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CHAPTER

Three-dimensional Echocardiography Guidance of Percutaneous Procedures

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**Snapshot**

- Fluoroscopy versus Echocardiography in Guiding Percutaneous Interventions
- Transseptal Puncture: A Common Element of Many Interventional Procedures
- Valvular Disease
- Occlusion of the Left Atrial Appendage
- Guidance of Electrophysiology Procedures
- Miscellaneous Procedures

**INTRODUCTION**

Catheter-based transcutaneous repair of both congenital and acquired cardiovascular defects has been performed by interventional cardiologists and other interventional specialists for the past half a century. This therapeutic approach was initially spearheaded by pediatric cardiologists. Atrial balloon septostomy, later referred to as the Rashkind procedure, is generally considered to be the first catheter-based transcutaneous repair procedure. The Rashkind procedure was first reported in 1971 as the initial treatment in neonates with transposition of the great arteries to improve mixing of venous and systemic blood through creation of an iatrogenic atrial septal defect (ASD).\(^1\)

In the beginning, catheter-based transcutaneous repairs were developed as less invasive alternatives to established surgical procedure but have since evolved into novel ways of treating structural heart defects. Catheter-based transcutaneous procedures to repair structural heart defects can be divided into the following groups:

- **Valvular disease:**
  - Mitral stenosis (percutaneous balloon valvuloplasty)
  - Mitral regurgitation [mitral valve clipping and transcatheter mitral valve replacement (TMVR)]
  - Aortic stenosis [transcatheter aortic valve replacement (TAVR)]
  - Closure of paravalvular prosthetic leaks
- **Device closure of cardiac shunts:**
  - Atrial septal defects [secundum ASDs; patent foramen ovale (PFO)]
  - Ventricular septal defects (VSDs) (congenital and acquired)
  - Patent ductus arteriosus (PDA)
- **Occlusion of the left atrial appendage (LAA):**
  - Intracardiac device closure of LAA
  - Epicardial suturing of LAA
- **Guidance of electrophysiology ablation procedures:**
  - Pulmonary vein isolation for atrial fibrillation
- **Miscellaneous procedures:**
  - Left ventricular (LV) pseudoaneurysm closure
  - Alcohol septal ablation for hypertrophic obstructive cardiomyopathy (HOCM)
  - Right ventricular endomyocardial biopsy.

In the interventional suites, echocardiography is typically used in conjunction with X-ray-based fluoroscopy...
in guiding catheter-based transcutaneous repairs in real time. Fluoroscopy and echocardiography images are typically presented side-by-side to interventionalists on adjacent monitors. Recently, commercial products that dynamically combine (coregister) in real-time three-dimensional (3D) ultrasound and interventional X-ray images into one are becoming available. Computed tomography (CT) and magnetic resonance imaging (MRI)—although often important in establishing the diagnosis of a structural heart defect—typically do not readily provide real-time imaging during percutaneous interventions in standard interventional suites.

Real-time 3D transesophageal echocardiography (3D-TEE) and intracardiac echocardiography (ICE) are the most useful echocardiographic techniques for real-time procedural guidance as their images are typically superior to and/or more relevant to interventionalists compared to the images obtained by either two-dimensional (2D) TEE (2D TEE) or transthoracic echocardiography (TTE). \(^2\)

In general, percutaneous coronary interventions (such as angioplasty and stenting) are not typically classified as catheter-based transcutaneous procedures to repair structural heart defects and thus will not be discussed in this chapter. The use of intravascular ultrasound techniques in the diagnosis and treatment of vascular disease is provided elsewhere in this textbook.

**FLUOROSCOPY VERSUS ECHOCARDIOGRAPHY IN GUIDING PERCUTANEOUS INTERVENTIONS**

Imaging is essential for the diagnosis, guidance, and assessments of results of all catheter-based transcutaneous procedures to repair structural heart defects. Detailed description of the basics of fluoroscopy and echocardiography is beyond the scope of this chapter; here we will discuss their advantages and shortcomings from the perspective of catheter-based transcutaneous interventional procedures.

X-ray-based fluoroscopy and contrast angiography have been historically considered as gold standards in guiding percutaneous repairs of structural heart defects. These radiographic techniques, which are very familiar to interventionalists, tend to have poor depth resolution, lack ability to differentiate between various soft tissues, and require the use of ionizing radiation and iodinated contrast agents.

While in principle TTE can be used to guide catheter-based interventions, its use is limited by both suboptimal imaging of relevant cardiac structures and by difficulties in acquiring TTE images in the sterile environment of an interventional suite.

Two-dimensional TEE and 2D ICE imaging, although extensively used during percutaneous procedure, suffer from the 2D, cross-sectional nature of their images. As a consequence, the movement of wires, catheters, and devices used during interventions cannot be tracked appropriately. In addition, neither 2D TEE nor 2D ICE can typically provide en face views of structures of interest to interventionalists. Furthermore, 2D ICE typically provides only monoplane images. It is also invasive and requires the use of expensive disposable transducers that are advanced under sterile condition into the heart via the venous system. Examples of ICE use are provided in the section on percutaneous ASD closure below.

In our practice, modern 3D-TEE imaging is the preferred echocardiographic technique for guiding interventional procedures as it provides detailed dynamic images (included en face views) of relevant cardiac structures in real time, something that is not easily achievable by any other imaging technique. \(^2\) Although 3D TEE has been around for decades (primarily as an off-line, postprocessed imaging technique), it has been revolutionized by the introduction of a 3D-TEE probe with a matrix-array transducer having 3,000 elements in the first decade of the 21st century. This approximately a 25–50-fold increase in the number of imaging elements compared with a standard 2D TEE probe has allowed for real-time 3D imaging, making 3D TEE ideally suited for guidance of cardiac interventions. General aspects of 3D echocardiographic imaging have previously been reviewed \(^4-7\) and are also discussed elsewhere in this textbook.

Three-dimensional ICE imaging is a novel echocardiographic imaging technique for the guidance of percutaneous repairs of structural heart defects. This technology has the advantage of allowing for the use of moderate sedation rather than general anesthesia typically required for TEE imaging. At present, 3D ICE provides a volume size of 90° (azimuth plane) × 22° (elevation plane), which can better view the trajectories of catheters; however, it provides limited en face views. Future improvements in ICE imaging will provide wider fields of view, which may be promising as an alternative to TEE imaging. A clinical application of 3D ICE is discussed further in the section on ASD closure.
The groove is known to surgeons as either the Waterston’s or Søndergaard’s groove.

The floor is derived from the septum primum. The fossa ovalis is surrounded by the rim (also referred to in Latin as the limbus) which is formed by the septum secundum. The location, size, and shape of the fossa ovalis varies widely among individuals. The fossa ovalis is readily distinguished on en face views of the right atrial aspect of the interatrial septum as a lighter colored ovoid crater. In contrast, the region of fossa ovalis cannot be readily recognized on the rather featureless left atrial (LA) aspect of the interatrial septum when standard image gain settings are used. However, at low gain setting, the area of fossa ovalis (which is thinner than the surrounding atrial walls) can be identified as an ovoid area of dropout, especially in patients with a concomitant atrial septal aneurysm (ASA) (Figs. 2A to D and Movie Clip 2). In individuals with PFO the opening in the floor of the fossa ovalis is present along the anterosuperior rim of fossa ovalis. In such individuals, transseptal puncture needle is often directed through the PFO opening.

On 3D TEE imaging can also readily characterize the size and the shape of the ASA, defined arbitrarily as a more than or equal to 10 mm sway of the interatrial septum in either direction from the midline. Anatomically, ASA is characterized by redundancy and floppiness of a typically enlarged fossa ovalis floor. The knowledge of an ASA is important to interventionalists; ASA may make transseptal puncture more difficult by requiring septal stretching and/or increased force to traverse the septum. These maneuvers may increase the risk for cardiac perforation during transseptal puncture.

It is important to emphasize that the term lipomatous hypertrophy of the interatrial septum is actually a misnomer as the fat accumulates not in the interatrial septum per se but rather outside of the heart in the groove between the muscular walls of the right and left atrium (Fig. 3 and Movie Clip 3). The groove is known to surgeons as either the Waterston’s or Søndergaard’s groove. Puncturing of the lipomatous hypertrophy area is dangerous as the needle exits the heart into the epicardial space.

En face 3D zoom views of the interatrial septum from the right and left atrial perspectives during tenting allow for better selection of the puncture site. Often transseptal puncture across the foramen ovale is the preferred route; however, for some procedures a puncture of a different portion of the interatrial septum may be more desirable (as, for instance, during closures of mitral paraprosthetic leaks).
VALVULAR DISEASE

Mitral Stenosis: Percutaneous Mitral Balloon Valvuloplasty

Rheumatic heart disease remains the leading cause of mitral stenosis worldwide. Rheumatic mitral stenosis is the most common form of valvular disease in the developing parts of the world. In contrast, rheumatic mitral stenosis in Japan, North America, and Northern and Western Europe is typically seen among immigrants from the less developed parts of the world. Rheumatic mitral valve disease is a progressive lifelong autoimmune-like disorder triggered by and further exacerbated by recurrent group A streptococcal infections (typically pharyngitis).21

Probably the very first description of rheumatic mitral stenosis anatomy was provided in 1668 by the British physician John Mayow (1641–1679) who recorded an “extreme constriction of the mitral orifice in a young man.”22 In 1715, Raymond Vieussens (1635–1715), a French physician, published the first comprehensive description of mitral stenosis.23 Rheumatic mitral stenosis is notable for several “firsts” in the history of medicine: it was the first valvular heart disease to be treated surgically; it was the first heart disease to be diagnosed by echocardiography,

Figs. 1A to C: 3D TEE guidance of transseptal puncture. (A and B) Biplane imaging of the interatrial septum demonstrates tenting of the interatrial septum (arrows) by the catheter containing the Brockenbrough needle. Note that the tenting occurs in the central region of the interatrial septum and away from SVC and the AV. Movie Clip 1B corresponds to this figure. (C) 3D TEE zoom image demonstrates the en face view of the right atrial aspect of the interatrial septum. The dashed line follows the limbus of the fossa ovalis. Note the location of transseptal puncture (arrow) in the superior portion of the fossa ovalis; (D) 3D TEE zoom image demonstrates the en face view of the left atrial aspect of the interatrial septum. Note the evagination of the interatrial septum into the cavity of the LA caused by the Brockenbrough needle assembly (asterisk). Movie Clip 1A corresponds to this figure (3D: three-dimensional; AV: aortic valve; IVC: inferior vena cava; LA: left atrium; MV: mitral valve; RA: right atrium; RUPV: right upper pulmonary vein; SVC: superior vena cava; TEE: transesophageal echocardiography; TV: tricuspid valve).
and it was the first valvular disease to be treated with balloon valvuloplasty.  

In the 1920s, Elliot Cutler (1888–1947) and Sir Henry Souttar (1875–1964) working at the Brigham and Women’s Hospital in Boston were the first to attempt surgical relief of rheumatic mitral stenosis using procedures that they termed “valvulotomy” and “finger dilation,” respectively. In the late 1940s, soon after World War II, techniques of rheumatic mitral stenosis surgery were rediscovered and improved by Charles Bailey and Dwight Harken who also coined the procedural terms that are still used today. Bailey called his procedure “commissurotomy” while Harken coined the term “valvuloplasty.”

In the 1950s, rheumatic mitral stenosis was the first heart disease visualized echocardiographically by Inge Edler (1911–2001) and Carl Hertz (1920–1990), inventors of echocardiography. In the 1960s, rheumatic mitral stenosis was the first valvular disease to be treated with a mechanical mitral valve by Albert Starr (born 1926) and Lowell Edwards (1898–1982). Finally, in the 1980s, Kanji Inoue of Japan developed the ingenious balloon [Inoue balloon, Toray Industries (America) Inc., San Mateo, CA,
USA] and the technique of percutaneous mitral balloon valvuloplasty (PMBV) which remains the preferred treatment for the relief of rheumatic mitral stenosis in eligible patients. In the absence of contraindications, PMBV is recommended in following instances:

- Symptomatic patients with moderate or severe mitral stenosis.
- In asymptomatic patients with moderate or severe mitral stenosis, PMBV is indicated when there is pulmonary artery systolic pressure more than 50 mm Hg at rest or more than 60 mm Hg with exercise, or when there is new onset atrial fibrillation.
- Percutaneous mitral balloon valvuloplasty may also be considered in symptomatic patient with mild mitral stenosis (valve area >1.5 cm²) when pulmonary artery systolic pressure is greater than 60 mm Hg, pulmonary artery wedge pressure greater than 25 mm Hg, or mean mitral valve gradient greater than 15 mm Hg during exercise.

Contraindication for PMBV include: unfavorable mitral valve Wilkins score (≥10; see below), more than moderate mitral regurgitation and the presence of intracardiac thrombus.

The role of 3D TEE in PMBV is three fold: confirmation of the diagnosis of mitral stenosis, possible refinement of the mitral valve Wilkins score, and guidance of PMBV per se.

Mitral valve planimetry by 3D TTE or TEE is becoming the gold standard for the anatomic assessment of the severity of mitral stenosis. The mitral valve is funnel shaped with its narrowest area located in the left atrium.
ventricle and often in a plane that is not parallel with standard imaging planes of 2D echocardiography. Using 3D echocardiography techniques of multiplane reconstructions one can overcome the limitations of 2D planimetry and measure the area of at the very tip of the mitral valve funnel. Mitral valve area can also be measured on zoomed en face views of the mitral valve either semiquantitatively using calibrated grids or even quantitatively using newer software techniques of on-image planimetry (Fig. 4A to D and Movie Clip 4).

Three-dimensional TEE may also help in calculating the mitral valve Wilkins score, an essential prerequisite for PMBV. The Wilkins score was originally developed in the late 1980s using 2D TTE and is based on mitral leaflet thickness, calcifications, and mobility as well as the thickness of the subvalvular apparatus. Each of the four categories is graded on a scale of 0 (normal) to 4 (severely abnormal). A normal mitral valve, thus, has a score of 0. The most unfavorable score is 16. PMBV is contraindicated when mitral score is more than 10. Significant thickening, calcifications, and immobility of mitral leaflets as well as significant thickening of the mitral subvalvular apparatus predispose mitral valve to leaflet tear, a known complication of PMBV that may lead to significant de novo

Figs. 4A to D: 3D TEE diagnosis of mitral stenosis. 3D TEE images obtained from a 53-year woman with rheumatic mitral stenosis who grew up in the former Soviet Union. Figures A to C demonstrate 3D TEE zoom images of the mitral valve from the left ventricular perspective. Figure D is a multiplane reconstruction image. (A) 3D TEE image demonstrates typical features of rheumatic mitral stenosis: commissural fusions (arrows) and the doming of the AML. On the accompanying Movie Clip 4, there is also diminished mobility of the PML. Figures B to D demonstrate various 3D TEE methods of calculating the mitral valve area: quantitative on-image planimetry (A), semiquantitative method using a 5 mm grid (B) and the multiplane reconstruction method (C). By all three methods, the patient has severe mitral stenosis with a mitral valve area of approximately 0.6 cm² (3D: three-dimensional; AML: anterior mitral leaflet; PML: posterior mitral leaflet; TEE: transesophageal echocardiography).
mitral regurgitation. 3D TEE may enhance the scoring through its superior ability to visualize leaflet mobility and the details of the subvalvular mitral apparatus.

Three-dimensional TEE provides guidance throughout the PMBV procedure which is performed in the following fashion. After obtained venous access (typically using the femoral vein), transseptal puncture of the interatrial septum is performed as described earlier in this chapter. Subsequently a deflated Inoue valvuloplasty balloon is brought into the left atrium through the transseptal puncture. Given its ability to visualize the LA aspect of the mitral valve en face, 3D TEE can precisely guide the positioning of the valvuloplasty balloon across the mitral valve. Once positioned across the mitral valve, the balloon is inflated under 3D TEE and fluoroscopy guidance with the intent to separate the two leaflets of the mitral valve along the commissures fused by the rheumatic process (Figs. 5A to D and Movie Clips 5A to C).

The outcome of PMBV can be assessed in real time by 3D TEE; en face views of the LV side of the mitral valve are particularly useful. The desired outcome is a controlled commissural tear which enlarges the mitral valve orifice.

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**Figs. 5A to D:** Guidance of PMBV. PMBV is the preferred method for alleviating mitral stenosis in appropriate patients. 3D TEE in conjunction with fluoroscopy provides excellent PMBV guidance. Figures A to C demonstrate 3D TEE zoom images of mitral valve from the left atrial perspective. Figure A is a fluoroscopy image. (A) Following the transseptal puncture, 3D TEE is used to guide the deflated Inoue valvuloplasty Inoue balloon into the orifice of the mitral valve. Movie Clip 5C corresponds to this figure. (B) In the next step, the balloon (arrow) is advanced through the mitral orifice and partly inflated. (C) In the final step, the balloon (arrow) is fully inflated in an attempt to relieve the mitral stenosis. Movie Clip 5B corresponds to this figure. (D) Fully inflated Inoue balloon seen on a fluoroscopy image in the anteroposterior projection. Arrows point to the balloon’s waist which should be in the plane of the mitral orifice. Movie Clip 5A corresponds to this figure (3D: three-dimensional; AML: anterior mitral leaflet; AV: aortic valve; LAA: left atrial appendage; PMBV: percutaneous mitral balloon valvuloplasty; PML: posterior mitral leaflet; TEE: transesophageal echocardiography).
and does not create de novo or worsens preexisting mitral regurgitation. 3D TEE can also visualize the mechanism of unfavorable outcome, namely a noncommissural leaflet tear often leading to significant de novo acute mitral regurgitation (Figs. 6A to D and Movie Clip 6).

**Mitral Regurgitation: Mitral Valve Clipping**

Medical management improves symptoms but does not alter the natural progression of mitral regurgitation. Current guidelines recommend surgical correction of moderate-to-severe or severe mitral regurgitation in patients with symptoms and/or evidence of LV dysfunction.\(^3\)

In general, surgical mitral valve repair is preferable over surgical valve replacement for correction of mitral regurgitation with lower hospital mortality, longer survival, better preservation of ventricular function, fewer thromboembolic complications, and reduced risk of endocarditis.\(^36,37\) To date, there are no commercially available techniques of percutaneous valve replacements for native mitral valve disease. In contrast, there is a commercially available alternative to surgical mitral valve repair, namely mitral valve clipping to treat selected forms of native mitral valve regurgitation.

**Figs. 6A to D:** Outcomes of PMBV. 3D TEE zoom images from patients with rheumatic mitral stenosis demonstrate the left ventricular aspect of the mitral valve. Figure A demonstrates severe mitral stenosis before PMBV; Figure B demonstrates the result of a successful PMBV. Note the increase in the mitral valve area due to separation of commissures of the mitral valve (arrows); Figure C demonstrates torn AML (arrow), an unfavorable outcome of PMBV which resulted in severe de novo mitral regurgitation seen in Figure D. Movie Clip 6 which corresponds to Figure D shows that the jet of mitral regurgitation is eccentric and directed laterally (3D: three-dimensional; AML: anterior mitral leaflet; PMBV: percutaneous mitral balloon valvuloplasty; PML: posterior mitral leaflet; TEE: transesophageal echocardiography).
The techniques of mitral valve repair have been pioneered in the 1970s by the French surgeon Alain Carpentier (He also coined the term “bioprosthesis” and was instrumental in developing bioprosthetic valves a few years earlier. 39). Most mitral valve repair techniques rely on leaflet reduction, chordal alteration, and annuloplasty ring insertion. These complete repairs cannot be replicated yet with current commercially available percutaneous techniques although many are in development. 40

In the 1990s the Italian surgeon Ottavio Alfieri developed a simple technique for surgical correction of mitral valve regurgitation that entails the placement of a surgical stitch to approximate the free edges of the leaflets at the site of regurgitant jet origin. Typically the stitch is placed centrally between A2 and P2 scallops of the mitral valve which results in a double-orifice mitral valve. Alfieri called his technique “edge-to-edge repair” but the technique has since become known colloquially as the Alfieri stitch. 41, 42

Mitral valve clipping is essentially the percutaneous version of the edge-to-edge surgical repair. Mitral valve clipping using the MitraClip® device (Abbott Vascular, Abbott Park, IL, USA) is approved for general use in Europe and is undergoing clinical trials in the United States. In the randomized Endovascular Valve Edge-to-Edge Repair Study II trial, mitral clipping using the MitralClip® device was associated with superior safety and similar improvements in clinical outcomes but was less effective at reducing mitral regurgitation compared to conventional surgery. 43

Echocardiography, including 3D TEE, is essential in selecting appropriate patients for mitral valve clipping, guiding of the procedure, and assessing the success of the procedure.

Selection of Patient Eligible for Mitral Valve Clipping

All eligible patients should have the following:

- Chronic moderate-to-severe or severe mitral regurgitation originating centrally between A2 and P2 scallops of the mitral valve.
- Mitral regurgitation may be functional (due to LV dysfunction) or degenerative (due to prolapsed or flail mitral leaflet) with certain anatomic limitations (for degenerative mitral regurgitation: flail gap less than 10 mm; flail width less than 15 mm; for functional mitral regurgitation: coaptation depth less than or equal to 11 mm; and coaptation length more than or equal to 2 mm). 44
- Either symptomatic with a LV ejection fraction (LVEF) of more than 25% or asymptomatic with at least one of the following: an LVEF of 25–60%, a LV end-systolic diameter of 40–55 mm, new atrial fibrillation, or pulmonary hypertension.

The details of echocardiographic diagnosis of mitral valve prolapse 45 or degenerative mitral regurgitation are discussed elsewhere in this textbook. It suffices to say here that 3D TEE (especially its en face views) allows for detailed evaluation of mitral valve anatomy and precise establishment of the mechanism of mitral regurgitation.

Three-dimensional Transesophageal Echocardiography Guidance of Mitral Valve Clipping

The MitraClip device is a 4 mm wide polyester-covered cobalt–chromium implant with two arms mounted on a sophisticated catheter-based delivery system. After obtaining femoral venous access and using standard transseptal approach over a guide wire and tapered dilator, the clip delivery system is brought into the left atrium through a guide catheter. 46

Echocardiographic guidance for transseptal puncture is provided in a standard fashion as described earlier in the chapter but with an important modification regarding the location of transseptal puncture. The site of transseptal puncture is extremely important for the success of mitral valve clipping. In general, a more posterior and superior puncture site is preferred. A distance of at least 4 cm between the site of puncture and the clip landing site on the mitral valve is recommended. 47 In particular, passage across PFO—the route commonly used in other percutaneous procedures in the left heart—should always be avoided during mitral valve clipping. Passage through a PFO usually results in a position that is too inferior and anterior. Furthermore, tunnel-type PFOs may impede free movement of the clip delivery system.

Following successful transseptal puncture, the clip with its arms closed and attached to the delivery system is brought into the left atrium through the guide catheter. After the clip delivery system emerges into the left atrium through the guide catheter, its tip is then bent toward the mitral valve. The arms of the clip are opened and subsequently oriented perpendicular to the leaflet coaptation line. 3D TEE guidance is absolutely essential in
guiding this orthogonal clip orientation (Figs. 7A to D and Movie Clip 7).

In the next step, the open clip is advanced below the mitral leaflet tips into the left ventricle. The arms of the clip are then partially closed, and the delivery system is pulled back until the mitral leaflets are captured in the arms of the clip. Using 3D TEE and color Doppler, the position and the degree of residual mitral regurgitation are assessed as the arms of the clip are gradually closed to complete the edge-to-edge repair and form a double-orifice mitral valve. Occasionally, the placement of a second clip may be necessary to treat residual mitral regurgitation. However, this increases the chance of procedure-related mitral stenosis (Figs. 8A to D and Movie Clip 8).

**Transcatheter Mitral Valve Replacement**

Although transcatheter mitral valve repair using the MitraClip® may be an effective percutaneous treatment for mitral regurgitation, the risk of mitral stenosis and residual mitral regurgitation are major limitations. Therefore multiple novel designs for transcatheter mitral replacement are currently under investigation.

Transcatheter mitral valve replacement using percutaneous delivery of a mitral bioprosthesis can be...
Figs. 8A to D: Delivery of mitral clip. (A and B) Fluoroscopy images of mitral clips. In Figure A the mitral clip is still attached to its delivery catheter and is being opened in preparation for grasping of mitral leaflets; Figure B obtained from a different patient, one mitral clip is already deployed (Clip 1), the other is being deployed (Clip 2); (C and D) 3D TEE zoom images of the mitral valve during diastole with one clip (arrows) fully deployed; Figure C demonstrates the left atrial aspect, and Figure D demonstrates the left ventricular aspect of the mitral valve. Note that clip deployment creates a double-orifice mitral valve. Movie Clip 8 corresponds to Figure C (3D: three-dimensional; AML: anterior mitral leaflet; AV: aortic valve; PML: posterior mitral leaflet; TEE: transesophageal echocardiography).
performed using transapical or transfemoral/transseptal access. Regardless of the route of access to the mitral valve, all TMVR procedures require 3D echocardiography during multiple procedural steps. For the transapically delivered TMVR systems, 3D echocardiography can be used to determine the correct site for transapical puncture as well as guidance of the delivery system from the LV side of the mitral valve to the LA side [Figure].

Three-dimensional echocardiography is critical for proper positioning of all types of TMVR designs. It is also used for the assessment of paravalvular or transvalvular residual mitral regurgitation.

Aortic Stenosis: Transcatheter Aortic Valve Replacement
The calcification of a seemingly normal trileaflet or a congenital bicuspid valve resulting from an atherosclerosis-like process is the most common form of acquire aortic stenosis. Rheumatic aortic stenosis is rare in the United States and other developed countries. It results from commissural fusion and leaflet calcifications and is invariable associated with concomitant rheumatic mitral valve disease. Once severe aortic stenosis becomes symptomatic, the survival is dismal (only a few years) and not much different from many metastatic cancers.

No medical therapy has ever been shown to alter the natural history of aortic stenosis; aortic valve replacement is the only effective therapy. Surgical aortic valve replacement (SAVR) has been shown to improve symptoms and is generally accepted to prolong survival based on historical comparisons and extensive experience over the past 50 years. The first orthotopic SAVR, albeit for aortic insufficiency, was performed in 1960 by the American surgeon Dwight Harkin. At present, about 13,000 SAVRs are performed annually in the United States for the relief of aortic stenosis.

Historically, two percutaneous alternatives to SAVR have been proposed: aortic balloon valvuloplasty (ABV) and TAVR also referred to at transcatheter aortic valve implantation. Balloon aortic valvuloplasty was first performed in 1986 by Alain Cribier in France. In contrast to PMBV (which is the treatment of choice for relief of mitral stenosis with good long-term outcomes), percutaneous ABV is used primarily as a bridge to aortic valve replacement; used alone ABV has high restenosis and complication rates.

The first TAVR in a human was performed in 2002 by Alain Cribier in France using a balloon expandable valve similar in design to the one tested in animals by Danish inventors a decade earlier. TAVR is the only intervention for aortic stenosis shown to prolong survival in a randomized trial. It is currently indicated for patients with severe aortic stenosis who are at high risk or unsuitable for SAVR.

At present the two most commonly used TAVR valves are: (1) balloon expandable Sapien™ valve (Edwards Lifesciences Inc., Irvine, CA, USA); and (2) self-expandable CoreValve™ (Medtronic Inc., Minneapolis, MN, USA). Both valves have undergone three iterations with each successive version enhancing the seal between the prosthetic valve and the native tissue. CoreValve™ versions progressed from the classic CoreValve™ to CoreValve™ Evolut R to CoreValve™ Evolut Pro. The Sapien family of valves progressed from the classic Sapien™ valve to Sapien™ X1 to Sapien™ S3. Echocardiographers should be familiar with the basic design and the mode of delivery of these two valves. Both are bioprosthetic pericardial valves suspended on a metal frame (Figs. 9A and B).

Sapien™ valve is currently made of bovine pericardium suspended on a chrome–cobalt alloy frame. A collapsed Sapien™ valve is mounted on a deflated balloon in a similar fashion used for coronary stents. Upon delivery,
the Sapien® valve is balloon expanded across the stenosed native aortic valve. In contrast, CoreValve® is made of porcine pericardium suspended on a nitinol alloy frame. Prior to CoreValve® implantation, balloon valvuloplasty of the native aortic valve is performed. Subsequently, a collapsed CoreValve® is brought into the ascending aorta which then self-expands across the stenosed native valve after it emerges from the delivery sheath. Both valves can be implanted using various arterial access points: the femoral artery, LV apex, or ascending aorta.

The role of echocardiography, including 3D TEE, is twofold: to identify appropriate patients and to provide intraprocedural monitoring.

Selection of Patient Eligible for Transcatheter Aortic Valve Replacement

Echocardiography is essential in establishing the presence of the only currently approved indication for TAVR: severe acquired calcific stenosis of a trileaflet valve (senile calcific aortic stenosis). At present, TAVR is not an on-label indication for aortic stenosis of a bicuspid aortic valve although it is frequently used off label. As mentioned earlier, the very first TAVR performed by Alain Cribier was in a patient with severe bicuspid aortic valve stenosis.

Can 3D echocardiography improve on standard techniques of assessing aortic stenosis severity discussed elsewhere in this chapter? Using the multiplane reconstruction techniques, 3D TEE can provide accurate measurements of the LV outflow tract (LVOT), aortic annulus, and the aortic annulus-to-left coronary artery ostium distance.

The calculation of the aortic valve area (AVA) by continuity equation is the principal echocardiographic method of assessing anatomic severity of aortic stenosis. The major source of error in AVA calculation by continuity equation is miscalculation of the cross-sectional area of the LVOT due to mismeasurement of the LVOT diameter and/or faulty geometric assumption of a circular LVOT shape. Using multiplane reconstruction techniques of either CT or 3D echocardiography (Figs. 10A to D), one can demonstrate that LVOT is typically ovoid rather than circular in shape. In addition, it can also be demonstrated that the LVOT “diameter” measured by 2D echocardiography is often a geometric chord rather than a true diameter. Since a chord (a line connecting two points on the circumference that does not cross the center) is by definition shorter than a diameter, 2D echocardiography will often underestimate the size of LVOT area and thus overestimate the severity of aortic stenosis.

The size of the aortic annulus is another measurement that is important for TAVR as the size of the replacement valve is based on the patient’s annular size. 2D echocardiography systemically underestimates the annular size compared to CT or MRI. In contrast, 3D TEE sizing of the annular size (Figs. 11A to D) is superior to 2D TEE and may be used when good CT data are unavailable for TAVR sizing.

Prior to Sapien valve placement, the annular to left coronary artery ostium height is important as well in selecting appropriate replacement valve size. Echocardiographically, this height cannot be measured by 2D TEE; however, such a measurement is possible with multiplane reconstruction techniques of 3D TEE (Figs. 12A to D).

Theoretically, AVA can also be measured by 3D planimetry. However, aortic valve calcifications create image dropout making this measurement imprecise.

Transcatheter Aortic Valve Replacement: Intra- and Postprocedural Monitoring by Echocardiography

In the early years of TAVR, TEE was the primary echocardiographic modality used to help guide the valve insertion, monitor for intraprocedural complications, and assessment of postimplantation success. Over the past several years, more and more centers have replaced TEE with TTE for intraprocedural TAVR monitoring. This trend parallels the replacement of general anesthesia with moderate sedation during TAVR procedures.

Transesophageal Echocardiography Imaging during Transcatheter Aortic Valve Replacement

In contrast to mitral valve procedures where 3D TEE plays the principal role in guidance, TAVR placement is performed primarily under fluoroscopic and CT guidance. Nonetheless, 2D and 3D echocardiography is used to provide important real-time information regarding aortic valve anatomy and function, and to observe for complications, such as pericardial effusion or ventricular dysfunction. Moreover, guide wires, catheters, valvuloplasty balloons, and the replacement valve (Figs. 13A to D) can continuously be observed by echocardiography; in this respect, 3D TEE is often superior to 2D TEE.
Immediately post-TAVR, Doppler echocardiography plays a crucial role in assessing the success of the procedure. Color Doppler is used to assess for paravalvular regurgitation (Figs. 14A to D), which may be present in at least 10% of TAVR patients and which portends poorer prognosis. Spectral Doppler reordered from transgastric windows is used to assess the gradients across the newly implanted TAVR (Figs. 15A to C).

Transthoracic Echocardiography Imaging during Transcatheter Aortic Valve Replacement

Transthoracic echocardiography is increasingly replacing TEE during TAVR procedures. TTE can rapidly establish if the key markers of good TAVR implantations have been achieved. We refer to these key markers as the SVS triad: seal, velocity, and shape (Figs. 16A to F):

- **Seal**—Absence of significant transvalvular or paravalvular aortic regurgitation
- **Velocity**—Systolic peak velocity across the TAVR valve less than 2.0 m/s
- **Shape**—Circular shape of TAVR prosthetic frame on short-axis view.

Closure of Paravalvular Prosthetic Leaks

The reported prevalence of clinically important paravalvular leaks (PVLs) due to valve dehiscence ranges between 3% and 12.5% of all surgically implanted prosthetic valves. In the early postsurgical period, prosthetic valve dehiscence is typically due to procedural mishaps (e.g. a loose suture in a patient with calcified native annulus). Late-onset prosthetic dehiscence is usually due to infective endocarditis. Irrespective of its
cause, prosthetic valve dehiscence leads to paravalvular regurgitation and hemolytic anemia. The magnitude of hemolytic anemia does not necessarily correlate with the severity of paravalvular regurgitation.70

Heart failure and transfusion-dependent anemia are major indications for PVL closure. Until recently, redo open-heart surgery was the only means of closing clinically significant PVLs. However, reoperation is associated with high morbidity and mortality, with reported in-hospital mortality rates of 13, 15, and 37% for the first, second, and third reoperations, respectively.71

It appears that in 1987 the first percutaneous PVL closure was performed.72 Percutaneous closure of PVLs is emerging as an alternative to redo surgery.73 Most initial experience has been with the closure of mitral PVLs74 but techniques are being developed for PVLs of prosthetic aortic valves as well.75 Percutaneous closure is becoming the treatment of choice for most clinically significant PVLs; surgery is still reserved for very large PVLs (involving more than 25% of the prosthetic ring circumference) or PVLs related to active endocarditis.76

At present, there are no closure devices that are specifically designed for PVL closure; instead either vascular plugs or occluders designed for ASD, VSD, or PDA closure are used off label. Depending on PVL size, one or more devices may be needed to successfully close the leak.77

Improvements in 3D TEE imaging are the major driving force behind the development of percutaneous PVL closures. 3D TEE is important both for establishing the precise diagnosis of PVL and for the monitoring of percutaneous closure.

Figs. 11A to D: 3D TEE assessment of the aortic annulus. Multiplane reconstruction 3D TEE imaging of the aortic annulus in a patient prior to CoreValve placement demonstrates a near-circular aortic annulus measuring 2.3 cm × 2.4 cm in diameter (3D: three-dimensional; LA: left atrium; LVOT: left ventricular outflow tract; TEE: transesophageal echocardiography).
Three-dimensional Transesophageal Echocardiography Diagnosis of Paravalvular Leak

The diagnosis of a PVL can be established by 2D echocardiography. However, 3D TEE provides incremental information regarding the exact location, size, and shape of a PVL (Figs. 17A and B). This information is crucial for the success of PVL closure procedure. With its ability to provide en face views of the entire mitral valve, 3D TEE demonstrates PVLs in an intuitive and accurate. It is essential to use color Doppler to confirm the location of PVLs and to avoid mischaracterization of periprosthetic image dropouts as PVLs. In summary, 3D TEE can accurately identify patients with suitable anatomy for percutaneous PVL closure.

Three-dimensional Transesophageal Echocardiography Monitoring of Percutaneous Paravalvular Leak Closure

For percutaneous closure of mitral PVLs, standard transseptal approach is used. 3D TEE is instrumental in guiding transseptal puncture as discussed earlier in this chapter. Occasionally, transaortic or transapical approach may be used. Irrespective of the approach used, 3D TEE is used intraprocedurally to guide the placement of wires, catheters, and closure devices (Fig. 18). Without 3D TEE guidance, many PVL closure procedures would be either impossible to perform using fluoroscopy alone or would expose the patient significant radiation. Postprocedurally,
2D and 3D echocardiography is used to assess for residual regurgitation and to evaluate for possible prosthetic valve malfunction due to closure device impingement. In general, closure of mitral PVLs located laterally (Figs. 18A to D) is technically easier than the closure of those located medially (Figs. 19A to C).

**Echocardiography–Fluoroscopy Fusion**

There has been great interest in novel technology which can integrate data from 3D echocardiography with fluoroscopy. Accurate juxtaposition of echocardiographic images with fluoroscopy is made possible by fluoroscopic imaging of the TEE probe, which allows for coregistration of images. Echocardiography–fluoroscopy fusion holds promise to improve communication between echocardiographers and interventionalists which can reduce fluoroscopy times and radiation exposure to patients and the structural heart team. The technology is particularly useful in providing a target on fluoroscopy during catheter-based closure of PVLs and other cardiac defects (Figs. 20A and B).

**Device Closure of Cardiac Shunts**

The surgical closure of cardiac shunt predates many other forms of cardiac surgery and was practiced well before the advent of cardiopulmonary bypass in the 1960s. Percutaneous closure has become the treatment of choice.
for many cardiac shunts, including PDA, secundum ASDs, and muscular VSDs with surgery typically being reserved for complex cases.

**Closure of Patent Ductus Arteriosus**

Ductus arteriosus is an arterial communication between the left pulmonary artery and the proximal descending thoracic aorta that develops embryologically from the left sixth aortic arch. Ductus arteriosus is an essential component of the normal fetal circulation; it directs the blood away from the very high-resistance fetal pulmonic circulation of the collapsed lungs to the low-resistance systemic circulation (physiologic right-to-left shunt). During fetal life, ductus arteriosus is kept open by vasodilators, such as prostaglandin PGE2 which is believed to be produced both locally in the ductus and by the placenta.

Soon after delivery, pulmonary vascular resistance drops below the systemic vascular resistance leading to shunt reversal; this left-to-right shunt is transient in most infants. The high oxygen content of ductal blood activates an oxygen-sensitive potassium channel which leads to the contraction of the ductal muscular layers and the cessation of ductal flow. In the majority of infants scarring
Figs. 15A to C: Assessment of aortic valve gradients before and after transcutaneous aortic valve replacement. Aortic valve gradients before (A) and after (C) percutaneous implantation of the Sapien aortic valve; the valve is seen on fluoroscopy in B.

Figs. 16A to F: TAVR TTE: SVS triad. Components of the SVS triad are: seal, velocity, and shape. Optimal TAVR valve seal (A) and suboptimal TAVR seal (B) are demonstrated, represented by the presence or absence of significant (mild or greater) paravalvular aortic regurgitation. A transaortic velocity of less than 2.0 m/s is considered optimal (C). Suboptimal (D) TAVR velocity is more than 2.0 m/s. Suboptimal TAVR shape is circular (E), suboptimal TAVR shape is elliptical (F) (LA: left atrium; PV: pulmonic valve; RV: right ventricle; TAVR: transcatheter aortic valve replacement; TTE: transthoracic echocardiography).
completely obliterates ductus arteriosus by the end of the neonatal period.\textsuperscript{78}

Patent ductus arteriosus results from the failure of physiologic closure of ductus arteriosus past the first year of life. It can be isolated or may be associated with a variety of other forms of congenital heart disease. Typically, PDA presents with a left-to-right shunt; however, shunt reversal can occur if pulmonary vascular resistance rises above the systemic vascular resistance.

Patent ductus arteriosus is the first congenital heart defect to be closed successfully by surgery and was the first congenital heart defect to be closed percutaneously. The first successful ligation of a PDA was performed in 1938 by Robert E Gross, the then chief surgical resident, and John P Hubbard at Boston Children’s Hospital.\textsuperscript{79} The first successful percutaneous closure of a PDA was reported by Werner Portsmann and colleagues working at Charité Hospital located in what was then East Germany.\textsuperscript{80}

Percutaneously or surgically closure of a PDA is indicated for the following:\textsuperscript{81}

- Left atrial and/or LV enlargement or if pulmonary arterial hypertension is present, or in the presence of net left-to-right shunt.
- Prior endarteritis.
- It is reasonable to close an asymptomatic small PDA by catheter device.

Surgical repair by a surgeon experienced in congenital heart disease is recommended when:

- Patent ductus arteriosus is too large for device closure.
- Distorted ductal anatomy precludes device closure.

Patent ductus arteriosus closure is contraindicated in patients with pulmonary arterial hypertension and net right-to-left shunt.

The general aspects of PDA diagnosis are discussed elsewhere in this book. From the percutaneous or surgical point of view the role of imaging is to establish the general anatomy of a PDA. Typically, PDAs have a conical shape with the wider opening at the aortic side and the smaller one at the pulmonary artery side. However, a variety of shapes have been described.\textsuperscript{82} There are limited data on the use of 3D echocardiography in the diagnosis of PDA and for the guidance of PDA closure (Figs. 21A to D).\textsuperscript{83,85}

In general, TEE allows for continuous monitoring of PDA flow during percutaneous closure; this minimizes X-ray exposure of concomitant fluoroscopy (Figs. 22A and B).\textsuperscript{86}

**Closure of Atrial Septal Defects**

There are at least four different types of ASDs in the descending order of prevalence: secundum ASD, primum ASD, sinus venosus ASD [which may be of the superior or inferior vena cava (IVC) type], and unroofed coronary sinus. Following bicuspid aortic valve, ASD is the most common congenital anomaly in adults occurring in approximately 1 out of 1,000 individuals.\textsuperscript{87}

The successful surgical closure of ASDs predates the advent of cardiopulmonary bypass. In 1952 the closure of...
Three-dimensional Echocardiography Guidance of Percutaneous Procedures

Three-dimensional Transesophageal Echocardiography Diagnosis of Atrial Septal Defects

Appropriate patient selection is of utmost importance for the success of percutaneous ASD closure.⁸¹ One should...
first establish the diagnosis of a secundum ASD, the only ASD type amenable to percutaneous closure at present. After obtaining 3D TEE images of the interatrial septum, we use the so-called TUPLE (tilt-up-then-left) maneuver to obtain en face images of the interatrial septum in anatomically correct orientations (Figs. 23A to C and Movie clips 9A and B). Briefly, the TUPLE maneuver is a three-step process in which the initial 3D zoom image of.
the interatrial septum is tilted up to reveal the right atrial aspect of the interatrial septum. The image is then rotated counterclockwise in the Z axis until the SVC is located at 12 o’clock. Finally, the image is then rotated to the left to reveal the LA aspect of the interatrial septum. After using the TUPLE maneuver, one can easily determine ASD type, location, shape, and size.

Secundum ASDs (Figs. 24A to D) are located in the fossa ovalis and come in a variety of shapes (circular, ovoid, and triangular). They may contain fenestrations (cribriform ASD) or may be associated with an ASA. The sizing of an ASD involves measuring of ASD diameters and determining the size of surrounding ASD rims; these data are essential for choosing an appropriate closure device. The three most commonly used ASD closure devices (Figs. 25A to C) are as follows:

- Amplatzer™ atrial septal occluder (St. Jude Medical, St. Paul, MN, USA) consists of two disks (the LA disk being larger than the right atrial disk) connected by a waist; it comes in a variety of sizes based on waist diameter (from 4 mm to 38 mm). Device selection is based on the measured diameter of the defect which should correspond to the waist diameter of the device. This device is used to close nonfenestrated secundum ASDs.
2. Amplatzer™ multifenestrated septal occluder (St. Jude Medical, St. Paul, MN, USA) is used to close fenestrated (cribriform) secundum ASDs. It contains two discs of equal diameter connected by a thin shaft; it comes in a variety of sizes based on the diameter of the LA disk (from 18 mm to 35 mm). Device selection is ultimately based on the measured diameter of the defect which should be proportional to the disk diameter of the device.

3. Gore-Helex atrial septal occluder (W. L. Gore and Associates, Inc., Flagstaff, AZ, USA) contains two equal-sized discs mounted on a spiral shaft; it comes in a variety of sizes based on the disk diameter (from 15 mm to 35 mm). The occluder size selected for the defect should achieve at least a 2:1 ratio between disk diameter and defect diameter. Recently, Gore-Helex device has been replaced with the newer version called Gore Cardioform with similar characteristics.
When selecting an ASD closure device, the maximum diameter of a secundum ASD cannot exceed device-specific cutoff value, and there should be sufficient ASD rim to anchor the device. Historically, the device size was selected based on an invasive measurement of ASD diameter using sizing balloons placed across an ASD (Figs. 26A and B) and gradually inflated until no color Doppler flow across the ASD is seen on 2D TEE (so-called stop-flow diameter). More recently, device selection is based on direct ASD diameter measurements by 3D TEE (Figs. 27A to C). The maximum ASD diameter amenable to closure with an Amplatzer™ atrial septal occluder is 38 mm; for a Gore-Helex device the maximum ASD diameter is 18 mm.

Three-dimensional TEE imaging is also important in measuring rims that surround a secundum ASD (Fig. 28). There are several different nomenclatures of ASD rims; we prefer the system which labels rims based on the surrounding structure (e.g. aortic rim) rather than on their anatomic orientation (e.g. anterosuperior rim). In general, there are five distinct ASD rims listed in a clockwise direction: SVC rim, aortic room (adjacent to the aortic valve), atrioventricular rim (adjacent to the tricuspid and mitral valve), IVC rim, and posterior rim (the rim opposite the aortic rim).

In general, the rims should be “sufficient”—that is they have to exceed certain minimum distance. This
minimum rim size is device specific. For instance, for the Amplatzer™ septal occluder the rims should be at least 5 mm. For the Amplatzer™ multifenestrated septal occluder the SVC and the aortic rim should be at least 9 mm. The absence of the IVC rim is considered a contraindication for device closure of a secundum ASD.

**Three-dimensional Transesophageal Echocardiography Monitoring of Percutaneous Atrial Septal Defect Closure**

Three-dimensional TEE allows for continuous visualization of the tip of the guiding catheter, as well as of the closure device as it is being delivered. After the secundum ASD is sized and deemed amenable to percutaneous repair by 3D TEE, the interventionalist may decide to confirm the ASD size using a balloon. Color Doppler echocardiography is used during balloon inflation. When no flow between the balloon and the ASD margins is seen by color Doppler, the interventionalist measures the ASD diameter on fluoroscopy image (stop-flow diameter).

Subsequently, a delivery catheter is brought into the left atrium across the ASD using a transvenous approach (typically via the femoral vein). A collapsed ASD closure device is advanced through the catheter into the left atrium. The LA disk is opened first and apposed against the...
Figs. 26A and B: ASD sizing balloon. (A) ASD sizing balloon seen on fluoroscopy extending from the RA to the LA. Note that the central portion of the balloon (waist) is located in the ASD. The balloon is inflated gradually until color flow across the ASD ceases on TEE imaging. At that moment, the waist diameter is measured; it represents the so-called stop-flow diameter and is used to choose appropriate ASD closure device size; (B) 3D TEE zoom image demonstrates the left atrial aspect of the sizing balloon (3D: three-dimensional; ASD: atrial septal defect; AV: aortic valve; LA: left atrium; MV: mitral valve; RA: right atrium; RUPV: right upper pulmonary vein; SVC: superior vena cava; TEE: transesophageal echocardiography).

Figs. 27A to C: 3D TEE sizing of ASDs. ASDs can be sized on 3D TEE using a variety of methods. In this figure the ASD is seen from the right atrial perspective. (A) ASD sizing using an overlay grid; in this instance the distance between the dots is 2 mm; (B) ASD sizing using direct on-image calipers; (C) ASD sizing using the multiplane reconstruction method. Also note the difference between the true ASD diameters and a chord. Distances presumed to be diameters on 2D TEE are frequently chords rather than true diameters (3D: three-dimensional; ASD: atrial septal defect; TEE: transesophageal echocardiography).
LA side of the defect. The right atrial disk is then opened and maneuvered until the device is firmly attached to the rims of the ASD. 3D TEE imaging is used to ascertain proper positioning of the closure device. Both discs can be visualized by 3D TEE although right atrial disk may be more difficult to visualize than LA disk. This is due to the fact that relative to the TEE probe located in the esophagus the right atrial disk in the far field and partly shadowed by the LA disk (Figs. 29 and 30).

In addition, 3D TEE helps determine if sufficient tissue rim is caught in between the two plates of the device. When rim capture is insufficient, 3D TEE can be used to guide repositioning of the device. At the end of the procedure, the device is fully deployed after its release from the delivery shaft. 2D and 3D TEE color Doppler imaging is crucial for assessing the success of percutaneous ASD closure. On color Doppler, ideally there should be no residual para-device leak (i.e. flow around the device between ASD rims and the edge of the device); the absence of such a leak is indicative of a complete ASD closure. The small amounts of color Doppler flow across rather than around the device may be normal; such flows will cease upon endothelialization of the device.

Intracardiac echocardiography is an alternative to 3D TEE for the monitoring of ASD closure. Historically, ICE had only 2D capabilities (Figs. 31A to C) but recently ICE catheters have started adding 3D imaging (Figs. 32A and B).

### Closure of Patent Foramen Ovales

Foramen ovale, a communication between the right and left atriums at the level of fossa ovalis, is an essential part of fetal circulation. It allows for shunting of oxygen-rich blood (arriving into the right atrium via umbilical veins) to systemic circulation. After birth the communication closes in the majority of children but remains open in about a quarter of adult population. The persistence of this communication is referred to as PFO.

Patent foramen ovale has been implicated in the pathogenesis of cryptogenic stroke, and its surgical or percutaneous closure has been advocated in the prevention of recurrent systemic embolism. The role of 3D TEE in percutaneous PFO closure is similar to that described for ASD closure.

Patent foramen ovales are typically closed percutaneously with devices that are specifically designed for PFO closure (Figs. 30A to C), such as the STARFlex occluder (previously referred to as CardioSEAL device; NMT Medical, Boston, MA, USA) and Amplatzer PFO Occluder (St. Jude Medical, St. Paul, MN, USA). Percutaneous PFO closure was first reported in 1992 using the Bard Clamshell Septal Occluder, a predecessor of the STARFlex device. Prior randomized trials had failed to demonstrate clear benefit of PFO closure with either STARFlex or Amplatzer PFO Occluder. However, recent trials using a variety of PFO closure devices including Amplatzer and Gore PFO...
Figs. 29 A and B: 3D TEE appearance of Amplatzer ASD occluder. Amplatzer ASD occluder (arrow) is well visualized from the right atrial side (A) and the left atrial side (B) (3D: three-dimensional; ASD: atrial septal defect; AV: aortic valve; IVC: inferior vena cava; RUPV: right upper pulmonary vein; SVC: superior vena cava; TEE: transesophageal echocardiography).

Figs. 30 A to C: 3D TEE and fluoroscopic appearance of ASD and PFO closure devices. (A) Gore-Helex atrial septal occluder (WL Gore & Associates, Inc., Flagstaff, AZ, USA); (B) Amplatzer™ multifenestrated (cribriform) septal occluder (St. Jude Medical, St. Paul, MN, USA); (C) STARFlex occluder (previously referred to as CardioSEAL device; NMT Medical, Boston, MA, USA).
Figs. 31A to C: Guidance of ASD closure using ICE. ICE images demonstrate steps in secundum ASD closure using an Amplatzer ASD occluder. (A) The ASD closure assembly is brought into the left atrium, and the left atrial disk is unfurled; (B) The right atrial disk is unfurled, and the closure device is placed within the ASD. The device is still attached to the delivery cable; (C) The ASD device is fully deployed and released from its delivery cable. Color Doppler imaging demonstrates no residual shunt (ASD: atrial septal defect; ICE: intracardiac echocardiography; LA: left atrium; RA: right atrium).

Figs. 32A and B: 3D ICE. (A) PFO closure procedure using 3D ICE. A catheter across a PFO is demonstrated. 3D ICE can provide better visualization of the trajectory of intracardiac catheters as compared to 2D ICE; (B) Amplatzer PFO occluder is demonstrated closing a PFO using 3D ICE. (2D: two-dimensional; 3D: three-dimensional; ICE: intracardiac echocardiography; LA: left atrium; PFO: patent foramen ovale; RA: right atrium).
occluders have demonstrated percutaneous closure of PFO in conjunction with antiplatelet therapy in patients with presumed cryptogenic stroke diminishes the risk of recurrent stroke.103-105

Closure of Ventricular Septal Defects

There are several types of VSDs: perimembranous (infracristal); muscular (further subdivided into inlet, trabecular, and infundibular or supracristal); and atroventricular defects (a communication between the left ventricle and the right atrium).106 Perimembranous VSDs often have a windsock appearance due to evagination of the membranous septum.107

Colloquially, the term “muscular VSD” is often used synonymously with the trabecular VSD. Muscular VSD may be congenital or acquired (e.g. following myocardial infarction or trauma). The closure of a VSD should be considered if one of the following criteria is present:

- $Q_p/Q_s$ (pulmonary-to-systemic blood flow ratio) more than or equal to 2.0 and clinical evidence of LV volume overload;
- History of infective endocarditis.
- The closure of a VSD may also be considered if:
  - $Q_p/Q_s$ more than 1.5 with pulmonary artery pressure less than two-thirds of systemic pressure and pulmonary vascular resistance less than two-thirds of systemic vascular resistance.
  - Net left-to-right shunting is present at $Q_p/Q_s$ more than 1.5 in the presence of LV systolic or diastolic failure.

The closure of a VSD is contraindicated in patients with severe irreversible pulmonary arterial hypertension (who typically present with pulmonary vascular resistance greater than two-thirds of systemic vascular resistance).

Percutaneous closure of a VSD was first performed in 1987 at Harvard Medical School. At present, percutaneous closure devices in the United States are approved for use in patients who are at high risk for standard surgical VSD closure and whose VSD is not in the proximity of cardiac valves. Thus percutaneous closure is primarily performed in patients with congenital muscular VSDs. Nonetheless, off-label use for the percutaneous closure of postinfarction VSDs has been reported.110

One such device approved in the United States is the Amplatzer™ ventricular septal occluder (St. Jude Medical, St. Paul, MN, USA). It consists of two disks of equal diameter (a LV disk and a right ventricular disk) separated by a waist that fits within the VSD. Device comes in a variety of sizes based on the waist diameter (from 4 to 18 mm). Outside the United States a specially designed device with eccentric discs is used to close perimembranous VSDs.111

Three-dimensional TEE is important for both the diagnosis and for the guidance of percutaneous closure of a VSD.112 With its unique ability to provide en face views, 3D TEE allows for accurate visualization of the VSD location, size, and shape (Figs. 33A to E). The information is important in establishing the feasibility of device closure and selecting the proper size of the closure device.

During percutaneous VSD closure the role of 3D TEE imaging is similar to that described for percutaneous ASD closures. 3D TEE visualization of intracardiac wires and catheters is helpful in guiding the placement of a closure device into the defect. Postdeployment, 2D and 3D TEE color Doppler imaging is crucial for assessing if VSD closure was successful or not (Figs. 34A to D). With complete VSD closure, there should be no residual para-device leak (i.e. flow around the device between VSD rims and the edge of the device) on color Doppler imaging. In contrast, small amounts of color Doppler flow across rather than around the device may be normal; such flows will disappear upon endothelialization of the device.

OCCCLUSION OF THE LEFT ATRIAL APPENDAGE

Atrial fibrillation, the most common sustained cardiac arrhythmia, is a risk factor for intracardiac thrombus formation and thromboembolism; it accounts for approximately 15% of all ischemic strokes.113 In nonvalvular atrial fibrillation the LAA is the primary site of thrombus formation accounting for 91% of all atrial fibrillation-associated intracardiac thrombi. Even in valvular atrial fibrillation (which is related to rheumatic heart disease and is uncommon in high-income countries), LAA thrombi account for 57% of all thrombi.114 Anticoagulation with warfarin or other oral agents is the standard of care for the prevention of thromboembolism in atrial fibrillation. In patients who cannot take anticoagulant, exclusion of LAA from the body of the left atrium is an alternative for the prevention of thromboembolism.

Left atrial appendage exclusion can be achieved either surgically or percutaneously. Surgical techniques of LAA exclusion include LAA amputation,115 clipping,116 and ligation.117 Surgical LAA exclusion is usually performed only as an adjunct to another cardiac surgery (such
Figs. 33A to E: Echocardiographic diagnosis of perimembranous VSD. (A) 2D TEE image obtained at 145° demonstrates a perimembranous VSD with left-to-right shunt (arrow) from the LVOT to the RV; (B) 3D TEE color Doppler visualization of the VSD jet. The arrow points to the vena contracta of the jet at the level of VSD; (C) Spectral Doppler demonstrates flow typical of a restrictive VSD. Note the high velocity systolic flow and only a low-velocity diastolic flow; (D and E) 3D TEE en face zoom view of the VSD orifice (arrow) from the left ventricular (D) and the right ventricular side (E). The VSD measures 8 mm × 7 mm and has an area of 36 mm² (2D: two-dimensional; 3D: three-dimensional; LA: left atrium; LCC: left coronary cusp; LVOT: left ventricular outflow tract; NCC: noncoronary cusp; PV: pulmonic valve; RCC: right coronary cusp; RV: right ventricle; TEE: transesophageal echocardiography; VSD: ventricular septal defect).
coronary bypass grafting or valvular surgery) which limits the number of patients who could benefit from LAA exclusion. Furthermore, surgical LAA exclusion is frequently incomplete.\textsuperscript{118} Percutaneous LAA exclusion can be achieved either by implantation of an endocardial occluder device or via transpericardial placement of an epicardial suture at the LAA ostium. 2D and 3D TEE imaging is important for patient selection and guidance of percutaneous LAA exclusion.\textsuperscript{119}

**Figs. 34A to D:** Echocardiographic visualization of a VSD closure device. The patient underwent perimembranous VSD closure in China; such a procedure is not available in the United States unless part of an investigational study. (A and B) 2D transthoracic echocardiography demonstrates a closure device obliterating a perimembranous VSD in the parasternal long-axis (A) and the parasternal short-axis views (B). (C and D) 3D TEE en face zoom view of a VSD closure device (arrow) obliterating a perimembranous VSD seen from the left ventricular perspective (C) and the right ventricular perspective (D) (2D: two-dimensional; 3D: three-dimensional; AV: aortic valve; LA: left atrium; LV: left ventricle; NCC: noncoronary cusp of the aortic valve; RA: right atrium; RCC: right coronary cusp; RV: right ventricle; TEE: transesophageal echocardiography; VSD: ventricular septal defect).

**Endocardial Device Closure of Left Atrial Appendage**

Although several occluders have been used, the general principles of percutaneous closure of LAA using the endocardial approach are the same.\textsuperscript{120,121} Using a venous access (typically the femoral vein) and the previously described transseptal puncture, a delivery catheter is advanced through the venous system into the right atrium and then across the interatrial septum into the...
left atrium near the ostium of the LAA. Subsequently, the occluder is brought through the catheter into the LAA and deployed. LAA occluders consist of a nitinol wire frame covered with cloth. To date, they have only been approved for investigational use in the United States. Several LAA occluders have been evaluated in clinical trials including PLAATO, Watchman™, Amplatzer™ occluders, and WaveCrest (Fig. 35).122

PLAATO (Appriva Medical, Inc., Sunnyvale, CA, USA) was the first device that was specifically designed for percutaneous LAA occlusion. Despite promising results, PLAATO device has been discontinued. Enrollment for the Amplatzer™ Amulet device (St. Jude Medical, St. Paul, MN, USA) and WaveCrest (Biosense Webster, Irvine, CA, USA) trials is in progress.123

Watchman™ (Boston Scientific, Natick, MA, USA) is the only LAA occluder whose clinical trials have been completed. In the PROTECT-AF trial, LAA exclusion with a Watchman™ device was shown to be noninferior to warfarin therapy.124 However, it is important to emphasize that all patients who received Watchman device were also treated with warfarin for six weeks and dual antiplatelet therapy (aspirin and clopidogrel) for six months post-device implantation. Aspirin therapy was then continued for life. Watchman device is the only currently approved LAA occluder in the United States for general clinical use.

Two-dimensional and 3D TEE is used for both patient selection and procedure guidance. TEE imaging can be used to accurately visualize the LAA prior to the procedure and to measure its size.125 For device placement, both the orifice size and LAA length are important.

![Fig. 35: Devices used for percutaneous closure of left atrial appendage. The greatest clinical experience to date is with the Watchman device, the only device that is approved for general clinical use in the United States. The PLAATO device is no longer available. The Amulet and WaveCrest are examples of devices currently in clinical trials.](image-url)
Historically, LA appendage was sized using 2D TEE imaging at various acquisition angles, typically at 0°, 45°, 90°, and 135° (Figs. 36A to D). 3D TEE imaging allows for more precise sizing of the LA appendage; both 3D zoom and multiplane reconstruction imaging are helpful (Figs. 37A to D).

On 3D TEE en face views the LAA orifice is often ovoid rather than circular in shape. Using on-image calipers, the orifice diameters can be measured precisely. For proper device implantation, LAA must have a minimum length (the distance between the LAA orifice and LAA tip). This distance can be measured very accurately on multiplane reconstruction of 3D TEE images of LAA. Multiplane imaging allows for keeping the plane of the LAA orifice constant across imaging planes, something that is very difficult with 2D TEE imaging.

Three-dimensional TEE is used in conjunction with fluoroscopy during LA appendage device closure (Figs. 38A to C). 3D TEE allows for visualization of intracardiac trajectories of catheters and introducers which helps with the transseptal puncture and deployment of an LAA occluder device (Figs. 39A to D).

An LAA occluder device is properly placed when its long axis is parallel to the long axis of the LAA. Improper off-angle positions of the occluder are much easier to demonstrate by 3D TEE than by 2D techniques. 2D and 3D color Doppler imaging is crucial for ascertaining that no significant residual communication between the LAA and the left atrium (para-device leak) persists after occluder device placement. For the Watchman™ device the residual para-device jet should be either absent or at least no larger than 5 mm in width. If the device is placed improperly...
at first attempt, 3D TEE is used to guide recapture and redeployment of the device.

**Epicardial Suturing of Left Atrial Appendages**

**Echocardiography/Ultrasound Examination and Training**

The Lariat procedure utilized both endocardial and epicardial access. The endocardial portion of the procedure is conceptually similar to the Watchman procedure except that no occluder device is placed in the LAA. The femoral vein is the typical venous access site for the Lariat procedure but upper extremity access can be used as well.

After transseptal techniques a magnet-tipped guide wire is threaded through the venous system, passed across the interatrial septum and placed in the tip of the LAA. Another magnet-tipped guide wire is threaded epicardially through a pericardial access until it binds magnetically to the already placed LAA wire (Figs. 40A and B).

Because of the need for this pericardial access, prior history of pericardial adhesions (such as due to pericardiotomy or pericarditis) is a contraindication for the Lariat procedure. In the next step, the Lariat™ Suture Delivery Device (SentreHEART, Inc.; Palo Alto, CA, USA) is introduced into the pericardial space over the epicardial wire to deliver a pretied suture loop over the LAA. This delivery device was not specifically designed for LAA occlusion; it has been used for soft tissue closure in other organ systems.

As the suture loop is being lassoed over the LAA orifice, a balloon attached to the endocardial wire is inflated at the LAA orifice to prevent the suture from slipping away from the orifice. When the suture is nearly completely tied,
the endocardial wire is removed from the LAA (Figs. 41A to D).

At the end of the procedure the suture is completely tied, and the LAA is excluded from the body of the left atrium (Figs. 42A and B). 2D and 3D color Doppler imaging is crucial for ascertaining that no significant residual communication between the LAA and the left atrium is present. In addition, TEE imaging is crucial in monitoring for possible procedure-related pericardial effusion.

The feasibility and safety of the Lariat procedure has been demonstrated in case series but the outcome data are still lacking. Specifically, there are no long-term data on the risk of pericardial injury related to pericardial access used in the Lariat procedure.

GUIDANCE OF ELECTROPHYSIOLOGY PROCEDURES

The role of TEE prior to or during electrophysiology procedures is well established. 2D and 3D TEE is routinely used to exclude left heart thrombus prior to cardioversion or to guide transseptal puncture. 3D TEE is valuable in visualizing the right atrial structures of special interest to electrophysiologists, such as the cavotricuspid isthmus and crista terminalis. In addition, 3D TEE is now being utilized to guide pulmonary vein isolation during atrial fibrillation ablation.

Pulmonary Vein Isolation for Atrial Fibrillation

As pointed out in the section on the LAA exclusion, atrial fibrillation is the most common sustained cardiac arrhythmia whose prevalence increases in age (from 1% in general population to about 10% in the octogenarians). Atrial fibrillation may present with disabling symptoms, thromboembolism, and tachycardia-induced cardiomyopathy. Despite its disorderly rhythm, atrial fibrillation is often triggered in an orderly fashion by ectopic beats in the region of pulmonary vein ostia. This insight led to the development of techniques for...
catheter-based pulmonary vein isolation\textsuperscript{133} and isolation of other atrial foci.\textsuperscript{134} Collectively these procedures are referred to as atrial fibrillation ablation.

Catheter-based atrial fibrillation ablation has been shown in a randomized trial to be more effective than drug therapy in preventing recurrence of paroxysmal atrial fibrillation.\textsuperscript{135} At present, catheter ablation is indicated for the maintenance of sinus rhythm in selected patients with significantly symptomatic paroxysmal atrial fibrillation who have failed treatment with an antiarrhythmic drug and have normal or mildly dilated left atria, normal or mildly reduced LV function, and no severe pulmonary disease. In addition, catheter ablation is reasonable to treat symptomatic persistent atrial fibrillation or symptomatic paroxysmal atrial fibrillation in patients with significant LA dilatation or with significant LV dysfunction.\textsuperscript{136}

In a typical clinical scenario, prior to atrial fibrillation ablation, patients undergo either CT or MRI of the chest to define the anatomy of the pulmonary veins and other cardiac structures. Subsequently, patients are brought to the electrophysiology suite where 2D TEE imaging is used primarily to exclude intracardiac thrombus and to further delineate cardiac anatomy.\textsuperscript{137} Patients then undergo atrial fibrillation ablation guided by electrical mapping and fluoroscopy. The major shortcomings of such a scenario that CT, MRI, TEE, fluoroscopy, and electrical mapping

\textbf{Figs. 39A to D:} Guidance of Watchman procedure by 2D/3D TEE. (A) LA appendage orifice (arrow) is visualized en face on 3D TEE; (B) 3D TEE aids in guiding the pigtail catheter (arrow) into the LA appendage; (C) 3D TEE is then used to guide deployment of the Watchman device. Arrow points to a fully deployed Watchman device obliterating the LA orifice; (D) On 2D TEE color Doppler imaging, no residual communication between the LA and LA appendage is seen indicative of a successful Watchman procedure (2D: two-dimensional; 3D: three-dimensional; LA: left atrium; TEE: transesophageal echocardiography).
are not done simultaneously and image integration from various modalities is still a challenge.

Some electrophysiologists opt to use ICE for real-time imaging during the ablation procedure. In addition to imaging cardiac structures, ICE can also visualize the esophagus and thus monitor for esophageal injury (left atrioesophageal fistula), a rare but serious complication of the ablation procedure. However, ICE has its own shortcomings: it is invasive and costly.

Three-dimensional TEE imaging during atrial fibrillation imaging overcomes more of the shortcomings of other imaging modalities. It can provide en face views of pulmonary veins and other cardiac structures in real time. Thus one can determine the number and location of pulmonary vein ostia. There are typically two pulmonary vein ostia on the right and two ostia on the left (Figs. 43A to C). However, there are many variations; the most frequent one being the common ostium (antrum) of the two left pulmonary veins or three pulmonary ostia on the right (with the right middle pulmonary vein entering the left atrium directly rather than being a tributary of the right upper pulmonary vein) (Figs. 44A and B). During the ablation procedure, 3D TEE can be used to guide the transeptal puncture. In addition, 3D TEE can provide real-time 3D anatomic guidance for the placement of mapping and ablation catheters that cannot be achieved at present by any other imaging technique (Figs. 45A to C).

Two-dimensional and 3D TEE can also be used to monitor for procedural complications, such as the pericardial effusion. Doppler imaging is used to assess for pulmonary vein stenosis, a long-term complication of pulmonary vein ablation. Pulmonary vein stenosis is defined as a combination of a diminished diameter of the pulmonary vein ostium (<0.7 cm; normal ~1.5 cm) and an increase in the peak velocity of the pulmonary vein diastolic (D) wave (>100 cm/s; normal 40–60 cm/s).

**MISCELLANEOUS PROCEDURES**

The utility of 3D echocardiography has also been demonstrated in a variety of other percutaneous procedures, such as the closure of the LV pseudoaneurysm, percutaneous treatment of HOCM (alcohol septal ablation and mitral clip) as well as right ventricular endomyocardial biopsy.

**Left Ventricular Pseudoaneurysm Closure**

Left ventricular pseudoaneurysm is a rare but potentially serious complication of myocardial infarction or cardiac surgery. It represents a rupture of the LV free wall that is contained by adherent pericardium or scar tissue. The goal
of therapy is to prevent conversion of this contained rupture into complete rupture leading to pericardial tamponade and possibly death. Unrepaired LV pseudoaneurysm has high mortality.

Historically, surgery has been the only means of repairing LV pseudoaneurysm (Figs. 46A and B; Movie Clip 10); however, such surgeries themselves have significant mortality and morbidity as well. Percutaneous closure of an LV pseudoaneurysm was first reported in 2004 from a hospital in the United Kingdom with an off-label use of the Amplatzer™ atrial septal occluder. Experience with percutaneous LV pseudoaneurysm closures is limited to case series, the largest to date consisting of seven patients. Multimodality imaging, including 3D echocardiography, is essential for the success of percutaneous LV pseudoaneurysm closure. The utility of 3D TEE of LV pseudoaneurysm closure is similar to that of VSD closure described earlier in this chapter.

**Percutaneous Therapies for Hypertrophic Obstructive Cardiomyopathy**

Percutaneous options for HOCM include alcohol septal ablation and mitral clipping in patients who are not candidates for surgical myectomy and mitral valve repair.
Alcohol septal ablation, first reported in 1995, is an alternative to surgical myomectomy used for the relief of LV obstruction is HOCM. It entails intracoronary injection of alcohol into the septal perforator branch supplying the myocardium in the region asymmetric septal hypertrophy. Successful alcohol septal ablation leads to limited iatrogenic septal infarction, septal thinning and subsequent diminution of mitral septal contact, and LV outflow obstruction. The role of 2D echocardiography is well established including the off-label use of microbubble echocardiography contrast injected intra-arterially into the septal perforator branch (Figs. 47A and B).

Three-dimensional TEE imaging may improve localization of the mitral–septal contact, which is often displaced eccentrically within the LVOT. However, in contrast to most other percutaneous interventions, 3D TEE imaging cannot provide immediate assessment of procedural success of alcohol septal ablation since LV obstruction relief is expected to occur hours or days after the septal infarct completion.

**Right Ventricular Endomyocardial Biopsy**

Right ventricle (RV) is the primary site of endomyocardial biopsies which are used in the diagnostic workup of...
myocarditis, infiltrative cardiomyopathies, cardiac transplant rejection, and other myocardial disorders. Although endomyocardial biopsy is often performed using fluoroscopic guidance alone, both TEE and ICE may help define the anatomy better, guide the deployment of the biopreme tip to the desired region of the heart, and potentially increase the safety of the procedure (by avoidance of the tricuspid valve apparatus, for instance). The utility of 3D echocardiography in RV endomyocardial biopsy has been shown in case reports and case series.152,153
Figs. 44A and B: 3D TEE appearance of common pulmonary vein variants. (A) 3D TEE zoom en face image demonstrates the most common variant of right-sided pulmonary vein ostia, namely the RMPV having a separate left atrial ostium. This is in contrast to most normal individuals in whom the RMPV is a tributary of the RUPV. (B) 3D TEE zoom en face image of the most common variant of left-sided pulmonary ostia, namely the common antrum created by the confluence of the LUPV and the LLPV. Irrespective of whether there is one common or two separate left-sided pulmonary ostia, the ligament of Marshall, also known as the left atrial or Coumadin ridge (arrow), separates the pulmonary ostia from the LAA (3D: three-dimensional; LAA: left atrial appendage; LLPV: left lower pulmonary vein; LUPV: left upper pulmonary vein; RLPV: right lower pulmonary vein; RMPV: right middle pulmonary vein; RUPV: right upper pulmonary vein; TEE: transesophageal echocardiography).

Figs. 45A to C: 3D TEE guidance of atrial fibrillation ablation. 3D TEE zoom images demonstrate the steps of the atrial fibrillation ablation procedure using pulmonary vein isolation; (A) In the first step the mapping catheter referred to as the lasso catheter is paced into the ostium of a PV; (B) After the lasso catheter is deployed inside a pulmonary vein, electrical mapping is performed. Thereafter, an ablation catheter is guided toward a PV ostium to deliver lesions along the perimeter of a pulmonary vein ostium; (C) In the final step, lesions to additional left atrial structures are delivered. This image demonstrates the ablation catheter delivering lesions to the carina, the left atrial tissue between the pulmonary ostia (3D: three-dimensional; PV: pulmonary vein; RLPV: right lower pulmonary vein; RUPV: right upper pulmonary vein; TEE: transesophageal echocardiography).
Figs. 46A and B: 2D/3D appearance of left ventricular PsA. (A) 2D TEE transgastric view demonstrating a large LV PsA in a patient with prior inferior wall myocardial infarction. Note the appearance of spontaneous echo contrast (smoke) in the PsA space; (B) Full-volume 3D TEE image of the LV PsA. The external wall of the PsA is cropped out to reveal the defect in the inferior wall which creates the orifice of the LV PsA. There is spontaneous echocardiography contrast (smoke) in the PsA space. Movie clip 10 corresponds to this image. This LV PsA was too large for percutaneous closure; the defect was subsequently closed surgically (2D: two-dimensional; 3D: three-dimensional; LV: left ventricular; PsA: pseudoaneurysm; TEE: transesophageal echocardiography).

Courtesy: Jan R. Purgess, Department of Anesthesiology, New York University School of Medicine and New York Veterans Affairs Hospital, New York, NY.

Figs. 47A and B: Alcohol septal ablation. (A) 2D TTE imaging during alcohol septal ablation procedure. Echocardiographic microbubble contrast is injected into the first septal perforator coronary artery. The territory supplied by this septal coronary artery is assessed using echocardiography, which should be limited to the basal one third of the interventricular septum and should not involve the right ventricular free wall or a significant portion of the right ventricular moderator band. If these criteria are not met, a different septal perforator artery may be chosen; (B) Fluoroscopy during alcohol septal ablation procedure. Intracoronary injection of microbubble echocardiography contrast into the first septal perforator coronary artery is demonstrated (2D: two-dimensional; TTE: transthoracic echocardiography).
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