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*i*REVIEWS

STATE-OF-THE-ART PAPER

Role of Echocardiography in Percutaneous Mitral Valve Interventions

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CME Objective for This Article: At the end of this activity the reader should be able to: 1) evaluate the role of transthoracic echocardiography (TTE) and transesophageal echocardiography (TEE) in the quantification of mitral stenosis severity, understanding the predictors for successful results following percutaneous mitral balloon valvotomy (PMBV); 2) understand the echocardiographic inclusion criteria for transcatheter edge-to-edge repair (Mitra-Clip); and 3) identify the role of intraprocedural TEE in patients undergoing transcatheter closure of periprosthetic regurgitation (TPPR).

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Role of Echocardiography in Percutaneous Mitral Valve Interventions

Intraprocedural imaging continues to evolve in parallel with advances in percutaneous mitral valve interventions. This didactic review uses several illustrations and rich intraprocedural videos to further describe and demonstrate the role of the most up-to-date echocardiographic and advanced imaging technologies in the patient selection and intraprocedural guidance of percutaneous mitral valve interventions. We will focus on 3 interventions: 1) percutaneous balloon mitral valvuloplasty for mitral stenosis; 2) transcatheter edge-to-edge repair of mitral valve regurgitation; and 3) transcatheter closure of periprosthetic mitral regurgitation. In addition, we discuss potential pitfalls of 3-dimensional transesophageal echocardiography and show examples of this technique.   (J Am Coll Cardiol Img 2012;5:733–46) © 2012 by the American College of Cardiology Foundation

Structural intervention procedures require clear delineation of intracardiac anatomy, which is currently not feasible with fluoroscopy and cineangiography, without the addition of echocardiography, mostly using transesophageal methods. The traditional strengths of echocardiography (spatial and temporal resolution and portability) have been supplemented by multiplane imaging and more recently the development of simultaneous biplane imaging and real-time 3-dimensional imaging (RT3D), based on parallel processing and faster computing technology. Although an extensive review of the 3-dimensional (3D) methodology is beyond the scope of this paper, readers can benefit from 2 recent important in-depth reviews (1,2).

This review will build on a worthy State-of-the-Art Paper by Naqvi (3), published in *iJACC* a few years ago, by further describing the role of the most up-to-date echocardiographic methods (including RT3D and simultaneous biplane transesophageal echocardiography [TEE]) in patient selection and intraprocedural monitoring of patients undergoing percutaneous mitral valve interventions. We will focus on 3 interventions: 1) percutaneous mitral balloon valvuloplasty (PMBV) for mitral stenosis; 2) transcatheter edge-to-edge repair (TE2E) of mitral valve regurgitation; and 3) transcatheter closure of periprosthetic regurgitation (TPPR).

PMBV for Mitral Stenosis

Patient selection. Since its introduction in 1984 by Inoue et al. (4), PMBV has become a safe, effective, less invasive alternative to surgery, with low complication rates, for some patients with symptomatic rheumatic mitral stenosis. In properly selected patients, PMBV obtains excellent immediate and sustained hemodynamic improvement, comparable to the results of surgical procedures, including open or closed mitral commissurotomy and mitral prosthetic replacement (5,6).

Proper patient selection is of major importance when predicting the immediate and long-term results of PMBV. The most validated and commonly used transthoracic echocardiographic (TTE) criterion is the one originated by Wilkins et al. (7), which we call the "splitability score." This assessment by TTE takes into account the severity and extent of leaflet calcification, leaflet thickening, leaflet mobility, and involvement of the subvalvular apparatus (Table 1), each graded qualitatively on a 1-to-4 scale (maximum total score = 16). An inverse relationship exists between the total splitability score and PMBV success, with the cutpoint of ≤8 reflecting best short- and long-term results. Of note, Wilkins score alone does not appear to be a good predictor of post-PMBV mitral regurgitation (MR), but rather the degree of commissural opening (8,9). In addition, it is important to carefully quantify the severity of underlying MR before percutaneous valvotomy (Online Video 1A and 1B, Figs. 1A to 1C). MR that is ≥2+ has been demonstrated by Palacios et al. (9) to be associated with worse outcome. Recent technological advances such as RT3D echocardiography with multiplanar reformatting have allowed more precise measurement of the mitral valve (MV) area before the procedure (Fig. 1D). 3D TEE allows interrogation of the commissures more directly, which is very helpful to understanding asymmetric fusion or calcification of commissures. These asymmetric defor-

mations of mitral orifice may increase the risk of MR with balloon valvuloplasty. Further, alteration in shape of mitral orifice in 3D is the consequence of subvalvular, valvular, and leaflet scarring, all of which are important determinants for the success of balloon valvuloplasty (10,11).

TEE before PMBV is useful to screen for left atrial (LA) or LA appendage thrombus or dense spontaneous echo contrast, which are common in mitral stenosis patients, due to LA blood stasis and atrial fibrillation.

A small single-center study of 23 patients evaluated the role of multiphase cine cardiac computed tomography (CT)–derived Wilkins score to predict MV area changes after PMBV. Cardiac CT-derived score was more predictive of MV area increase after PMBV than echocardiographic-based Wilkins score was. In particular, increased posterior leaflet mobility, decreased leaflet thickness, and absence of subvalvular disease were all associated with MV area improvement following PMBV (12). To this date, cardiac magnetic resonance imaging has not been used in patient selection or procedural guidance in PMBV.

Intraprocedural monitoring. After obtaining venous and arterial access, TEE is typically performed under conscious sedation in the catheterization laboratory. Adequate anesthesia of the posterior pharynx and suctioning is the key to success for patient comfort. Prior to septal puncture, the atrial appendage and LA are carefully assessed to rule out thrombus. Thrombus can develop in the appendage very rapidly, especially when anticoagulation is withheld for the procedure. Reassessment of MR and gradients at this time can serve as an important baseline to compare after balloon inflations to judge adequacy of the procedure.

Although the transseptal puncture can be performed primarily by fluoroscopic guidance, ultrasound imaging with TEE or intracardiac echocardiography can be useful, improving visualization of the contiguous structures and mainly avoiding aortic puncture. The specific location of the transseptal puncture may be customized to meet the needs of the specific procedure. Crossing at the level of the fossa ovalis in the posterior inferior part is best for most PMBV. The transseptal puncture site can be chosen using the visualization by TEE of tenting of the atrial septum by the catheter before advancing the needle. Figure 2 shows TEE guidance, using multiple planes/views. For example, the bicaval view secures the proper height, whereas the proper distance from the aorta is best

appreciated in the short-axis view. This becomes particularly important in patients with previous septal surgeries or punctures, excessively mobile septum, and in patients with very large atria or distorted anatomy as seen in patients with scoliosis or pneumonectomy.

Although fluoroscopy has an important role, TEE is very helpful to optimize balloon position across the MV leaflets and avoid entrapment in the subvalvular apparatus. TEE imaging with 2 simultaneous orthogonal planes is helpful to visualize the best position for Inoue balloon placement between the MV leaflets and guide during its quick inflation (Online Video 2A and 2B). TEE use is critical to identify and prevent complications such as pericardial effusion and aortic puncture.

Immediately following PMBV, the TEE exam should be targeted to answer quickly 4 important questions:

1. How severe is the MR and does it emerge from a commissural location? (Online Video 3A and 3B, Figs. 3A and 3B)
2. What are the post-PMBV MV area and the peak/mean MV gradients? (Figs. 3C and 3D)
3. Is there good commissural opening? Is it bilateral or unicommissural? (Fig. 3D)
4. Is there any increase in pericardial effusion? If so, what is the size, and what are the hemodynamic consequences?

RT3D with multiplanar reformatting immediately after PMBV provides superior estimation of MV area compared with conventional TEE (Fig. 3D) (13). Intraprocedural RT3D immediately after balloon inflation can diagnose the presence and extent of leaflet tears better than TTE, 2-dimensional (2D) TEE, or intracardiac echocardiography can (14).

RT3D also provides improved ability to determine the degree of commissure opening after PMBV, which is an important prognosticator of the clinical procedural success in addition to the traditional measurement of MV area and gradients (15). Immediate post-procedure measurements of valve area and gradients might obtain different results than measurements performed later after LA remodeling and changes in wall compliance. Furthermore, changes in heart rate may also have an impact on mitral gradients, potentially misleading interpretation of comparative readings.

ABBREVIATIONS AND ACRONYMS

LA = left atrial

MR = mitral regurgitation

MV = mitral valve

ParaVR = paravalvular regurgitation

PMBV = percutaneous mitral balloon valvuloplasty

RT3D = real-time 3-dimensional imaging

TE2E = transcatheter edge-to-edge repair

TEE = transesophageal echocardiography

TPPR = transcatheter closure of periprosthetic regurgitation

Table 1. Assessment of MV Anatomy According to the Wilkins Score

Grade	Mobility	Thickening	Calcification	Subvalvular Thickening
1	Highly mobile valve with only leaflet tips restricted	Leaflets near normal in thickness (4–5 mm)	A single area of increased echo brightness	Minimal thickening just below the mitral leaflets
2	Leaflet mid and base portions have normal mobility	Mid-leaflets normal, considerable thickening of margins (5–8 mm)	Scattered areas of brightness confined to leaflet margins	Thickening of chordal structures extending to one-third of the chordal length
3	Valve continues to move forward in diastole, mainly from the base	Thickening extending through the entire leaflet (5–8 mm)	Brightness extending into the mid portions of the leaflets	Thickening extended to distal third of the chords
4	No or minimal forward movement of the leaflets in diastole	Considerable thickening of all leaflet tissue (>8–10 mm)	Extensive brightness throughout much of the leaflet tissue	Extensive thickening and shortening of all chordal structures extending down to the papillary muscles

The total Wilkins score (3) is the sum of the 4 items and ranges between 4 and 16.
MV = mitral valve.

TE2E Repair of MV Regurgitation

This percutaneous mitral clip technique mimics the surgical mitral repair procedure introduced in 1991 by the Italian surgeon Ottavio Alfieri who successfully treated a patient with anterior leaflet prolapse. Using a pledgeted stitch to approximate the edges of the middle portions of the anterior and posterior mitral valve leaflets, Alfieri created a double orifice ("figure of 8") (16). In the largest surgical series from this same group, including 260 patients who underwent such repair, 80% of the cohort had additional MV annuloplasty that was associated with reduced reoperation at a mean follow-up of 5 years (17).

TE2E implants a clip that grasps the free edges of the middle portions of the MV, to reduce the degree of MR. For example, a portion of 1 leaflet that is prolapsing or flail can be supported by attaching it via the clip to the opposite leaflet that has intact chordae.

Several other devices designed to mimic a surgical annuloplasty are under development and/or earlier stages of clinical trials. However, as documented by CT (18), the method of coronary sinus implantation has some dangers of affecting the circumflex artery and missing the desired annulus location.

The MitraClip system (Evalve Inc., Menlo Park, California) has been the most studied device currently available for transcatheter treatment of MR. The EVEREST I (Endovascular Valve Edge-to-Edge Repair Study) established the safety, feasibility, and hemodynamic improvements in patients with moderate to severe (3+) to severe (4+) MR. The morbidity and mortality were low, and the MR was reduced to <2+ in the majority of patients, along with sustained freedom from death (19). Recently, the results of the EVEREST II trial were reported, which randomized patients with 3 to 4+ MR to either percutaneous repair or surgical repair/replacement. Percutaneous repair was less effective at reducing MR than conventional surgery was (approximately 23% patients were left with ≥3+ MR), but the procedural risk of TE2E was low. The surgical and the TE2E groups with successful treatment showed similar improvements in reduction in LV size as assessed by echocardiography and
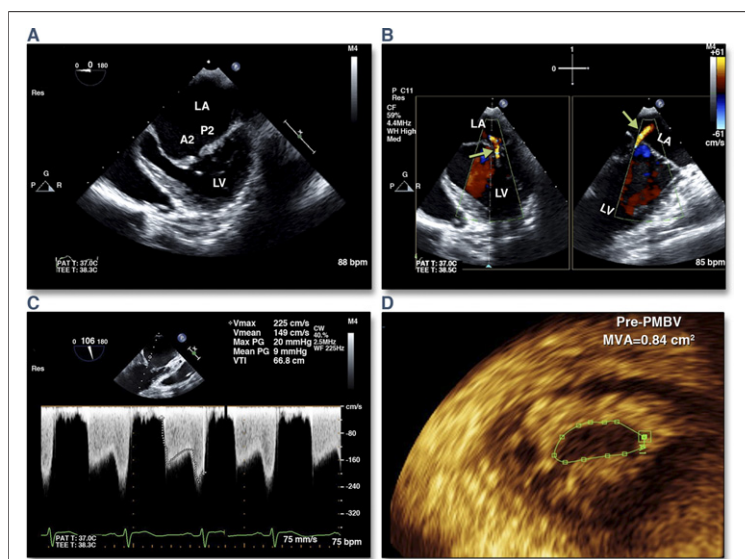

Figure 1. Pre-Procedural Assessment of a Stenotic MV by TEE

(A) Transesophageal echocardiography (TEE) at mid-esophageal level at 0° ("4-chamber view"). Note moderate bileaflet thickening involving the mid-distal segments of the mitral valve (MV) with reduced opening. **(B)** Simultaneous biplane imaging of the MV at the mid-esophageal level at 0° and 90° **(right)** with color Doppler showing mild mitral regurgitation **(arrow)** at baseline. **(C)** Continuous-wave Doppler indicating increased transmitral gradients. **(D)** Real-time 3-dimensional imaging with multiplanar reformatting showing a severely stenotic MV with important commissural fusion (MVA = 0.84 cm²). A2 = middle anterior scallop; LA = left atrium; LV = left ventricle; MVA = mitral valve area; P2 = middle posterior scallop; PMBV = percutaneous mitral balloon valvuloplasty.
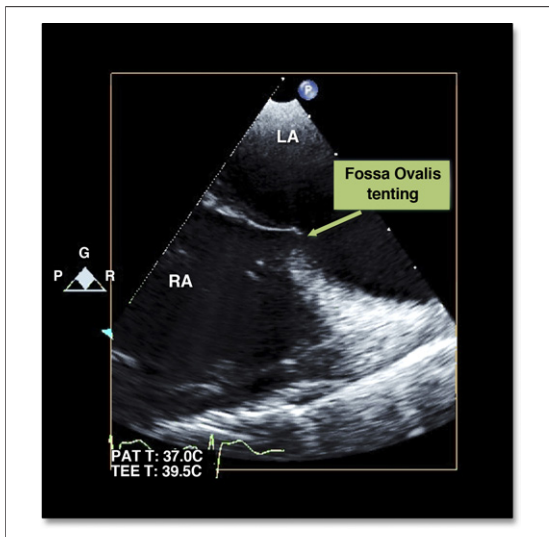
Figure 2. Transseptal Puncture Under TEE Guidance

Note tenting of the fossa ovalis by the catheter before advancing the needle. RA = right atrium; other abbreviations as in Figure 1.

similar clinical improvement in symptoms and exercise capacity (20). The high-risk registry data recently showed improvement in MR in a majority of patients, resulting in improvement in clinical
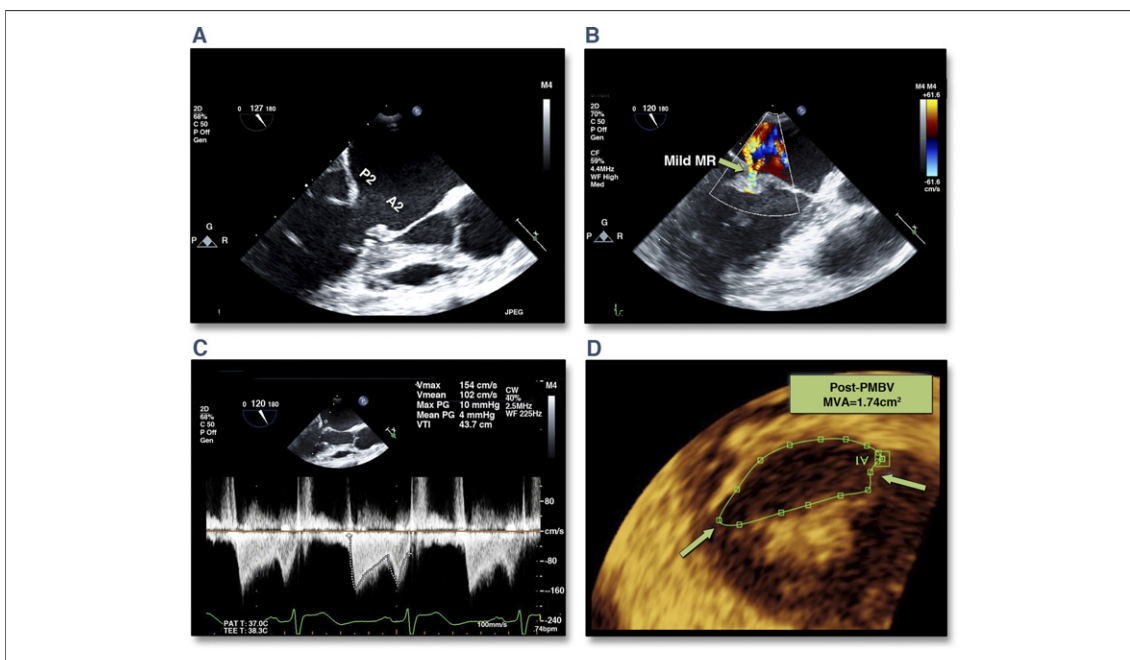
symptoms and significant left ventricular reverse remodeling over 12 months (21).

Patient selection. TE2E has been successful in reducing MR in 2 groups of patients: those with excessive leaflet motion (myxomatous degeneration with prolapse or flail); or those with functional MR (apical tethering of normal leaflets), including patients with left ventricular enlargement from ischemic heart disease. TE2E is not applicable to patients with MR due to restricted leaflet motion (rheumatic MR) and those with flail or prolapse that does not involve the middle portion of the anterior or posterior mitral leaflets, the "grasping area" for the TE2E procedure, or in whom that area is calcified (22).

A key TTE inclusion criterion for the MitraClip requires a regurgitant jet origin associated with the A2 to P2 segments of the MV and not at the commissures. For patients with functional MR, the coaptation length must be at least 2 mm, and the coaptation depth less than 11 mm. For patients with flail leaflet, the flail gap must be <10 mm and the flail width <15 mm (19) (Fig. 4). Calcification of the grasping area of the leaflets is also a contraindication because of potential risk of embolization. A critical goal of the

Figure 3. Post-PMBV Assessment of the MV by TEE

(A) Post-PMBV TEE, from the same patient illustrated in Figure 1, shows improved mobility of both MV leaflets (still diastolic frame). **(B)** Mild MR is observed after PMBV with integrity of the mitral leaflets and subvalvular apparatus. **(C)** Continuous-wave Doppler across the MV reveals significant improvement of transmitral gradients. **(D)** Post-PMBV real-time 3-dimensional imaging with multiplanar reformatting shows significant improvement in the MVA (from 0.84 to 1.74 cm²), and commissural opening **(arrows)** making planimetry a less valid parameter. Compare MVA differences before and after PMBV with Figure 1D. MR = mitral regurgitation; other abbreviations as in Figure 1.
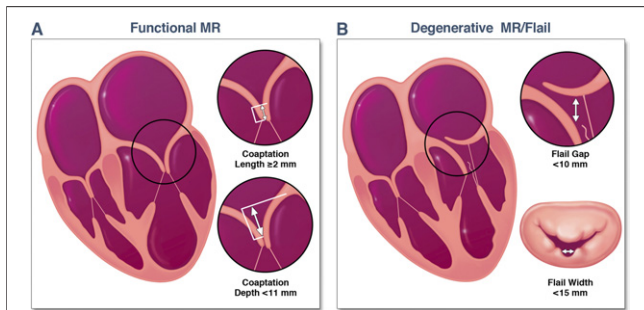
Figure 4. Anatomic Eligibility Criteria for MitraClip (EVEREST Trial)

(A) In functional MR, the primary mechanisms are mitral annular dilation and leaflet restriction secondary to LV remodeling. The posterior mitral leaflet is more commonly involved from scarring of the inferior wall and posteromedial papillary muscle. These processes lead to apical tethering with malcoaptation of the MV leaflets as shown. The coaptation length must be at least 2 mm, and coaptation depth must be <11 mm so that there is some tissue the clip can grasp. (B) In degenerative MR with MV prolapse and/or flail, measurements such as flail depth <11 mm and a flail width on short axis <15 mm are important anatomic features associated with increased MitraClip procedural success. EVEREST = Endovascular Valve Edge-to-Edge Repair Study; other abbreviations as in Figures 1 and 3.

moving abnormally is determined using long-axis views. Which portion of the leaflet is moving abnormally is determined from 2D short-axis views, 2D intercommissural long-axis views, or RT3D; this has improved the complete visualization of MV scallops (23,24) (Online Video 5, Fig. 6).

The potential role of cardiac CT (25,26) and cardiac magnetic resonance (25) in the assessment of a patient's eligibility and intraprocedural guidance for percutaneous MV procedures has been reviewed elsewhere (25). The feasibility and true clinical utility of these techniques remain untested in a large-scale cohort of patients.

Another important goal of the pre-procedural echo is to quantitate carefully the severity of MR using American Society of Echocardiography guidelines. For this, important images are zoom mid-esophageal long-axis or 4-chamber views of the flow convergence, for measurement of the aliasing radius (to calculate regurgitant orifice area) and the diameter of the vena contracta, although for MR jets that are eccentric, not holosystolic, or have proximal constraint, the assumptions of these calculations may be misleading. Additional useful views include a pulsed Doppler assessment of the
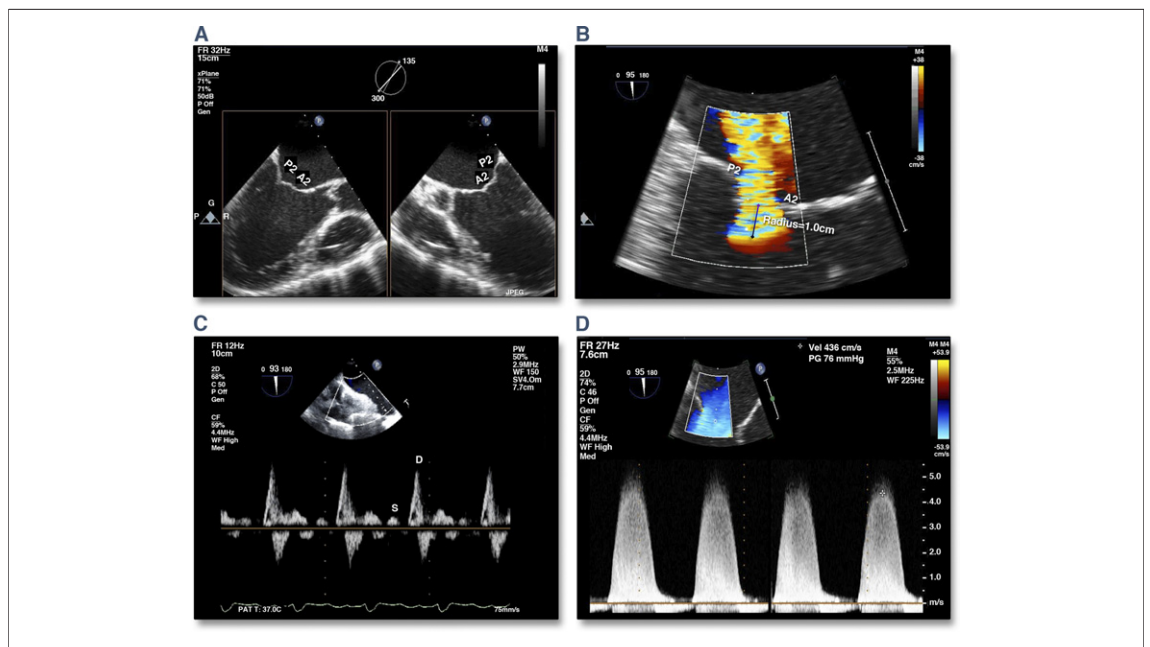
pre-procedural echo imaging study is the determination of the MR mechanism and severity (Online Video 4A and 4B, Figs. 5A to 5D). Which leaflet is

Figure 5. TEE Assessment of MV Morphology, Regurgitation Mechanism, and Quantification

(A) Two-dimensional TEE at mid-esophageal level 0° using real-time biplane imaging with orthogonal planes showing functional MR with MV annular dilation and leaflet tethering leading to central malcoaptation between A2 and P2 scallops. (B) Mid-esophageal zoomed view at 95° of the MV with color Doppler showing systolic frame representing severe central mitral regurgitation jet. Note the proximal flow convergence zone with large radius (1.0 cm). (C) Pulse-wave Doppler interrogation of the right upper pulmonary vein flow showing marked systolic blunting (S) indicative of elevated LA pressures. (D) Continuous-wave Doppler through the MV, which demonstrates a dense holosystolic regurgitant jet with high peak velocity. All these features are consistent with severe MR. Abbreviations as in Figure 1.
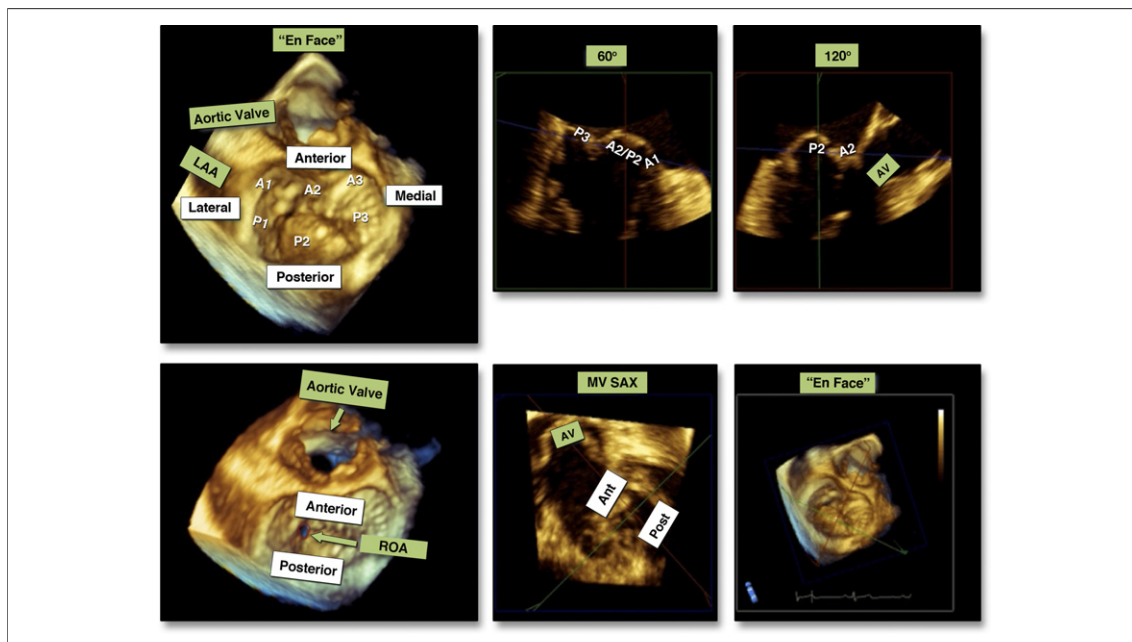
Figure 6. RT3D TEE With En Face View of the MV (Systolic Frame)

Marked myxomatous changes of the MV leaflets, with particularly severe P2 prolapse and mild A2 prolapse. Note the regurgitant orifice area (ROA) created by the malcoaptation of the prolapse scallops (**D**). Post-processing software allows multiplanar reconstruction (**B,C,E,F**) adding detailed information about the anatomy of MV scallops and relationship with other structures. Anterior is to the top, where the aortic valve (AV) is, and the left atrial appendage (LAA) is to the left of the figure. RT3D = real-time 3-dimensional; SAX = short axis; other abbreviations as in Figure 1.

pattern of systolic reversal of flow in 1 or more pulmonary veins (Fig. 5C) and the density of continuous wave Doppler recordings through the mitral orifice (Fig. 5D). These assessments provide an important baseline for comparison after repair, although the flow convergence methods are very difficult or nearly impossible once the MitraClip is in place, mostly due to the multiplicity of residual regurgitant jets after clip deployment.

Intraprocedural monitoring. The success in delivering the MitraClip under real-time echocardiographic guid-

ance is a result of the unique collaboration between interventionalists and echocardiographers. The TE2E procedure entails a standard sequence of maneuvers, all of which are monitored and guided by echocardiography (Table 2).

Table 2. Role of Transesophageal Echocardiography in Edge-to-Edge MV Repair Technique (MitraClip)

Assessing the mechanism of MR
Quantitating the severity of MR
Guiding transseptal crossing
Aligning the delivery system perpendicular to the mitral plane at the location of the MR jet
Alignment of clip's arms perpendicular to MV coaptation line
Determining success of grasping both leaflets
Verification of clip stability after release from delivery system
Reassessing MR severity
Locating of persistent leak(s)

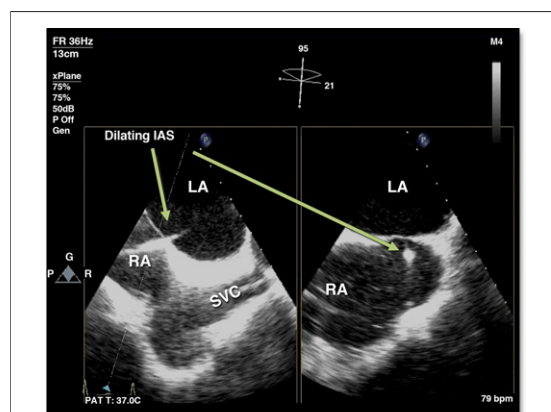MR = mitral regurgitation; MV = mitral valve.

Figure 7. TEE Bicaval View With Simultaneous Biplane Imaging Showing IAS Dilation by the Guiding Sheath

Arrows indicate the interatrial septum (IAS) dilation by the guiding sheath. SVC = superior vena cava; other abbreviations as in Figures 1 and 2.
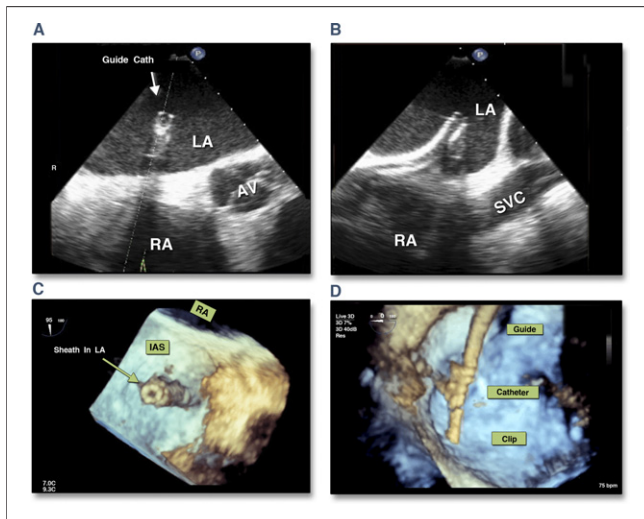
Figure 8. TEE at Mid-Esophageal Level With Simultaneous Biplane Imaging Showing the Guide Sheath Transversing the Interatrial Septum and Into the LA

(A) Guide sheath **(arrow)** into the LA at a safe superior distance from the AV. **(B)** Semibicaval view showing the guide sheath tip pointing away from the LA walls. **(C)** Live 3-dimensional (3D) view from the LA perspective, looking toward the RA. **(D)** Components of the MitraClip shown by 3D echo: guide sheath, delivery catheter, and MitraClip at the distal tip. Abbreviations as in Figures 1, 2, 6, and 7.

Supervision of transseptal puncture and crossing is the first goal of TEE imaging. As mentioned before, TEE or intracardiac echocardiography can visualize the location where the catheter indents the atrial septum, allowing the interventionalist to adjust the location of septal crossing, aiming far enough superiorly and posteriorly to allow the arc of the catheter to easily reach the middle of the mitral orifice. A mid-esophageal aortic valve short-axis view (multiplane angle of approximately 30° to 60°) and the bicaval view at 90° to 100° are useful during the transseptal puncture to visualize all the adjacent structures avoiding device-endocardial contact. The transverse 4-chamber (0°) imaging plane can assess the height of proposed septal puncture above the valve plane (22).

Once the interatrial septum is crossed, the next step is to dilate the interatrial septum to allow the passage of the delivery system and clip toward the regurgitant MV (Fig. 7). During advancement of the super stiff wire, monitoring with TEE can help to avoid puncture of the LA appendage or LA wall to avoid pericardial tamponade. The catheter tip is echodense and should be imaged during most manipulations to avoid contact with the posterior and lateral structures such as the lateral LA wall and LA appendage (Online Video 6, Fig. 8). Then the delivery catheter is turned inferiorly and aligned parallel to the antegrade mitral flow. For this, the en face RT3D of the MV "surgeon's view" from the LA perspective (23) (Fig. 9A) is helpful. We particularly use the biplane real-time imaging with 1 plane in the intercommissural orientation (at multiplane angles of about 45° to 70°), and the other in a long-axis orientation (Fig. 9B). The clip should be positioned where the largest mitral regurgitant jet is located by color Doppler mapping, such that it splits the jet and is pointed parallel to the direction of mitral antegrade flow (Online Video 7).

Once the tip of the delivery catheter is poised in the LA just above the MV, the arms of the clip device are then opened. It is important to rotate the
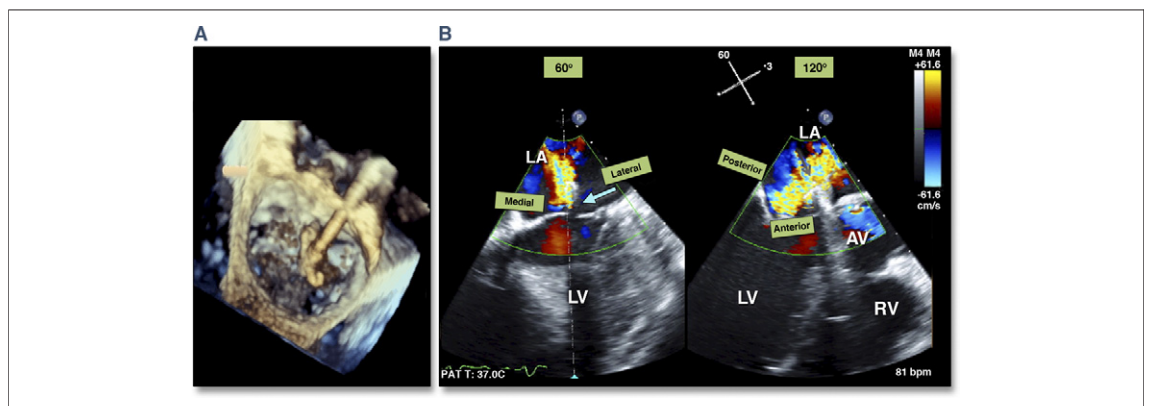

Figure 9. Advancing the MitraClip Into the LV

(A) RT3D of the mitral valve in the en face/surgeon's view using proper perpendicular alignment of the MitraClip. **(B)** Mid-esophageal view using simultaneous biplane imaging showing the MitraClip being advanced into the MV. Color Doppler mapping is used to guide the correct position where the MR jet is. Although the image frame rate decreases due to increased processing demand, we tend to use it intermittently to aid in the fluoroscopic guidance for the interventional cardiologist. Abbreviations as in Figures 1, 3, and 6.

clip arms so that they are perpendicular to the mitral coaptation line, primarily using the RT3D surgeon's view; when it is unavailable, the transgastric 2D short-axis view of the MV should be used, although it is difficult to obtain in about one-third of patients (Online Video 8, Figs. 10A and 10B).

After passage of the clip into the left ventricle, and final verification of its position and orientation, the open device is pulled up to grasp the leaflets from their underside. Both RT3D and simultaneous biplane imaging are crucial at this point to determine the success of grasping both leaflets (Figs. 11A and 11B). Once both leaflets are grasped, the arms of the clip are closed and an assessment is made of the new severity of the MR (Online Video 9, Fig. 11C). If the MR has not been substantially reduced, the clip is everted and brought back into the LA, and a repeat placement of the same clip is attempted. If the MR has been substantially reduced, the clip arms are tightened and the delivery system is detached. After verification of the stability of the clip, the suture attached to the clip is pulled through to remove the final tether of the clip (Online Video 10, Fig. 11D). Finally, repeat assessment of the severity of the residual MR and the mitral gradient, before and during afterload manipulation with phenylephrine, helps to determine whether a second clip should be placed, which is indicated usually if moderate or greater (≥2+) MR is present. If needed, the second clip should be positioned where the flow convergence and vena contracta are largest. Before a second clip is deployed, it is important to search for any significant increase in transmitral gradients resulting from the first clip. This routine practice is probably the explanation why no cases have been reported of acute mitral stenosis with this procedure. Finally, in patients with hypotension, it may be useful to manipulate afterload and pre-load to evaluate the severity of MR under hemodynamics more comparable to ambulatory conditions.

This TE2E procedure can be lengthy and very demanding on both the echocardiographer and interventionalist. Both RT3D and simultaneous biplane imaging provide substantial value over single-plane 2D TEE by reducing the need to flip the image back and forth between the intercommissural and long-axis views. Frequent monitoring of the pericardial space allows early detection of growing effusions before hemodynamic compromise develops. As mentioned previously, good communication between the echocardiographer
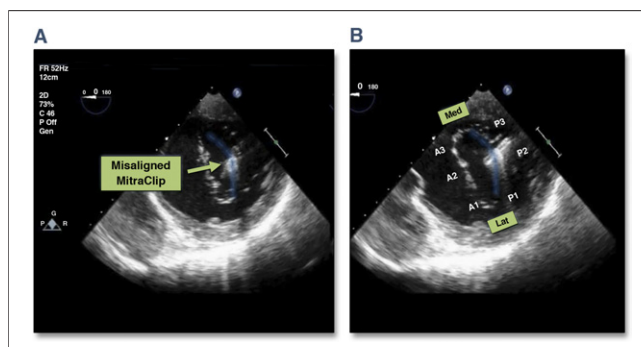

Figure 10. Transgastric View With Retroflexion Showing the LV in Short-Axis View With the MitraClip Straddling the MV Leaflets

(A) Note that the MitraClip **(arrow)** is not orientated perpendicular to the MV coaptation line **(dashed blue line)**. (B) MitraClip position is corrected with 30° of clockwise rotation of the delivery catheter. Lat = lateral; Med = medial; other abbreviations as in Figure 1.

and the interventionalist, using standardized vocabulary and anatomical landmarks, is essential to decrease maneuvering error and to increase procedural efficiency. With the advent of 3D echocardiography, there is also a need for proper training of the interventional cardiologist on the basic 3D views. This is of critical importance if
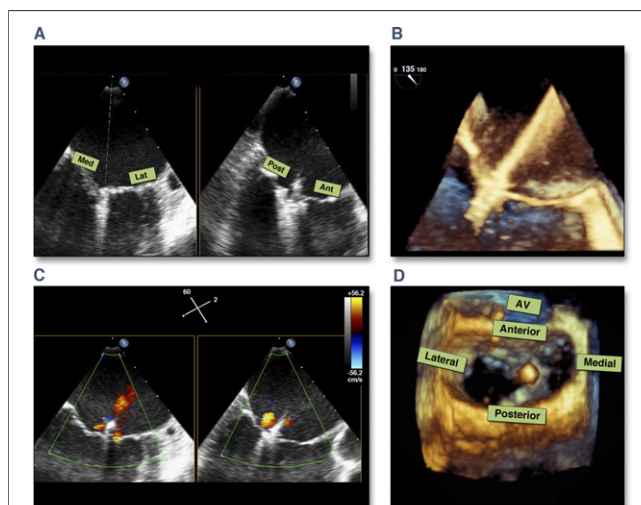

**Figure 11. Sequence of Events in the Deployment of Edge-to-Edge MV Repair Technique (MitraClip)**

(A) Simultaneous biplane imaging at 60° and 150° demonstrates the exact location of the MitraClip within the MV structure. Once the position is confirmed, grasping of the MV leaflet occurs. (B) Live 3D zoomed view of the delivery catheter and MitraClip grasping the A2 and P2 scallops of the MV. (C) Similar to A, simultaneous biplane imaging at 60° and 150° demonstrates trivial to mild (1+) MR after MitraClip grasps the MV leaflets. (D) MitraClip system is finally released from the delivery system and seen **(arrow)** in the center of the new "figure-of-8" MV. Ant = anterior; Post = posterior; other abbreviations as in Figures 1, 3, 8, and 10.

Table 3. Role of TEE in TPPR
Assessing the severity of ParaVR
Identification of the location and number of holes
Guiding atrial septal puncture or LV apical puncture (in patients with the combination of prosthetic aortic and mitral valves or issues of crossing the aortic valve)
Guiding placement of the veno-arterial rail
Assessing reduction in ParaVR during balloon inflation
Assisting with placing the disk in the defect
Monitoring the effects of the device on prosthetic leaflet (occluder) motion
Reassessing the severity of ParaVR
LV = left ventricular; ParaVR = paravalvular regurgitation; TEE = transesophageal echocardiography; TPPR = transcatheter closure of periprosthetic regurgitation.

this technique is used for real-time navigation. Orientation in the 3D domain can be particularly confusing the absence of internal anatomical landmarks. A recent document from the European Association of Echocardiography and the American Society of Echocardiography provides an important practical guide on the image acquisition, interpretation, as well as current and potential clinical applications of 3D echocardiography (2).
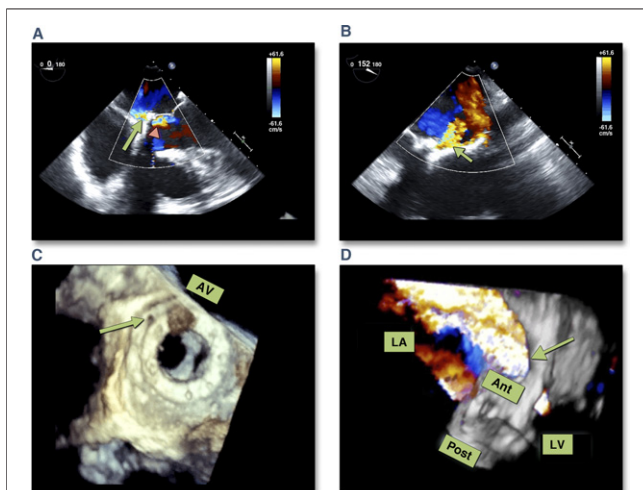
Figure 12. TEE Baseline Assessment of ParaVR

(A) Two-dimensional (2D) TEE at mid-esophageal 4-chamber view (0°) showing paravalvular regurgitation (ParaVR) **(arrow)** outside the anterior aspect of the MV bioprosthesis annulus. Also note the flow convergence zone **(arrowhead)**, which suggests significant regurgitant flow. **(B)** At 150°, shown from another angle, is the severe anterior paravalvular leak **(arrow)**. **(C)** RT3D of the MV bioprosthesis demonstrating the paravalvular hole **(arrow)**. Note the AV is on the top. **(D)** RT3D with color Doppler shows the large anterior paravalvular leak **(arrow)**. Abbreviations as in Figures 1, 6, and 11.

TPPR

Patient and device selection. Paravalvular regurgitation (ParaVR) is common, but most cases are small and asymptomatic. Clinically important ones, occurring in as many as 5% of patients who have undergone valve replacement, tend to present with congestive heart failure, hemolytic anemia, or arrhythmias. This may result from suture dehiscence due to infection (endocarditis), annular calcification, technical problems, and/or a combination of all of those.

Surgical intervention is usually recommended to patients with symptomatic ParaVR, especially if it is associated with infection, although increased morbidity and mortality associated with reoperation have stimulated the development of other options to address this complex problem. TPPR appears as an attractive, albeit challenging, alternative. Most published evidence comes from single-center experience with case reports predominantly involving ParaVR of the MV prosthesis. More recently, technical success has ranged from 63% to 100% (27–30). In this new field of work, the design of specific "plugging" devices is in its early phase (31). Most reports of TPPR have entailed off-label use of devices designed to close congenital septal defects or vascular plugs.

Goals of imaging in TPPR and description of the procedure. Transprocedural echocardiographic imaging in TPPR is critically important because it can help the interventionalist to: 1) locate the optimal region for transseptal puncture; 2) guide the crossing of the hole that leads to ParaVR; 3) monitor the decrease in ParaVR during balloon inflation; 4) monitor the onset of possible complications (pericardial effusion, iatrogenic post-procedure atrial septal defect or prosthetic leaflet entrapment); and 5) assess the final result of the device implantation. Table 3 summarizes the important aspects of TEE for this particular procedure.

The role of transesophageal echo in TPPR begins with assessing the severity of the ParaVR. This is difficult in mitral ParaVR because the left ventricular side of the mitral prosthesis, where the flow convergence would ideally be measured, is commonly shadowed by the prosthesis itself. The presence of a mitral prosthesis also shields the left ventricular outflow tract where the periprosthetic aortic regurgitation would be observed. Furthermore, wall constraint often prevents the flow convergence from forming hemispheric isovelocity forms, so quantitation of the MR is often difficult.

Probably the most important role of TEE in TPPR is identification of the location and number of holes that are present. Single-plane and biplane 2D TEE with color Doppler imaging is the mainstay tool for this purpose (Figs. 12A and 12B). Use of RT3D with color Doppler imaging appears to be useful (27,32,33) (Figs. 12C and 12D), although low temporal resolution, lack of standardized angles, and potential motion creating "stitching artifacts" are current limitations of this imaging technique. Nonetheless, for mitral prosthetic regurgitation, the RT3D TEE with en face/surgeon's view from the LA is most helpful. Although necessitating another step, the best convention should be to rotate the image so the aortic valve is at the top of the image (Figs. 11D and 12C). Multiple simultaneous biplane 2D views also are useful for characterization of anatomic relationships. Note should be made of which TEE imaging plane/angle best visualizes the regurgitant jet.

We also frequently use a fluoroscopic overlay technique with CT scanning produced by rotating the C-arm at high speed around the patient (Syngo DynaCT Cardiac, Siemens, Erlangen, Germany). Several hundred images are acquired and reconstructed as 3D volumes. Anatomic details of interest are marked on the pre-procedural CT angiography, which is coregistered to an intraprocedural CT acquired in the catheterization laboratory. The CT-CT registration is then fused to the real-time fluoroscopic image, allowing better procedural navigation with fluoroscopy and with less use of a contrast medium (34). Furthermore,

guidance in the optimum site for transseptal puncture (Fig. 13A) and overlaying the ParaVR location, defined by TEE, on the fluoroscopy are other important strengths of this new imaging technique (Fig. 13B).

Access to the defect may be either antegrade via a venous transseptal approach or retrograde in the direction of the regurgitation from arterial access (coming across the aortic valve or transapical). The site of transseptal puncture in TPPR is highly variable and dependent on the location of the ParaVR. For example, lateral defects are better approached with transseptal access in the posterior part of the fossa via the inferior vena cava, whereas medial defects adjacent to the septum require even lower and posterior puncture (35). Therefore, imaging guidance of atrial septal puncture either by intracardiac or TEE or with the CT/fluoroscopy overlay as aforementioned is important in TPPR.

The objective is to pass a wire through from the right atrium to the LA. The venous wire is then snared using another wire introduced through the femoral artery. In patients who have both aortic and mitral valve replacements in place, the echo can help guide LV apical puncture for downstream access (27). The first (venous) wire is pulled through and its tip exteriorized, which can thus be called a veno-arterial rail (36). This allows better support for the delivery catheter in situations where numerous defects and/or acute angles are encountered thereby making transit of the delivery catheter difficult across the ParaVR or creating excessive kinking on it. Hence, TEE has
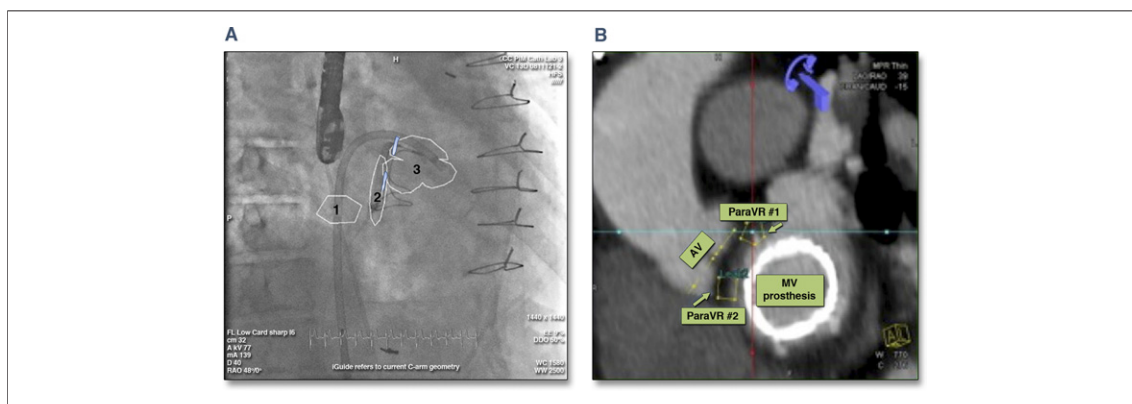

Figure 13. Fusion/Overlay of the ParaVR Information by TEE With Fluoroscopic Overlay Technique With CT Scanning Produced by Rotating the C-Arm at High Speed Around the Patient

This technique allows better procedural navigation with fluoroscopy. **(A)** Fluoroscopic right anterior oblique projection with the interventionist drawings indicating the site of transseptal puncture **(1)**, the prosthetic MV **(2)**, aortic valve ("t3-leaf-clover") **(3)**, and the 2 sites of ParaVR **(blue circles)** (not well-seen in this projection but corresponding to the sites on the next panel). **(B)** Computed tomography (CT)/fluoroscopy imaging overlay demonstrating the prosthetic MV and the 2 sites of ParaVR **(pentagon and square shapes)** according to appropriate en face TEE. Abbreviations as in Figures 1, 6, and 12.
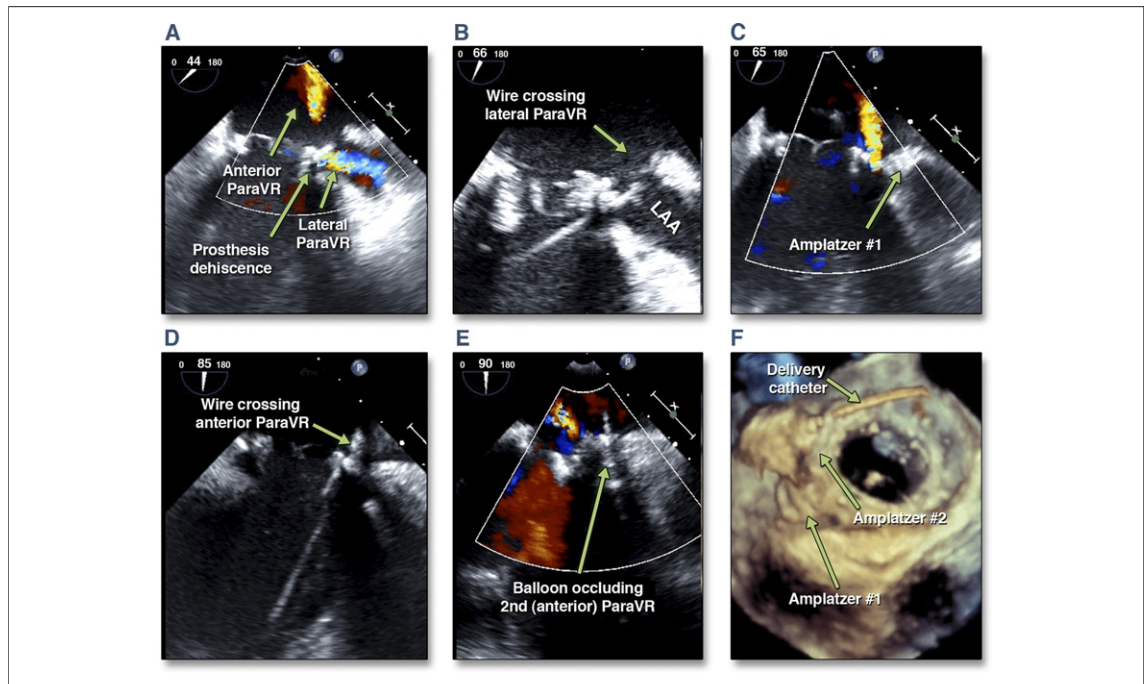
Figure 14. Percutaneous Closure of ParaVR From a Dehisced Mitral Bioprosthesis

(A) There are 2 separate ParaVR jets (anterior and lateral) that are moderate (2 to 3+) in severity and arising from the area of annular dehiscence. **(B)** Under fluoroscopic and TEE guidance, transseptal puncture allows the venous wire to cross the lateral defect. **(C)** Post-deployment of first Amplatzer device (St. Jude Medical, St. Paul, Minnesota). Note resolution of lateral ParaVR and close proximity of moderate residual anterior ParaVR. **(D)** The anterior ParaVR is now approached with the venous wire crossing of the ParaVR defect. **(E)** Once position is confirmed, transient balloon inflation within the ParaVR defect allows confirmation of adequate position (no significant ParaVR) for subsequent deployment of the second Amplatzer device. **(F)** Live 3D view of the mitral bioprosthesis shows the 2 Amplatzer devices in close proximity to each other and, more important, normal MV leaflet functioning. Abbreviations as in Figures 1, 6, 8, and 12.

an important role in guiding placement of the wire. Once the wire is in place, the interventionalist can move and approach placement of the occluder device from either direction. Some operators use balloon inflation within the defect with TEE to see if the regurgitation is reduced by this temporary occlusion of the defect. If balloon occlusion reduces the regurgitation substantially, TEE guides placement of the occluder device within the defect. After the device is expanded, TEE monitors for changes in the motion of mechanical disks or other adverse effects on the heart (Online Video 11, Fig. 14).

Reassessment of the ParaVR severity by TEE enables a decision whether a second occluder device is needed. This reassessment of the severity of regurgitation again is problematic because often there are unusual anatomy and perivalvular tracts that are eccentric and shielded by a prosthetic valve and the interventional device. Therefore, assessment of the aliasing radius for calculation of the regurgitant orifice area is problematic; other means of regurgitation assessment, including spatial color
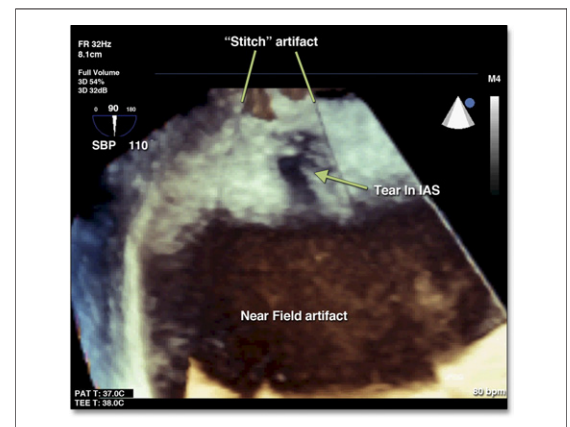

Figure 15. Post-Procedural Complication in a Patient Who Underwent TPPR and RT3D Artifacts

Aside from the iatrogenic atrial septal defect created **(arrow),** also note 2 common artifacts seen with the use of 3D TEE: 1) "stitch" artifact due to irregular cardiac rhythm, probe, and/or patient (respiratory) movements during the image acquisition, creating clear artificial lines that divide/fragment the structure being imaged; and 2) near-field artifact due to improperly high gain-settings in the near field creating a "dark zone" over the area of interest. SBP = systolic blood pressure; TPPR = transcatheter closure of periprosthetic regurgitation; other abbreviations as in Figures 1, 6, 7, and 8.

Doppler mapping and pulmonary vein flow profiles, are required.

In summary, TEE is useful in guiding transcatheter closure of ParaVR by guiding access to the area from the arterial and venous side, placement of the occluder device, and assessment of the amount of reduction of regurgitation.

Future Directions

Intraprocedural imaging (RT3D TEE, biplane imaging, CT/fluoroscopy overlay, etc.) will continue to evolve in parallel with advances in percutaneous MV interventions. In terms of TE2E, better patient selection along with further refinements on the device technology addressing the annulus component in addition to the leaflet problem would be crucial for the long-term success. In TPPR, better design with low-profile devices could avoid complications such as inflow/outflow obstruction or leaflet impingement.

Although 3D TEE is a powerful tool with several advantages for use in percutaneous interventions, improvements, in particular, the frame rate when using simultaneous RT3D with color Doppler are needed. Furthermore, during acquisition of full volume 3D dataset, stitch artifacts can occur due to irregular heart rhythm, patient's respiratory motion, or fine probe movements, making interpretation more difficult. Improper gain adjustments along with device shadowing can also reduce the quality of both 2D and 3D TEE, creating dropout or near-field artifacts and potentially leading to incorrect diagnosis (Online Video 12, Fig. 15). For these percutaneous procedures, we more frequently use the live 3D option.

Finally, an experienced team composed by an interventional cardiologist, an interventional echocardiographer, a cardiothoracic surgeon, a cardiac anesthesiologist, and nurses that are able to perform both catheterization lab and operating room duties is needed. Due to the overlap of domains of knowledge, it is key that all parties, in particular the echocardiologist and interventionalist, use not only the same vocabulary, but also share crossed training skills (e.g., training of the interventionalist on basic echocardiographic views critical for the procedure, and possession of unique interventional imaging skill by the echocardiologist) (3,37).

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Key Words: balloon valvuloplasty ■ mitral regurgitation ■ mitral valve ■ 3-dimensional echocardiography ■ transcatheter repair ■ transesophageal echocardiography.

⊞ **APPENDIX**

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