluoroscopy and allows the procedure to be performed in the catheterization laboratory, at the bedside, or in the echocardiography laboratory. Increased safety and markedly lower cost compared with surgery ensure that echocardiography-directed pericardiocentesis is a procedure of choice.**

## VI. USE OF ECHOCARDIOGRAPHY TO GUIDE MYOCARDIAL BIOPSY

Endomyocardial biopsies are typically performed in the right ventricle to diagnose a wide variety of myocardial disorders, including infiltrative cardiomyopathy and cardiac transplant rejection. Although endomyocardial biopsy is often performed with fluoroscopic guidance alone,<sup>62-66</sup> some centers use 2D TTE to complement or replace fluoroscopy. Similarly, others have reported using TEE or ICE to guide biopsies of masses in the right heart and aorta in selected patients.<sup>10,67-69</sup>

With echocardiographic guidance, it is possible to provide a wider choice of biopsy sites. In addition to the ventricular septum, both the right ventricular apex and free wall can be biopsied. Moreover, this approach improves the yield of the biopsy by reducing the number of fibrotic samples due to “bites” in the same site (midventricular septum). This approach may also reduce the likelihood of perforation and damage to the tricuspid valve.<sup>66</sup> Other potential advantages of echocardiography-guided endomyocardial biopsy include the reduction of radiation exposure and portability.

Optimal views on TTE for guiding right ventricular biopsies include the apical 4-chamber view and the subxiphoid 4-chamber view (Figures 5 and 6). The transducer may be positioned more medially (midclavicular line) to optimally visualize the right ventricle during



**Figure 6** TTE. Apical 4-chamber view demonstrating a biptome (arrow) in the right ventricle in a suboptimal position as it appears free in the right ventricular cavity. Echocardiography facilitates recognition of nonideal biopsy site and repositioning of the biptome. Note, however, that the tip of a catheter cannot always be visualized with certainty. LA, Left atrium; LV, left ventricle; RA, right atrium.

biopsy. Optimal views on TEE include the midesophageal 4-chamber view, as well as the transgastric short-axis and long-axis views. ICE from either the right atrium or the right ventricle can be used for the guidance of right ventricular biopsy. Note, however, that the tip of a catheter cannot always be visualized with certainty.

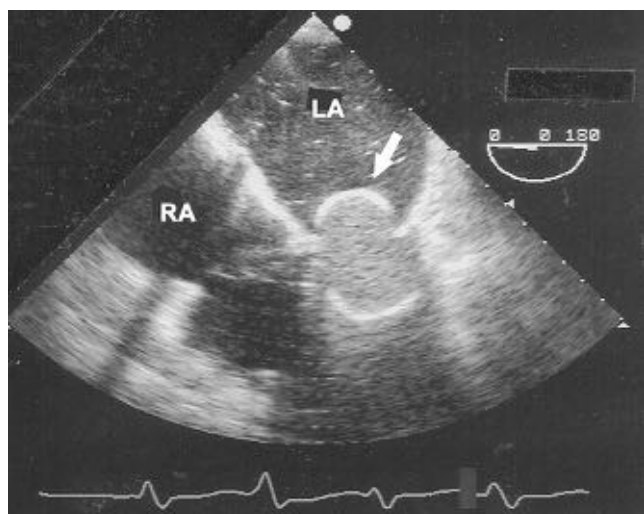
Other limitations to the use of echocardiography for guiding myocardial biopsy include the difficulty in performing TTE in patients in the catheterization laboratory who are in the supine position and the difficulty in imaging patients such as those with chest tubes and bandages, obesity, or chronic lung disease. TEE and ICE overcome these limitations in image quality, although with the need for additional echocardiography physician support and sedation (for TEE), as well as additional cost and attendant vascular risks (for ICE).

**Echocardiography, particularly TTE, is useful as an adjunctive imaging modality in patients undergoing intracardiac and intravascular biopsy procedures. Although TEE and ICE may offer improved imaging over TTE, the additional risk and cost must be outweighed by significant procedural benefits, and the modalities are recommended for use only in highly selected patients.**

## VII. ECHOCARDIOGRAPHIC GUIDANCE OF PERCUTANEOUS TRANSVENOUS BALLOON MITRAL VALVULOPLASTY

### A. General Imaging Considerations

PBMV is performed with fluoroscopic guidance alone at many centers, but radiographic anatomic landmarks can mislead even experienced operators. Kronzon et al<sup>49</sup> recommended 2D TTE (in the apical 4-chamber and parasternal short-axis views) as a useful adjunct to fluoroscopy during transseptal cardiac catheterization during



**Figure 7** TEE. Midesophageal 4-chamber view demonstrating the valvuloplasty balloon (arrow) as it is inflated across the mitral valve. LA, Left atrium; RA, right atrium.

PBMV. Pandian et al<sup>70</sup> advocated the use of subcostal views to assist PBMV as well. Disadvantages of TTE include that it interrupts the flow of the procedure, potentially interferes with sterile technique, and provides inadequate imaging in some patients.

TEE is an alternative to TTE for guiding PBMV<sup>71-75</sup> (S. A. Goldstein, personal communication). The role of TEE before and during balloon mitral valvuloplasty is well established. TEE can be used for patient selection<sup>76,77</sup> and for all aspects of online procedural guidance<sup>71-75</sup> (S. A. Goldstein, personal communication). It is used to guide the transseptal catheterization and is generally superior to TTE in this regard. TEE is also superior to TTE when it is used to exclude left atrial and LAA thrombus, and it facilitates wire and balloon position before and during inflation (Figure 7). TEE is used to measure transmitral gradients and mitral valve area and to assess the degree of MR immediately after each balloon inflation. Finally, TEE can be used to look for complications of PBMV, such as severe MR, pericardial effusion or tamponade, dislodgement of thrombus, and residual ASD. Moreover, some authors have suggested that the use of online TEE can both reduce fluoroscopic and procedure time and improve results<sup>71-75</sup> (S. A. Goldstein, personal communication).

ICE provides another alternative for online guidance of PBMV.<sup>32,48,78</sup> It provides an excellent view of the fossa ovalis and can be used to guide the transseptal puncture.<sup>48</sup> Newer phased-array intracardiac echocardiographic catheters provide pulsed-wave, continuous-wave, color flow Doppler, and Doppler tissue imaging. Thus, like TEE and TTE, ICE can facilitate the immediate assessment of the results of the valvuloplasty, including the transmitral gradient, the mitral valve area, the presence or worsening of MR, and the detection of complications, such as cardiac perforation, tamponade, or a torn mitral valve. Like TEE, ICE does not interfere with the catheterization process and can be used for each of the sequential tasks needed to perform mitral valvuloplasty.<sup>32,78</sup> The relative value of ICE compared with TTE and TEE has yet to be determined. Cost is a significant consideration, because a phased-array intracardiac echocardiographic catheter costs approximately \$2,500 to \$3,000, for a catheter that may only be used up to 3 times. Visualization of left-sided structures on ICE may be inferior or superior to that provided by TEE or TTE, depending on the chamber from which the catheter is providing images. In particular, the LAA may not be well visualized

when intracardiac echocardiographic images originate only from the right atrium, and the presence or absence of an intracardiac thrombus cannot be confirmed. Imaging from the left atrium or pulmonary artery may overcome this limitation. On the other hand, ICE visualizes the mitral valve structures, especially the subvalvular structures of chordae tendineae and papillary muscles, with superior spatial resolution compared with TEE or TTE.<sup>78</sup> Images should be transmitted to a monitor that is easily viewed by the catheterization operator, usually adjacent to the fluoroscopic monitor.

## B. Immediate Assessment of Results

Online echocardiography during the procedure is ideally suited for the immediate assessment of the results of PBMV.<sup>7</sup> The adequacy of valvulotomy can be determined by evaluating the maximal mitral leaflet separation and by continuous-wave Doppler determination of the mean mitral gradient and mitral valve area. With TEE and ICE in addition, the pulmonary venous flow profile can be assessed, with a more rapid diastolic deceleration expected after successful PBMV.<sup>79</sup> Finally, new or worsening MR is sought by color Doppler. Decisions about the adequacy of the procedure versus the need for further dilation should be made on the basis of both echocardiographic and hemodynamic data.

## C. Early Detection of Complications

Although uncommon, serious complications do occur with PBMV. The majority of these (eg, the development of severe MR, cardiac perforation and tamponade, ASDs) can be identified accurately and quickly by online echocardiography during the procedure. An increase in the degree of MR occurs in approximately half of patients after PBMV<sup>49,70,80,81</sup> (S. A. Goldstein, personal communication). In most, this increase is mild, but the reported incidence of the development of severe MR is 1% to 6%.<sup>74</sup> Acute, severe MR may be caused by tear or rupture of the mitral leaflets, by ruptured chordae tendineae, or rarely by avulsion of a papillary muscle.<sup>82</sup> Each of these can be detected readily by echocardiography, particularly by TEE or ICE. Moreover, the presence and severity of MR can be determined without the need for ventriculography.

The incidence of cardiac tamponade during PBMV has been reported to be between 0% and 9%.<sup>74,83</sup> Perforation of the atrial free wall at the time of transseptal puncture is the most common cause of bleeding into the pericardial space. Echocardiographic detection of such fluid is immediate and permits rapid pericardiocentesis before major hemodynamic compromise occurs. Perforation of the left ventricle, especially with the double-balloon technique, has also been reported. Online TEE can lead to rapid detection and treatment of this potentially life threatening complication.<sup>83</sup>

The reported incidence of ASD resulting from PBMV is highly variable depending on the technique used for its detection. A left-to-right shunt at the atrial level is detected by oximetry in only 8% to 25% of patients.<sup>73</sup> TTE can detect an atrial shunt after PBMV in 15% to 60% of patients. TEE, a more sensitive technique, has been reported to detect shunts in as many as 90% of patients. ICE, with its excellent visualization of the fossa ovalis, should offer comparable sensitivity. Because the defects are usually small and because left atrial pressure in these patients is high, the small left-to-right shunting jets are easily detected by transesophageal echocardiographic or intracardiac echocardiographic color Doppler imaging. The creation of a small ASD should be considered an expected consequence rather than a true complication in the majority of patients.



#### D. Limitations

Several investigators have pointed out that immediately after PBMV, Doppler evaluation of mitral valve area by the pressure half-time method should be interpreted with caution because of a reduced correlation with hemodynamic measurements obtained by cardiac catheterization. This discrepancy may be related in part to acute alterations in left atrial and left ventricular compliance and a reduced initial peak mitral valve gradient.

#### E. Effect on Outcomes

The use of echocardiographic guidance during the procedure may improve the procedural success and complication rates.<sup>84,85</sup> Online imaging can provide more precise targeting of the transeptal needle toward the fossa ovalis region of the atrial septum, thereby minimizing the likelihood of perforation.<sup>75,83,86,87</sup> In addition, imaging not only has the potential to reduce the risk for procedural complications but may also allow immediate identification of these complications should they occur, permitting more prompt correction. Moreover, echocardiographic guidance may reduce procedural and fluoroscopic time<sup>83</sup> (S. A. Goldstein, personal communication). Park et al<sup>83</sup> evaluated fluoroscopic guidance only (n = 64) and patients who underwent PBMV with online transesophageal echocardiographic guidance (n = 70). The procedural time was significantly shorter in the latter group ( $99 \pm 48$  vs  $64 \pm 22$  minutes;  $P < .0001$ ). The average fluoroscopic time was also shorter in the TEE-guided group ( $30 \pm 17$  vs  $19 \pm 15$  minutes), but this was not statistically significant ( $P = .25$ ). Echocardiographic guidance may also reduce the risk for worsening MR as a result of the better assessment of the number of balloon inflations required and better positioning of the balloon catheter. Further studies are required to validate the incremental safety and efficacy of echocardiographic guidance to supplement or replace fluoroscopic guidance of PBMV.

**Echocardiography provides significant benefit in percutaneous balloon valvuloplasty for mitral stenosis and is recommended for the assessment of patient selection and to assess the adequacy of results. Online intraprocedural echocardiography offers significant advantages compared with fluoroscopic guidance, in monitoring procedural efficacy and monitoring for complications. TEE can also be used to guide the procedure. TTE is recommended for procedural guidance, monitoring for complications, and to assess the adequacy of results, when preprocedural TEE has already been performed. ICE can be used for procedural guidance and provides imaging that is comparable with TEE.**

### VIII. ECHOCARDIOGRAPHIC GUIDANCE OF ATRIAL SEPTAL DEFECT AND PATENT FORAMEN OVALE CLOSURE

#### A. Introduction

Percutaneous transcatheter closure of ASDs and PFO is an increasingly attractive alternative to surgical repair. These procedures are widely performed for hemodynamically significant left-to-right shunting, to prevent recurrent paradoxical embolism, and for the platypnea-orthodeoxia syndrome. A variety of different approaches are used to guide PTC of ASDs and PFO, each with unique advantages and disadvantages. These include primary fluoroscopic guidance and echocardiographic guidance with TTE, TEE, and, most recently, ICE.<sup>15,17,20,25,27,29,88-90</sup>

#### B. Echocardiographic Modalities

TTE, TEE, and ICE are used to evaluate and guide the percutaneous closure of PFOs and ASDs. TTE has the advantage of offering multiple planes to evaluate the device and atrial septum, but it has limited ability to interrogate the lower rim of atrial septal tissue above the inferior vena cava after device placement, because the device interferes with imaging in virtually all planes. In addition, because the septum is relatively far from the transducer (relative to TEE or ICE), color imaging is suboptimal in larger patients. Some centers, however, use TTE for monitoring in all patients. In adult patients, TTE typically provides more limited imaging of the interatrial septum and surrounding structures, and as such, most adult centers typically use TEE or ICE to guide PTC.

Transesophageal echocardiographic guidance has been described extensively in adult patients and offers the advantages of providing real-time, highly detailed imaging of the interatrial septum, surrounding structures, catheters, and closure device.<sup>15,20,25</sup> TEE requires either conscious sedation, with attendant aspiration risk in a supine patient, or general anesthesia, with an endotracheal tube to minimize this risk. This approach also requires a dedicated echocardiographer to perform the TEE while the catheterization operator performs the closure procedure, as well as anesthesia support personnel if general anesthesia is used.

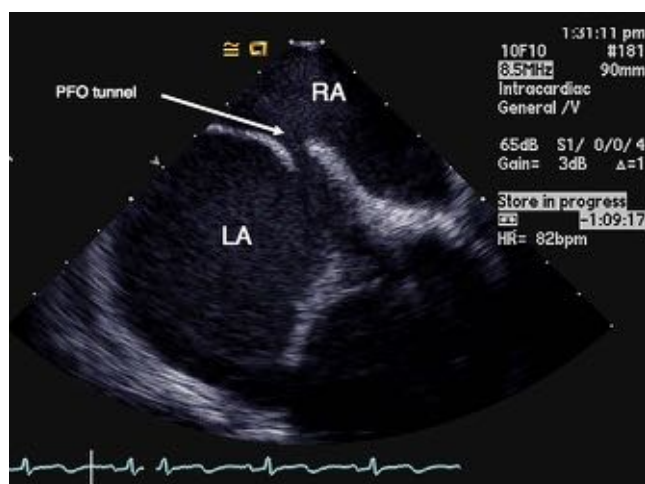
ICE provides imaging of the interatrial septum and surrounding structures that is comparable with TEE but does not require additional sedation or general anesthesia to perform. Currently available intracardiac echocardiographic systems provide a single-use 8Fr to 10Fr mechanical or phased-array intracardiac ultrasound-equipped catheter and require additional 8Fr to 11Fr venous access. The development of newer, smaller caliber catheters has allowed the use of ICE in smaller pediatric patients. In addition to obviating the need for general anesthesia in adults, ICE offers the potential to reduce the need for additional echocardiographic support, because the operator performing the percutaneous closure can also manipulate the catheter. At some centers, however, additional echocardiography expertise is used to assist in ICE during these procedures. This is particularly helpful in patients with large defects, for whom the risk for misplacement or embolization is greater. In these patients, continuous evaluation with echocardiography during device placement can prevent complications of the procedure.

Additional advantages of ICE in the guidance of PTC compared with TEE include shorter procedure and fluoroscopy times, improved imaging, and the addition of supplementary incremental diagnostic information, and as such, it is emerging as the standard imaging modality for evaluation of the interatrial septum and for guiding PTC.<sup>15,17,20,27,29,88</sup> ICE can be used as the primary imaging modality, without supplemental TTE or TEE. Recently, ICE has been shown to offer comparable cost with TEE-guided PTC when general anesthesia is used for those undergoing TEE-guided closure.<sup>15,17,20,25,27,29,88,89,91</sup>

#### C. General Procedural Considerations

A number of different devices are currently in use for PTC, and the method of implantation is variable and unique to each device. The mechanism of closure of all devices ultimately involves stenting the defect, with subsequent thrombus formation and neoendothelialization along the interatrial septum.

Preprocedural assessment of the interatrial septum includes evaluation of the entire interatrial septum and surrounding structures. A PFO is defined as any anatomic communication through the foramen ovale, and a stretched PFO is defined when resting or intermittent left-to-right



**Figure 8** ICE. Phased-array ICE from the right atrium (RA), demonstrating the bulging of septum primum, which opens a large PFO (arrow) into the left atrium (LA).

flow on color Doppler imaging is seen (Figure 8). Right-to-left shunting through a PFO is typically demonstrated by the injection of agitated saline microbubbles at rest and with provocative maneuvers such as the Valsalva maneuver. An atrial septal aneurysm is typically defined as 11 to 15 mm of total movement of a 15-mm base of atrial septal tissue.

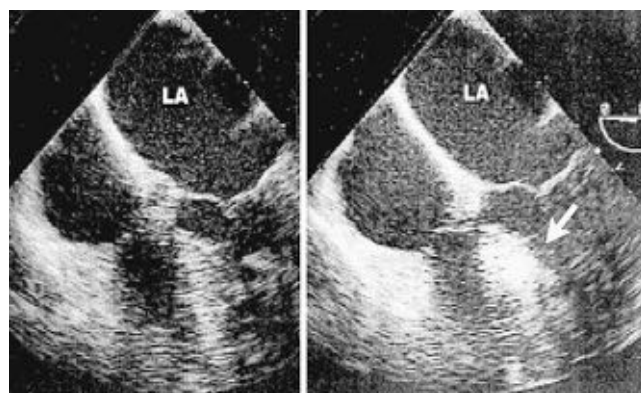
Echocardiography offers the ability to define ASD type (ostium secundum, ostium primum, sinus venosus, or coronary sinus), maximum ASD diameter, and defect number if multiple defects are present. Presently, only ostium secundum ASDs are amenable to PTC, and an interatrial septum that contains multiple small fenestrations may not be suited to PTC with currently available devices. Defects up to 40 mm in diameter have been closed successfully via PTC, as have multiple ASDs and those associated with atrial septal aneurysms. Associated abnormalities of the pulmonary veins, inferior vena cava, superior vena cava, coronary sinus, and atrioventricular valves should be excluded. Consideration of the size of the atrial septal rim of tissue surrounding the defect is important in evaluating patients for successful PTC, and a surrounding rim of 5 mm is generally considered adequate. The inferior and superior rims may be particularly important for successful PTC, although small series have reported success in patients with deficient rims.<sup>90</sup> In smaller patients, assessment of total septal length is an important additional consideration, because this may limit the size of the device that can be placed successfully.<sup>92</sup>

**Echocardiography is recommended to guide PTC of PFO and ASDs. All modalities of echocardiography can be used, but ICE should be considered when suitable expertise is available. Numerous factors must be considered when choosing the ideal echocardiographic modality for procedure guidance, including the patient population, specific anatomy, and local expertise.**

## IX. ECHOCARDIOGRAPHIC GUIDANCE OF ALCOHOL SEPTAL ABLATION FOR HYPERTROPHIC OBSTRUCTIVE CARDIOMYOPATHY

### A. Introduction and Indications

Surgical myectomy for severely symptomatic patients with hypertrophic obstructive cardiomyopathy (HOCM) has been performed for



**Figure 9** TEE. Midesophageal 4-chamber view before (left) and after (right) the injection of contrast (small arrow). A radiographic contrast agent is used in this illustration and may be used in patients to demonstrate the perfusion territory supplied by the chosen septal perforator; this is an alternative to the use of an ultrasound contrast agent.

>40 years but is performed at only a relatively small number of experienced centers with acceptable morbidity and mortality.<sup>93,94</sup> Atrial-ventricular sequential pacing is an alternative to surgical myectomy, but after initial enthusiasm, randomized controlled trials reported less favorable results, with incomplete gradient reduction and a lack of sustained symptomatic improvement.<sup>95</sup> A second alternative to surgery is the more recently developed alcohol septal ablation technique.<sup>96</sup> This technique involves the introduction of alcohol into a target septal perforator branch of the left anterior descending coronary artery for the purpose of producing a myocardial infarction within the proximal ventricular septum.

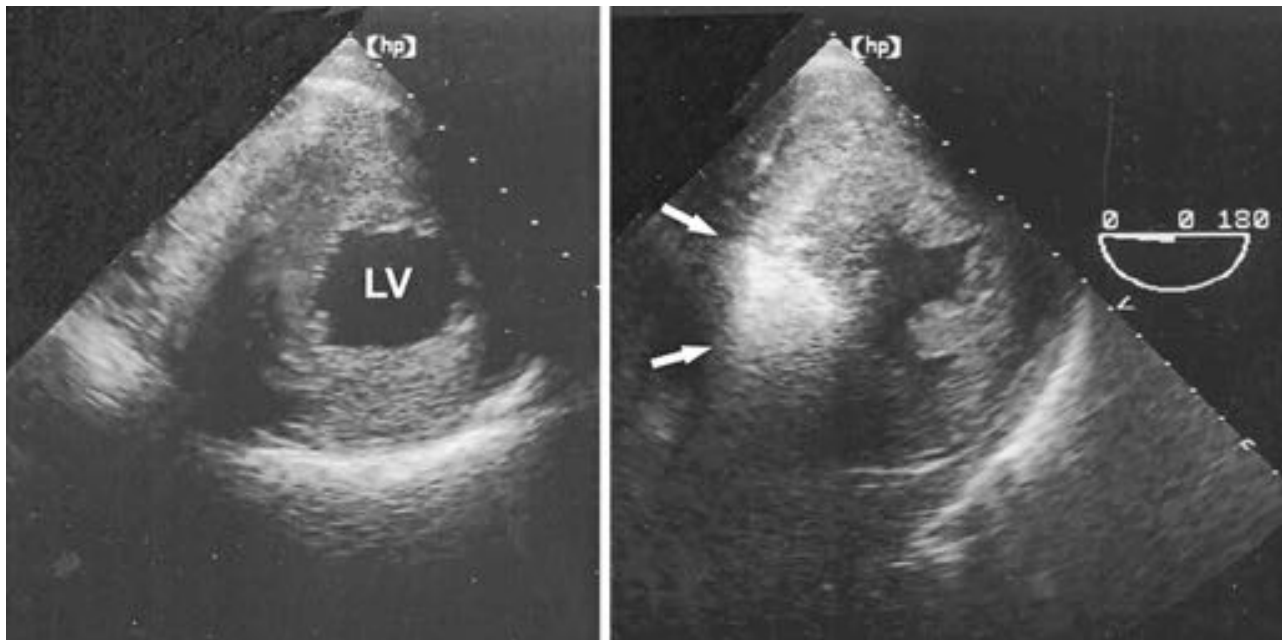
This procedure, which results in a localized septal infarction, was referred to as nonsurgical septal reduction therapy by Sigwart,<sup>96</sup> who first described the procedure in 1995. Since the introduction of this procedure by Sigwart, a number of other groups have applied and modified this technique with good results.<sup>97-101</sup> Perhaps the most important modification has been the use of myocardial contrast echocardiography to delineate the vascular distribution of the individual septal perforator branches of the left anterior descending artery. In fact, the use of contrast echocardiography is paramount to the success of this procedure.<sup>102</sup>

TTE is the conventional approach for intraprocedural echocardiographic monitoring of transcatheter ablation of septal hypertrophy for HOCM. Some laboratories prefer TEE because it provides more precise imaging of the subaortic anatomy of the left ventricle than TTE.<sup>103</sup> ICE is a third imaging alternative for use during this procedure.

### B. Methods for Guidance

Because the septum is perfused through a number of septal perforators, with significant individual variation and overlap in distribution, exact delineation of the vascular territory of each perforator artery is important to determine the vessel or vessels that should receive the alcohol injection.<sup>104,105</sup> To determine that the presumed target septal perforator was correctly selected, intraprocedural myocardial contrast echocardiography should be performed. After verification of the correct balloon position and the hemodynamic effect of balloon occlusion, 1 to 2 mL of diluted echocardiographic contrast agent followed by a 1-mL to 2-mL saline flush is injected through the





**Figure 10** TEE. Transgastric short-axis view before (*left*) and after (*right*) the injection of ultrasound contrast (*arrows*) demonstrating the site of perfusion of the selected septal perforator. Ultrasound contrast is used not only to define the desired perfusion area of the target septal perforator but also to exclude perfusion of unwanted areas, such as the papillary muscles, the distal (apical) portion of the ventricular septum, and the right ventricle. This transgastric short-axis view is particularly useful to delineate the papillary muscles. LV, Left ventricle.

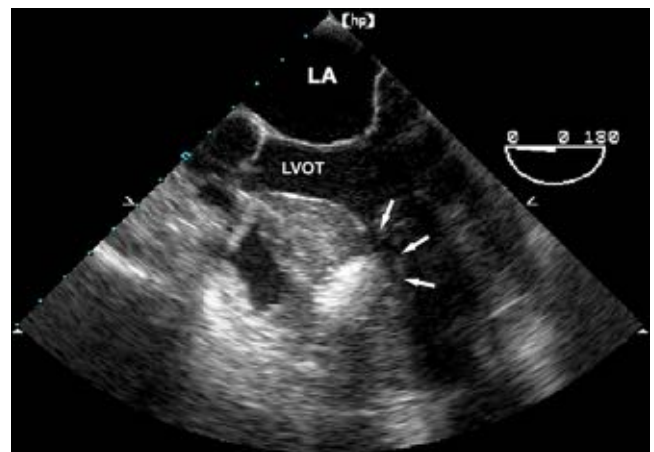
inflated balloon catheter under continuous TTE or TEE. The echocardiographic contrast agent should be diluted with normal saline to optimize myocardial opacification and to minimize attenuation. Details of the dilution vary with the contrast agent used. Agitated radiographic contrast can be used instead of an ultrasound contrast agent (Figure 9).

The optimal target territory of the basal septum should include the color Doppler–estimated area of maximal flow acceleration and the area of systolic anterior motion–septal contact without contrast opacification of any other cardiac structures (Figures 9–11). After myocardial contrast echocardiography confirms that the presumed target septal perforator perfuses the desired region of the basal septum, alcohol can be administered.

If TTE is used, apical 4-chamber and 3-chamber (long-axis) views should be used. These views may be supplemented with parasternal long-axis and short-axis views. If TEE is used, the apical 4-chamber view (at 0°) and the longitudinal view (usually 120°–130°) should be used. These views may be supplemented by the transgastric short-axis view to help ensure that no erroneous perfusion of the papillary muscles occurs. The deep transgastric view, which resembles an apical 4-chamber transthoracic view, is useful for measuring the intracavitary gradient with TEE.

### C. Immediate Assessment of Results

Intraprocedural echocardiography is also useful for evaluating the results of the procedure in the catheterization laboratory.<sup>103,105,106</sup> The region of the basal septum, which is infarcted by the infused alcohol, is typically intensely echo dense. In addition, this region of the septum should have reduced thickening and contractility.<sup>103</sup> There should also be resolution or improvement of the degree of systolic anterior motion of the anterior mitral leaflet and usually reduction in the de-



**Figure 11** TEE. Midesophageal 4-chamber view after the injection of contrast (*arrows*), demonstrating that the site of perfusion of the selected septal perforator is too apical and therefore not related to the point of septal contact of the mitral valve. LA, Left atrium; LVOT, left ventricular outflow tract.

gree of MR. In addition, there should be elimination or reduction of the intracavitary gradient. This is readily measured by TTE and can often be measured by TEE with a deep transgastric view or midesophageal long-axis view.

### D. Outcome Data

Several studies have suggested a favorable impact of echocardiographic monitoring during this procedure.<sup>102,105,107</sup> Echocardiographic monitoring of percutaneous transluminal septal myocardial

ablation has resulted in the reduction of the amount of injected alcohol and the number of occluded septal branches.<sup>102</sup> Online echocardiography may also reduce the need for repeat interventions with occlusions of several septal branches, thus avoiding unnecessary enlargement of the septal scar with all of the associated potential negative consequences for left ventricular systolic and diastolic function.

Another important advantage of myocardial contrast echocardiography during the procedure is that opacification of myocardium distant from the intended target septal area can prevent erroneous instillation of alcohol into unwanted territory, such as the papillary muscle, left ventricular free wall, or right ventricle (Figure 11).

A recent American College of Cardiology and European Society of Cardiology consensus document on HOCM stated that “myocardial contrast echocardiography guidance...is important in selecting the appropriate septal perforator branch.”<sup>108,109</sup> Nevertheless, a randomized multicenter study with respect to this issue does not exist.

**Echocardiography is recommended in selecting the appropriate septal perforator during alcohol injection during septal ablation for HOCM. Both TTE and TEE can be used. They provide an assessment of immediate procedural results and allow monitoring for complications.**

## X. INTRACARDIAC ECHOCARDIOGRAPHY AND CARDIAC ELECTROPHYSIOLOGY

### A. Anatomy-Dependent Arrhythmias

Catheter-based ICE has been applied extensively in cardiac electrophysiology laboratories to guide ablative procedures. To a large degree, this early adoption has occurred because of the critical dependence of specific cardiac arrhythmias on underlying anatomy. For example, accessory atrioventricular pathways bridge from atrial to ventricular tissue across the mitral or tricuspid annulus, requiring selective energy delivery at a specific anatomic location to successfully eliminate related supraventricular tachycardias. In addition, clarification of the pathophysiology of typical atrial flutter demonstrated that the cavotricuspid isthmus was a critically important component of the underlying reentrant circuit.<sup>110,111</sup> Because of this, the nomenclature of this arrhythmia was changed to “isthmus-dependent, counterclockwise atrial flutter.” It follows that the ability to visualize specific anatomic structures should be of substantial importance in the non-pharmacologic treatment of these arrhythmias.

### B. Phased-Array Imaging

The application of phased-array technology with a transesophageal probe was shown in early studies to be useful for imaging during VT ablation<sup>112</sup> and the treatment of accessory pathway-mediated tachycardias.<sup>113-115</sup> The miniaturization of this technology and application via intracardiac catheters allowed deeper penetration and standard 2D visualization and Doppler imaging of both right-sided and left-sided structures from within the right heart.<sup>116</sup> Long-axis imaging with phased-array technology has been particularly suited for the electrophysiology laboratory environment. Within the context provided by forward imaging, intracardiac ultrasound frequently has been used to guide the insertion of catheters into specific cardiac chambers, across the cardiac valves into the ventricles, and to guide transeptal catheterization into left-heart structures, from a single imaging viewpoint or with minimal catheter rotation. Intracardiac ultrasound has been preferable to transesophageal imaging because it does not require prolonged esophageal intubation, accompanying patient

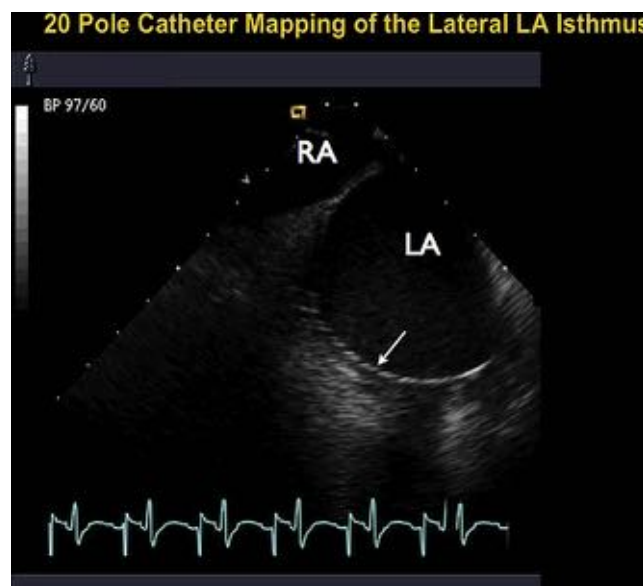


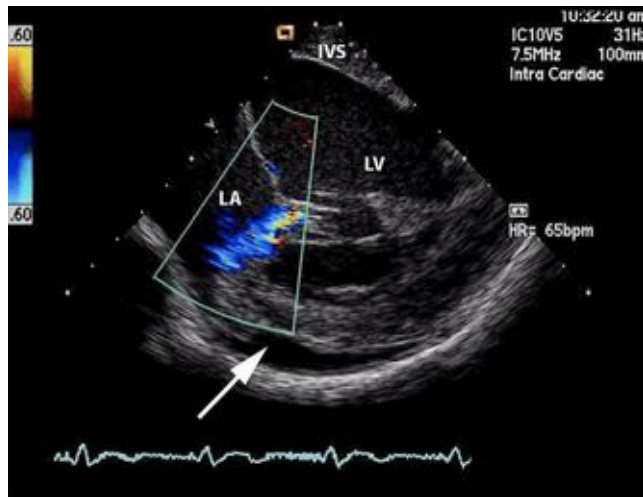
Figure 12 ICE. Phased-array ICE of long-axis view of the left atrium (LA) from the right atrium (RA). Shown is the catheter-tissue contact of a 20-electrode catheter positioned along the posterior mitral annulus (arrow).

discomfort, or the risk for aspiration. It is also routinely performed by a single interventionist, without the need for other personnel for further image acquisition and interpretation.

### C. Ultrasound-Guided Anatomic Ablation

Intracardiac ultrasound has been applied to guide the positioning of ablation catheters near specific cardiac structures for ablation of the related arrhythmia, as seen in Figure 12. The value of such intracardiac echocardiographic imaging extends to establishing a clear-cut relationship between the catheter tip and underlying tissue, a critically important determinant of ablation success. In many cases, the lesion produced in the delivery of ablation energy can be visualized in tissue adjacent to the catheter tip. This observation is of theoretical importance, because the identification of each individual lesion could facilitate the juxtaposition of subsequent energy deliveries, as required in linear ablation. This utility has also been documented in linear ablation studies from several centers.<sup>21,117-119</sup> However, the visualization of an evolving lesion is a function of the imaging frequency, the distance of the ablation site from the transducer, the catheter tip–tissue contact, the delivered energy, and the thickness of the underlying tissue. Therefore, the lesions formed by the ablation of ventricular myocardium are more readily seen than with atrial ablation.<sup>120-122</sup> Furthermore, continued energy delivery in the ablation of atrial tissue to the point of lesion visualization is not necessary for a successful outcome and may be excessive. In short, lesion visualization with B-mode imaging is insufficiently sensitive for establishing an end point for ablation. Other means of enhancing lesion detection are currently being studied.<sup>123</sup>

A variety of studies have tested the utility of intracardiac ultrasound in the setting of atrial tachycardias,<sup>124</sup> atrioventricular nodal reentrant tachycardia,<sup>125</sup> sinus tachycardia,<sup>126</sup> ventricular arrhythmias,<sup>127</sup> atrial flutter,<sup>110,121,128,129</sup> and AF.<sup>18,21,22,24,130</sup> Ablation of the cavotricuspid isthmus has been found to be 95% to 98% successful in eliminating atrial flutter simply through the identification of the anatomic site of origin of that arrhythmia.<sup>110,111</sup> Recent studies<sup>131,132</sup> have also shown



**Figure 13** ICE. Phased-array ICE from the right ventricle. Imaging through the interventricular septum (IVS) to display the left ventricle (LV) and left atrium (LA) demonstrates an emerging pericardial effusion (arrow) during an ablation procedure. MR is also shown by color Doppler mapping.

the utility of imaging the left ventricular scar that results from myocardial infarction in ablation of postinfarct VT. Typically, stable VT arises within the border zone of an infarct. In such cases, intracardiac ultrasound can be used to guide ablation and create lesion bridges from the center of the scar, across the infarct border zone, on to a neighboring electrically inert cardiac structure such as the mitral annulus. Such lesions interrupt the VT circuit that passes through the spared tissue immediately around the infarct, such as the submitral valve isthmus in the setting of inferior wall infarction.<sup>133</sup> Linear ablation along the border of an infarction, such as is required for ablation of fast, unstable VT, has also been facilitated by direct imaging.<sup>131</sup> Such left ventricular imaging is best conducted from below the tricuspid valve from a venue near the right ventricular outflow tract. From this position, both long-axis and short-axis images of the left ventricle can be created.<sup>116</sup>

#### D. Ablation of AF

ICE has been used most consistently for the guidance of ablation of AF. This approach establishes the number and position of pulmonary veins and determines whether a left pulmonary vein antrum, formed by the confluence of the left superior and inferior pulmonary veins, is present. ICE also clarifies the branching patterns of the right pulmonary vein, guides the positioning of interventional catheters, verifies catheter tip–tissue contact, assesses underlying pulmonary vein physiology, helps in the positioning of balloon-type catheters for ablative interventions, and monitors for excessive tissue heating as manifested by the occurrence of microbubbles. Furthermore, ultrasound establishment of the venoatrial junction has recently been shown in preliminary studies to be more accurate than is possible with contrast venography.<sup>134,135</sup> Given its position in relationship to the left pulmonary veins, the location of the vein of Marshall, relevant in AF ablation, can also be identified from imaging of the “Q-tip” ridge, seen between the LAA and those pulmonary veins.<sup>136</sup>

Not only does the ultrasound beam allow identification of the underlying pulmonary vein and other relevant structures, it also enables positioning of guidance catheters, such as the circular Lasso catheter, to a position immediately at the orifice of the pulmonary vein. This is

particularly critical because these catheters have a tendency to drift into the vein, providing a false sense of the true orifice of the vessel.<sup>137</sup>

Ablation too far into a vein increases the risk for pulmonary vein stenosis and decreases the efficacy of AF ablation.<sup>138</sup> Several studies<sup>18,22,130,139,140</sup> have shown the utility of intracardiac ultrasound to guide ablation at or outside the pulmonary vein orifice, which results in increased efficacy for AF ablation.

#### E. Monitoring for Ablation-Related Complications

Microbubble formation has also been widely observed with intracardiac ultrasound imaging.<sup>21,141,142</sup> This phenomenon may be even more accurate than catheter-tip temperature monitoring for the assessment of heat generation during the ablation of cardiac tissue.<sup>142,143</sup> Nevertheless, although this finding has been proposed as an end point to guide ablation, recent studies have demonstrated that microbubble appearance frequently reflects excess tissue heating to substantially greater temperatures than reflected by catheter-tip temperature monitoring.<sup>139,141</sup> This inadvertent tissue overheating, in turn, may lead to clot, char, or crater formation; intracardiac thrombus; or even pulmonary vein stenosis. Therefore, ultrasound visualization of microbubbles is most useful for prompting discontinuation of energy delivery when microbubbles are seen.

Along this same line, intracardiac ultrasound is useful in monitoring for potential complications of ablative intervention. In addition to the observation of the untoward results of tissue overheating, several studies have recently demonstrated the utility of ultrasound for detecting thrombus formation on the interventional catheter, which could lead to either a stroke or a peripheral thromboembolic event.<sup>144,145</sup> Ongoing surveillance of the pericardium during an interventional case is useful for the early detection of an effusion (Figure 13), before its physiological relevance is manifested by tamponade physiology. Imaging from an intracardiac venue also facilitates the catheter-based treatment of the effusion.

Doppler imaging likewise has contributed in the surveillance process. Pulsed-wave Doppler imaging, available with phased-array imaging over the course of an ablation, reveals an increase in flow velocity with pulmonary vein narrowing. An increment to a level in excess of 1.6 m/s has been found to be predictive of subsequent stenosis.<sup>146</sup> In contrast, veins with lower flow velocities,  $\leq 1.0$  m/s, are unlikely to progress to any significant degree.<sup>147</sup> It is noteworthy, however, that these intracardiac Doppler flows are highly dependent on the presence of AF or catecholamines.<sup>148</sup>

**ICE is recommended for radiofrequency ablation for AF. It is used to guide transeptal catheterization, as well multiple aspects of the procedure, to monitor for complications, and to assess pulmonary vein flow before and after ablation.**

### XI. FUTURE DIRECTIONS

#### A. Echocardiography in Complex Mitral Valve Procedures (Investigational Devices)

Newer investigational percutaneous mitral valve repair systems are being developed as an alternative to surgical repair for MR, either using the concepts of the edge-to-edge repair technique developed by Alfieri et al<sup>149-151</sup> but performed with a percutaneous endovascular repair system<sup>152-158</sup> or by the performance of a percutaneous mitral annuloplasty repair with a device placed in the coronary sinus or at the level of the mitral annulus. A variety of delivery approaches for these devices have been proposed. For example, an endovascular mitral repair system uses a steerable guide catheter to precisely



manipulate and position a clip that approximates the middle anterior and posterior leaflet scallops of the mitral valve, thus reducing or eliminating MR.<sup>155</sup> This system is currently being investigated in humans in phase I and II trials. Additional percutaneous mitral repair devices that use the concept of edge-to-edge repair are also being developed.

The delivery of the percutaneous edge to edge mitral valve repair system has 5 steps that require echocardiographic guidance: transseptal catheterization, alignment of the clip delivery system perpendicular to the plane of the mitral valve and centered with reference to the line of coaptation, alignment of the clip with the open arms perpendicular to the coaptation line of the mitral valve, closing of the arms and approximation of the tips of the mitral valve, and release of the implant device. A combination of TEE and supplemental TTE has been used to guide the procedure.

Other coronary sinus and mitral annular devices are also being developed to perform percutaneous mitral annuloplasty repair, thereby reducing MR by enhancing mitral coaptation. TEE or ICE can be used to guide cannulation of the coronary sinus ostium, place the device, monitor for procedural complications, and assess the degree of MR and transmitral gradients before and after the procedure.

#### B. Role of Echocardiography in the Placement of LAA Occluders (Investigational Devices)

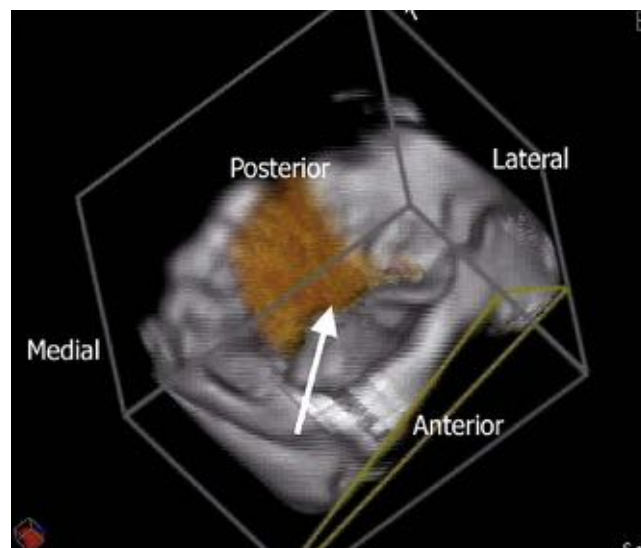
The majority of thromboemboli in AF arise in the LAA.<sup>159-161</sup> That observation led to the hypothesis that functional obliteration of the LAA could prevent stroke. For this reason, surgeries for several indications often include prophylactic intraoperative ligation of the LAA,<sup>162,163</sup> and some have recommended LAA ligation in all patients having cardiac surgery, regardless of the indication.<sup>164</sup>

A percutaneous transcatheter approach for the prevention of cardioembolic stroke in patients with AF has been proposed, by the placement of an implantable prosthetic device that seals that the communication between the LAA and the left atrium. Initial testing in animals<sup>31</sup> and humans<sup>165</sup> and, more recently, anatomic and hemodynamic data<sup>166</sup> have suggested successful occlusion and stroke prevention. A percutaneous LAA transcatheter occlusion device was the first device tested in humans; ultimately, the trials of this first device were halted because of increased morbidity and mortality. TEE had been used in all published human trials of this device. A newer device has been described.<sup>167</sup> This nitinol metal device is designed to be placed in the LAA via a percutaneous transcatheter approach by a standard transseptal approach with fluoroscopic and TEE guidance. TEE is important in sizing the ostium of the LAA and selecting an appropriately sized device for implantation.

After device release, TEE is repeated to confirm the proper deployment of the device and to assess for procedural complications. The device is examined for stability and leakage. Atrial septal examination is performed to look for an ASD; a small residual defect is common after the procedure. The pericardium is reevaluated for effusion.

#### C. 3D Echocardiography

A new application of echocardiography, 3D imaging, offers the potential to contribute significantly to interventional procedures. For example, myocardial biopsy has been performed with 3D imaging as a guide for biptome position (as opposed to the standard approach with fluoroscopy). In one study of 63 routine right ventricular biopsy procedures in cardiac allograft recipients, 3D imaging was deemed feasible, and improved localization of the biptome was observed, with the potential to improve cardiac biopsy efficacy and safety.<sup>168</sup>



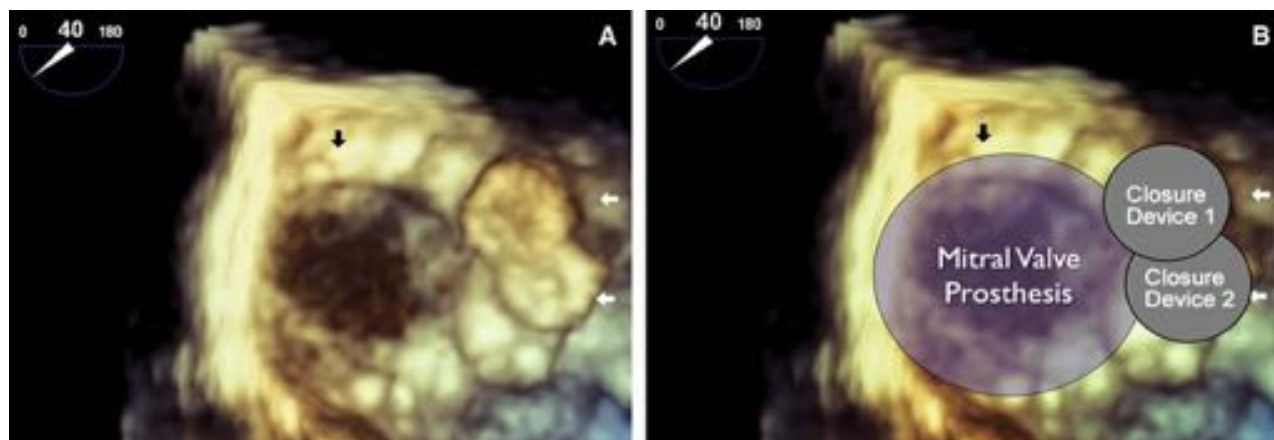
**Figure 14** TEE. Reconstructed 3D image of the left atrial surface of the mitral valve in a patient with severe MR originating from nearly the entire coaptation surface (arrow indicating red flow into the left atrium on color mapping). Anatomic coordinates are indicated for reference.

Mitral valve anatomy may be better studied with 3D imaging than with 2D imaging (Figure 14), and therefore, 3D imaging can play a significant role in the planning of surgical or percutaneous approaches to mitral valve repair<sup>169-171</sup> (Figure 15). Human studies with intraoperative 3D TEE have shown excellent correlation with surgical findings (94% [34 of 36 patients]) in the correct identification of scallop or segment prolapse.<sup>171</sup>

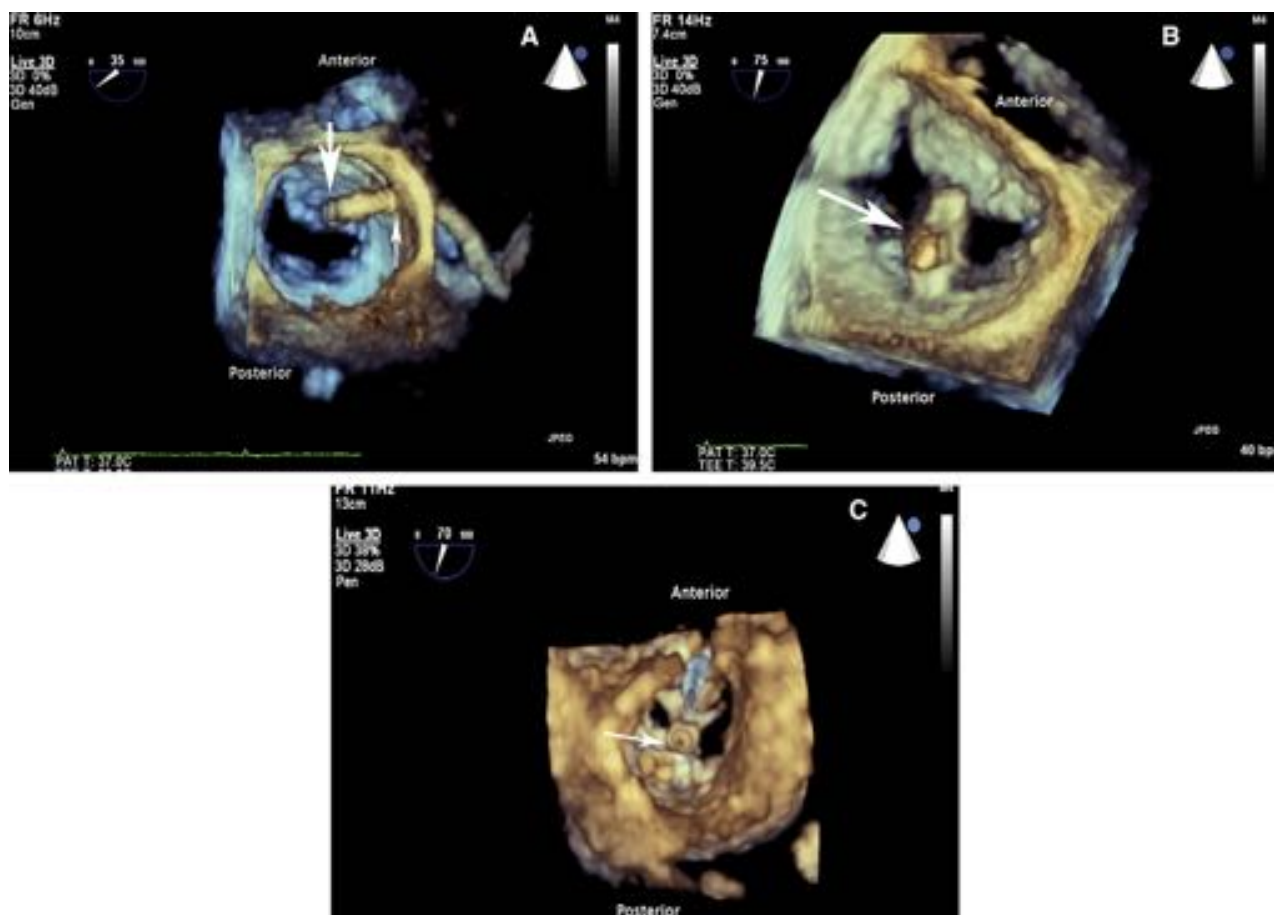
Others have found incremental value from 3D TEE and TTE over 2D echocardiography for the selection of appropriate patients and the accurate visualization of postprocedural commissural splitting and leaflet tears in patients undergoing PBMV.<sup>172,173</sup> Similarly, it is expected that 3D echocardiography will play a role in the planning of percutaneous mitral repair of MR, such as that shown in Figure 16.<sup>174</sup>

The use of percutaneously delivered devices for ASD or PFO repair is increasing. Three-dimensional imaging allows for accurate anatomic assessment before the procedure and can localize the closure device during the procedure in relation to other cardiac structures, potentially enhancing success and possibly decreasing the complication rate.<sup>175</sup> In 40 of 41 patients (98%) undergoing device ASD closure, 3D images of defects were obtained, and these images more accurately assessed ASD size (using balloon sizing as the "gold standard") than did 2D TEE. Additionally, device position was more accurately assessed with 3D imaging.<sup>176</sup> Real-time 3D echocardiography has also been used for accurate assessment of the morphology and efficacy of transcatheter devices used for ASD and PFO closure.<sup>177</sup> In 4 patients who underwent percutaneous closure of ASDs or PFO (3 ASDs, 1 PFO), real-time 3D echocardiography provided comprehensive anatomic assessment of ASD and PFO closure devices.<sup>177</sup>

Interventional approaches for the treatment of patients with HOCM are also increasing.<sup>101</sup> Real-time 3D echocardiography has also been successfully used to guide the surgical approach to myectomy and mitral valve repair in 10 patients in whom a "surgeon's view" by 3D echocardiography allowed refinement of the planned surgical approach.



**Figure 15** Three-dimensional TEE. **(A)** Three-dimensional image of a mitral bioprosthesis (*black arrow*) and two closure devices (*white arrows*) used to close paravalvular MR. **(B)** Explanatory overlays added. The perspective is from the left atrium. It is often difficult to identify the exact site of regurgitation and also to guide interventional devices to the correct location when repairing paravalvular regurgitation using occluder devices. In this case, real time 3D imaging was critical in positioning the closure devices and defining the location and extent of the paravalvular jet.



**Figure 16** Three-dimensional TEE. Percutaneous edge-to-edge repair of MR using a clip. **(A)** Percutaneous clip being aligned over the mitral valve in the left atrium. The *large arrow* indicates a clip prior to opening, and the smaller arrow indicates a guide catheter tip. **(B)** The open "arms" of the prosthesis (*arrow*) as they are aligned perpendicularly to the line of coaptation prior to grasping of the leaflets. **(C)** Imaging from the left ventricle perspective demonstrates a closed clip (*arrow*) creating a double-orifice mitral valve repair.

# D. Echocardiography in Percutaneous Aortic Valve Replacement

Recently, percutaneous transcatheter aortic valve replacement has been described, and initial studies are presently being performed with two distinct biologic valves mounted on stents, which are crimped onto a balloon and delivered using a valvuloplasty technique.<sup>178-181</sup> These valves can be percutaneously placed via a retrograde transaortic approach or via a surgical direct transapical approach.<sup>182-184</sup> Echocardiography plays a critical role in patient selection, particularly in choosing the appropriate size of the prosthesis to be implanted. In particular, the aortic annular diameter is important in determining prosthesis size.<sup>182</sup> Small differences in aortic annular diameter and geometry have been demonstrated between TTE and TEE. During the procedure, TEE has been used to help ensure appropriate positioning of the prosthesis and to assess for paravalvular regurgitation after the valve has been implanted. Real-time 3D TEE has also been described during this procedure, but its role and incremental value compared with standard TEE are not fully known at this time.

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