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iREVIEW

STATE-OF-THE-ART PAPER

Imaging Guidance for Transcatheter Mitral Valve Intervention on Prosthetic Valves, Rings, and Annular Calcification

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ABSTRACT

Catheter-based interventions to improve mitral valve function are dependent on anatomic and functional information provided by noninvasive imaging to plan, perform, and evaluate each intervention. In this review we highlight the importance of imaging guidance for catheter-based interventions on prosthetic mitral valves, surgical rings, and native valve annular calcification. Both repair and replacement procedures are discussed. We review the general features common to this collection of procedures and discuss specific imaging issues and concerns for each procedure. Figures and intraprocedural videos emphasize central messages using case examples. (J Am Coll Cardiol Img 2020;■:■–■)

Transcatheter replacement or repair are treatment strategies that address dysfunctional prosthetic mitral valves or native mitral valves with significant annular calcification. In this review we discuss applications of transcatheter valve implantation within: 1) a surgical mitral ring; 2) a bioprosthetic mitral valve; and 3) native mitral annular calcification (MAC), and we review imaging elements of transcatheter repair of paravalvular mitral regurgitation (PVR). We begin with common anatomic considerations and a discussion of the imaging principles that guide valve interventions. For each intervention, we review the relevant imaging considerations during planning, device delivery, and post-implantation. The common elements are highlighted as well as specific concerns for each intervention.

COMMON PRINCIPLES AND CONSIDERATIONS

The mitral valve is composed of 2 leaflets (anterior and posterior), 2 papillary muscles (posteromedial and anterolateral), and multiple chordae tendineae

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ABBREVIATIONS AND ACRONYMS

3D = 3 dimensional

CT = computed tomography

LA = left atrium

LV = left ventricle

LVOT = left ventricular outflow tract

MAC = mitral annular calcification

MR = mitral regurgitation

MViR = mitral valve-in-ring

MViV = mitral valve-in-valve

PVR = paravalvular regurgitation

TEE = transesophageal echocardiography

THV = transcatheter heart valve

SHV = surgical heart valve

ViMAC = valve-in-mitral annular calcification

that connect the papillary muscles to the leaflets and the mitral annulus.

The anterior mitral leaflet is the longest leaflet and forms a curtain between the left ventricular (LV) inflow and outflow. The posterior leaflet is attached to the mitral annulus and covers approximately two-thirds of the mitral valve circumference (Figure 1). The healthy mitral annulus is saddle-shaped and undergoes phasic geometric changes including systolic reduction in the anterior-posterior dimension, and decent toward the LV apex. After surgical valve implantation, the annulus assumes a circular shape, becomes uniplanar, and dynamic motion is greatly reduced or lost.

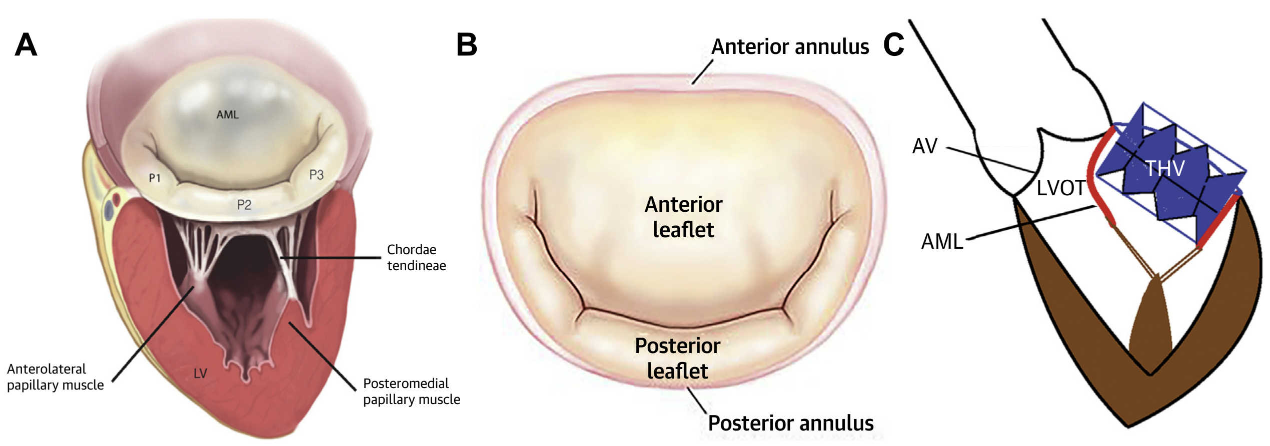
When a transcatheter heart valve (THV) is implanted within a bioprosthetic surgical heart valve (SHV), surgical ring, or MAC, the THV effectively becomes a covered stent with the SHV leaflet or native anterior leaflet opposed to the external stent frame. This interplay between the THV frame and the native or SHV leaflet may compromise systolic flow within the left ventricular outflow tract (LVOT). The most predictable results are achieved with a mitral valve-in-valve procedure because a round THV is implanted within a round SHV producing a circumferential seal with low risk of paravalvular regurgitation. In addition, as the native anterior mitral leaflet is absent in most cases, the risk of LVOT compromise is minimized. When the native anterior leaflet is present, procedural outcomes and patient selection are more challenging.

The risk of LVOT obstruction is higher if the aorto-mitral-annular angle is less obtuse (<115°) (Figure 2), and if the left ventricular cavity is small. A sigmoid septum with a significant septal bulge into the LVOT, and a predicted neo-LVOT ≤1.7 cm^2 are additional recognized risks (1-3).

Currently, a balloon-expandable THV (SAPIEN/SAPIEN XT/SAPIEN, Edwards Lifesciences, Irvine, CA) is used for most interventions. The self-expanding Melody THV (Medtronic Inc., Minneapolis, MN) and mechanically expanding Lotus THV (Boston Scientific, Marlborough, Massachusetts) are used but are less common due to longer stent profile. Although the 3 interventions, that is, mitral valve-in-valve (MViV), mitral valve-in-ring (MViR) and valve-in-MAC (ViMAC), share similarities, they are procedurally very different. For patient selection, procedural planning and optimal performance, both native and surgical anatomy, should be considered.

In addition to confirmation of SHV size, noninvasive imaging of native valves must examine the extent of leaflet calcification because this measurement affects THV size selection. The length of the anterior mitral valve leaflet also should be defined. A general comparison of key anatomic and functional concerns and a summary of key measurements is presented in Table 1.

FIGURE 1 Mitral Valve Components



(A) The mitral valve is composed of 2 leaflets, 2 papillary muscles, and chordae tendineae. **(B)** Relationship between mitral annulus and 2 leaflets. Anterior leaflet has narrower attachment but larger surface area. **(C)** Illustration to demonstrate displacement of AML in to the left ventricular outflow tract (LVOT) "fixed SAM." AML = anterior mitral leaflet; AV = aortic valve; THV = transcatheter heart valve.

PREPROCEDURE

MITRAL VALVE-IN-VALVE. The dimensions of the SHV determine the size of the THV to be implanted. Compared with valve-in-valve procedures in the aortic valve position, the pressure on the closed valve leaflets is much higher for mitral valves. Consequently, acute or delayed embolization of an improperly sized THV can occur after a MViV procedure. The internal diameter of the SHV determined by computed tomography (CT) helps to choose the optimal THV size because the goal is to achieve a conical shape of the THV after implantation (4,5) (Figure 3).

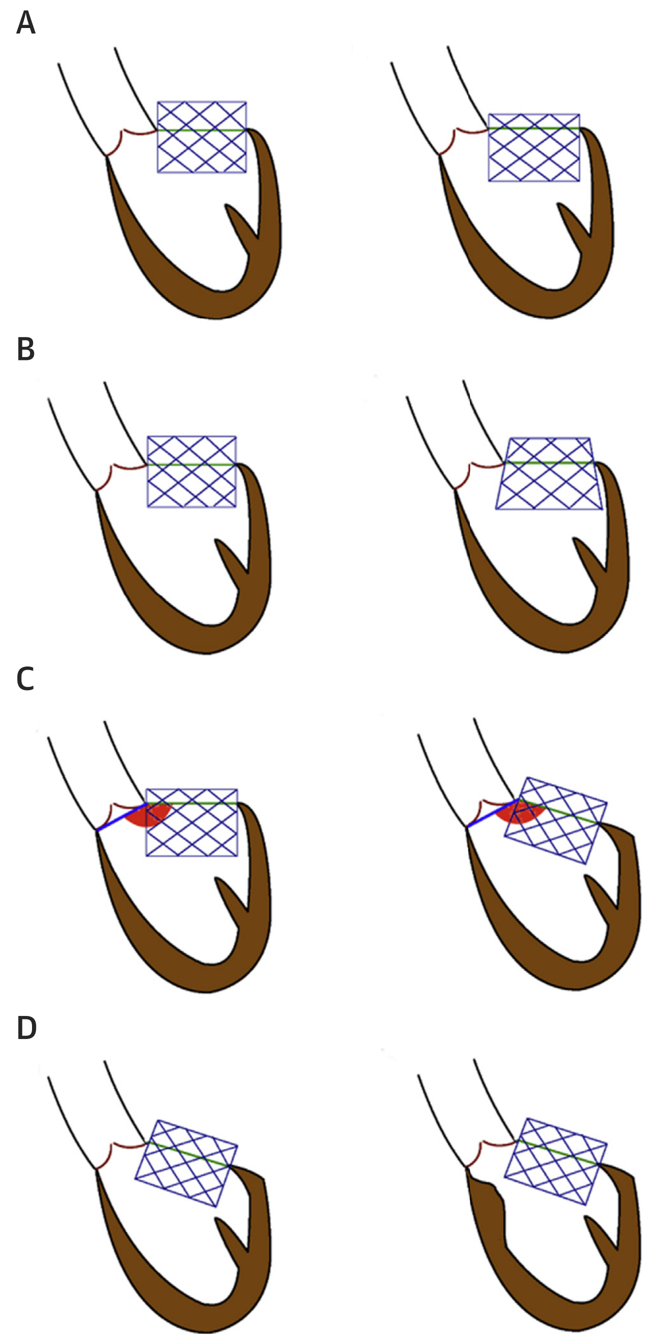
When the true internal diameter falls between 2 recommended THV sizes, a smaller THV size can be used if the valve is stenotic, but a larger one should be used to decrease risk of embolization if the valve is regurgitant. The height of the SHV and thus the projection of the mitral prosthesis into the left ventricle should be measured as it may influence the risk of LVOT obstruction. Thus, whether the valve is stenotic or regurgitant influences choice of THV size.

CT measurements are highly dependent on image quality, acquisition and reconstruction technique, prosthetic material opacity, and associated blooming, as well as measurement technique (Figure 4). Imaging-derived measurements are not equivalent to the stent true internal diameter and caution is advised. In addition, the internal diameter of a SHV can change due to thickening and calcification of degenerated leaflets. Ideal reference charts should allow correlation of CT measurements with the manufacture's stated SHV size. CT imaging is helpful to confirm SHV size or to establish SHV size in patients with unclear surgical history.

Bioprosthetic heart valves have 3 posts from which the prosthetic leaflets are suspended. At the time of surgical implantation, the valve can be oriented such that 2 posts straddle either the posterior annulus or the LVOT (Figure 5). Most surgeons prefer the second configuration because there is no strut projecting into the LVOT; however, when the posterior mitral leaflet cannot be preserved, the posterior annulus may be favored because of the risk of a strut in contact with the posterior ventricular wall that can increase ventricular injury (6). The SHV orientation does not influence the risk of LVOT obstruction during an MViV procedure because the new THV is fully covered irrespective of the SHV orientation.

However, the type of SHV may influence severity of LVOT obstruction. The leaflets of the SHV are made from porcine valve leaflets or bovine pericardial tissue. The stent frames of pericardial valves are taller than porcine bioprosthetic mitral valves. When a THV is implanted within bovine pericardial leaflets, the leaflets are pushed outward but cover the stent fully. Porcine leaflets are shorter and provide less cover for

FIGURE 2 Factors Influencing LVOT Obstruction



(A) Increase protrusion/projection of the transcatheter heart valve (THV) in left ventricle. **(B)** Increase THV flare in the left ventricle. **(C)** Less obtuse aortic-mitral annular angle. **(D)** Presence of septal bulge. LVOT = left ventricular outflow tract.

TABLE 1 Procedural Planning for Transcatheter Mitral Valve Implantation

Procedure	Anatomic and Functional Concerns	Essential Parameters by Computed Tomography
Mitral valve-in-ring	Anterior leaflet displacement into LVOT Exclude ring dehiscence	Predicted neo-LVOT area Ring internal dimension Leaflet calcification Length of anterior leaflet
Mitral valve-in-valve	LVOT obstruction Residual paravalvular regurgitation	Predicted neo-LVOT area SHV tissue-type SHV dimensions: internal diameter, height, projection into left ventricle
Valve-in-mitral annular calcification	Anterior leaflet displacement into LVOT (LVOT obstruction) Risk of embolization Residual paravalvular regurgitation	Predicted neo-LVOT area MAC distribution and morphology Landing zone dimensions

LVOT = left ventricular outflow tract; MAC = mitral annular calcification; SHV = surgical heart valve.

the THV stent frame. This translates into less risk of LVOT obstruction with porcine SHVs (**Figure 6**). Several approaches have been developed to aid in patient selection because LVOT preservation is such an important element of the MViV procedure. Many centers now use digital modeling to overlay the shape of a THV onto a patient-specific image to predict the neo-LVOT flow area. This can be done using a generic THV shape (e.g., a simple cylinder with defined dimensions), or this step can be performed using a THV model that replicates the device frame shape and dimensions of a specific manufacturer's THV. This simulation of MViV can be performed at multiple time points within the cardiac cycle with end-systolic dimensions typically being smallest and end-diastolic being largest. Recently published data suggest that a predicted neo-LVOT <1.7 to 1.9 cm^2 is associated with high risk of LVOT obstruction; however, this value does not consider variations in body surface area (2).

MITRAL VALVE-IN-RING. There are multiple types of surgical MV annuloplasty rings. They can be classified into the following: complete versus incomplete; rigid, semirigid, and flexible; and fluoroscopically visible, barely visible, or not visible. Not all rings are suitable for an MViR procedure. To provide a solid anchor for a THV implant, the surgical ring must become circular or nearly circular. Thus, incomplete bands and rigid complete rings are associated with suboptimal outcomes following an MViR procedure (**Figure 7**). Unfortunately, the dimensions of the ring provided by the manufacturer are not reliable for sizing an MViR procedure, as the shape of the ring can be altered during the surgical implantation.

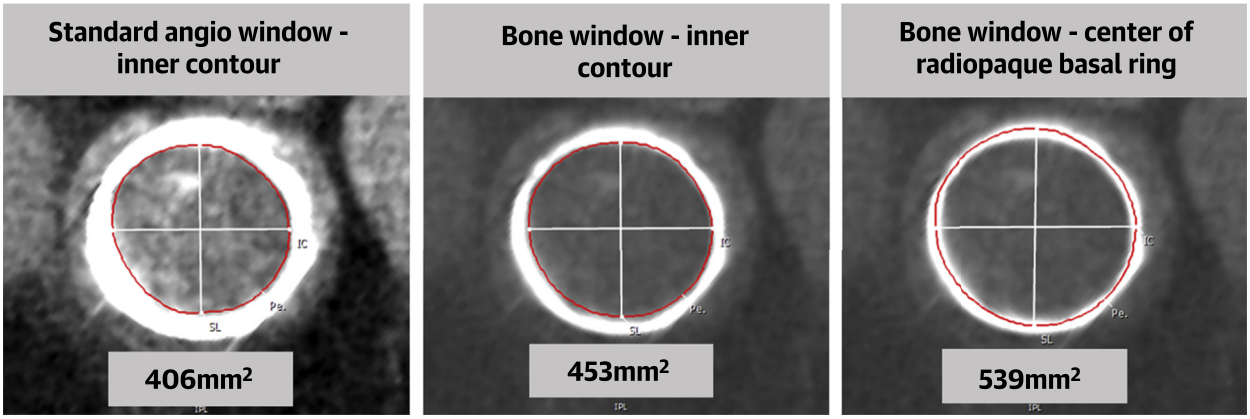
Furthermore, the MV annulus area increases after an MViR procedure, as the shape changes from oval to circular. This is important to consider when the ring area is between 2 THV sizes (**Figure 8**).

Mitral valve rings are surgically implanted with a partial thickness suturing technique and can undergo dehiscence when increased radial force is exerted within the ring during an MViR procedure. It is important to exclude valve ring dehiscence as a source of regurgitation which can be determined by transesophageal echocardiography (TEE).

VALVE-IN-MAC. Key elements for ViMAC procedural planning include an evaluation of calcification quality, distribution, and severity; presence of spurs and gutters; and landing zone dimensions (7). The distribution of MAC can be classified as circumferential versus noncircumferential, such that circumferential calcium provides optimal THV anchoring. The severity of calcium can be reported using a segment-based, subjective semiquantitative approach, ranging from mild (fleck-like), to moderate (coalescing) to severe (bulky, protruding). Density of calcium can be brittle, caseous, or highly dense calcium. Although CT imaging identifies caseous versus dense calcium, no imaging method can yet predict the patient-specific biomechanical properties of calcified tissue. Prediction of landing zone suitability is further complicated by spurs (calcium projections onto the leaflets) and gutters (indentations in the annular contour).

An evaluation of the symmetry and circumferential extent of MAC is crucial. The presence of MAC in the posterior annulus is not usually a sufficient anchor for THV implantation. A CT-based MAC score has recently been described to categorize MAC severity and predict THV embolization during ViMAC procedures (8). Commissural calcification, preferably bilateral, and some degree of anterior calcification are vital, as they provide a more circumferential anchor for ViMAC (**Figure 9**). Other characteristics of the MAC are important. If MAC protrudes into the mitral orifice, it may deform the THV device and prevent effective sealing between the annulus and the THV, which then results in paravalvular regurgitation

FIGURE 3 **En Face, Thin-Sliced Multiplanar Reformat Aligned With the Basal Ring Bioprosthetic Mitral Valve**

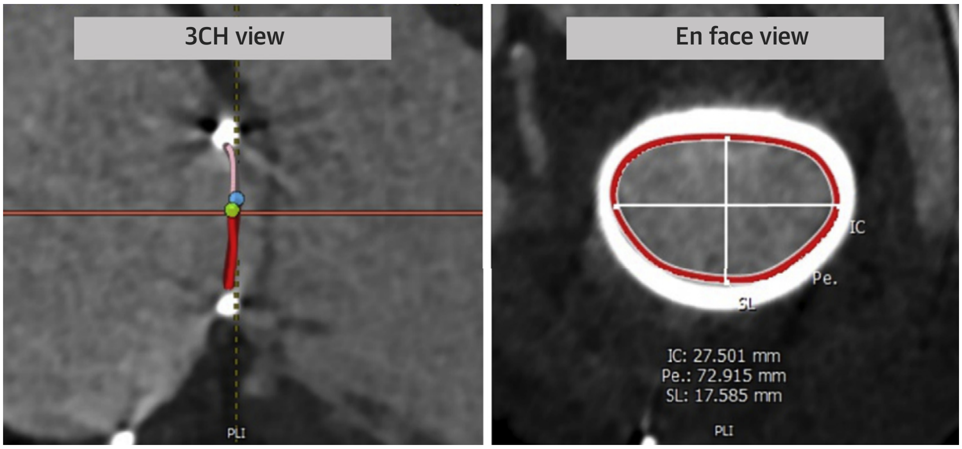


Assessed dimensions are dependent on the windowing used and the subsequent degree of blooming, in particular when using a contour drawn along the inner edge of the radiopaque ring. The contour is large in a bone window setting compared with a standard window. A contour drawn in the center of the metal frame is independent of the window setting but even larger.

Choosing the correct size of the THV in MAC is challenging because it is difficult to measure accurately the "true orifice" of the mitral valve-in-MAC (Figure 10). Landing zone dimensions are assessed using a 3-dimensional (3D) spline image segmentation similar to native, noncalcified mitral valve disease. However, as opposed to clear identification of the mitral annulus for segmentation placement in noncalcified anatomies, the MAC obscures and distorts the anatomy. The fibrous annulus cannot serve as a device landing zone. Instead, segmentation needs to follow the anticipated landing zone, where the contact between the device and the annular calcification is expected.

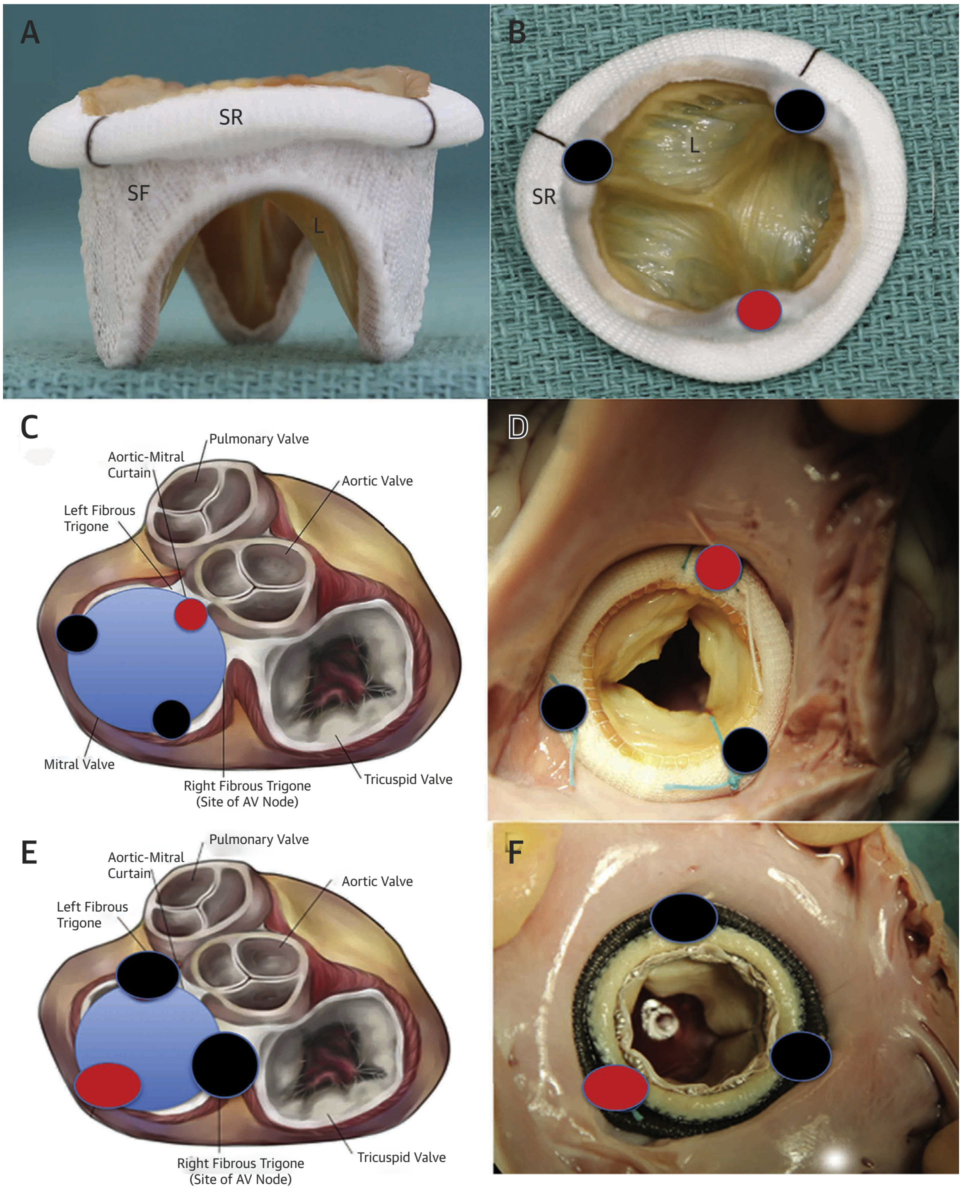
Further, segmentation needs to reflect the likely 3-dimensionality of the calcium that could have a nonplanar zone of contact (e.g., atrial in some portions and more ventricular in others). As opposed to thin-sliced multiplanar reformats, thick-slab multi-intensity projections increase segmentation and therefore anatomic understanding (Figure 11). Calcium blooming, that is, the exaggerated appearance of calcium on CT reconstruction due to partial volume averaging, is not an important problem for

FIGURE 4 **Segmentation of a Complete Annuloplasty Ring Deriving Minimum and Maximum Dimensions as Well as Perimeter and Area**



3CH = 3-chamber

FIGURE 5 **Mitral SHV Implantation Techniques**

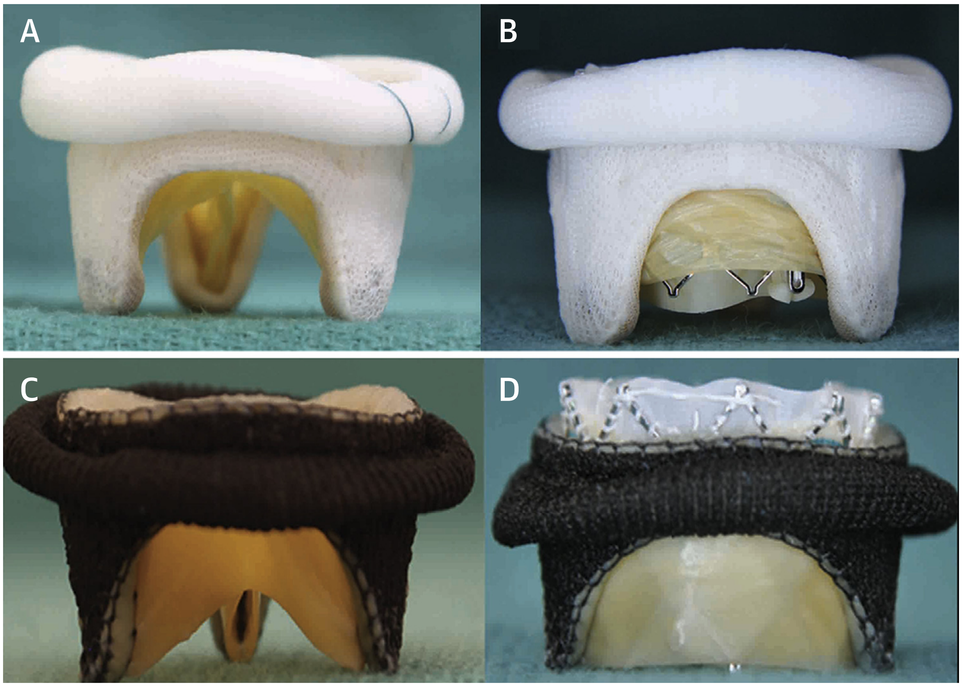


(A and B) Mitral surgical heart valve (SHV) example demonstrating structure (SR = sewing ring, SF = stent frame, L = leaflets). **Red and black dots** represent position of the 3 struts. **(C and D)** SHV implantation orientation 1. Single strut **(red dot)** comes to lie in relation to left ventricular outflow tract (LVOT). **(E and F)** SHV implantation orientation 2. Single strut **(red)** is posterior and the 2 other struts **(black)** straddle the LVOT and hence may not project within LVOT.

mitral annular segmentation. Although there is a degree of blooming, segmentation is usually performed to the inner edge of the calcification to maintain a harmonious contour. Spurs that could fracture are included into the segmentation, whereas gutters are excluded from the segmentation. Depending on the postprocessing software being used, averaging the 3D MAC contour to a 2D plane allows an assessment of MAC area, perimeter, and select diameters.

The ViMAC procedure has the added challenge of an intact anterior mitral leaflet that can be displaced into the LVOT. Like the MViV procedure, the size of the remaining neo-LVOT is multifactorial and the

FIGURE 6 Effect of Type of SHV on LVOT Obstruction Risk



(A) Porcine surgical heart valve (SHV) before SAPIEN XT implantation with leaflets closed as in systole. **(B)** Porcine SHV after valve-in-valve (VIV): leaflets are pinned open after VIV. The leaflets are thinner, shorter and cover less of SAPIEN XT stent. **(C)** Pericardial SHV before SAPIEN XT implantation with leaflets closed as in systole. **(D)** Pericardial SHV after VIV: leaflets are pinned open after VIV. The leaflets are thicker, longer, and cover entire SAPIEN XT stent.

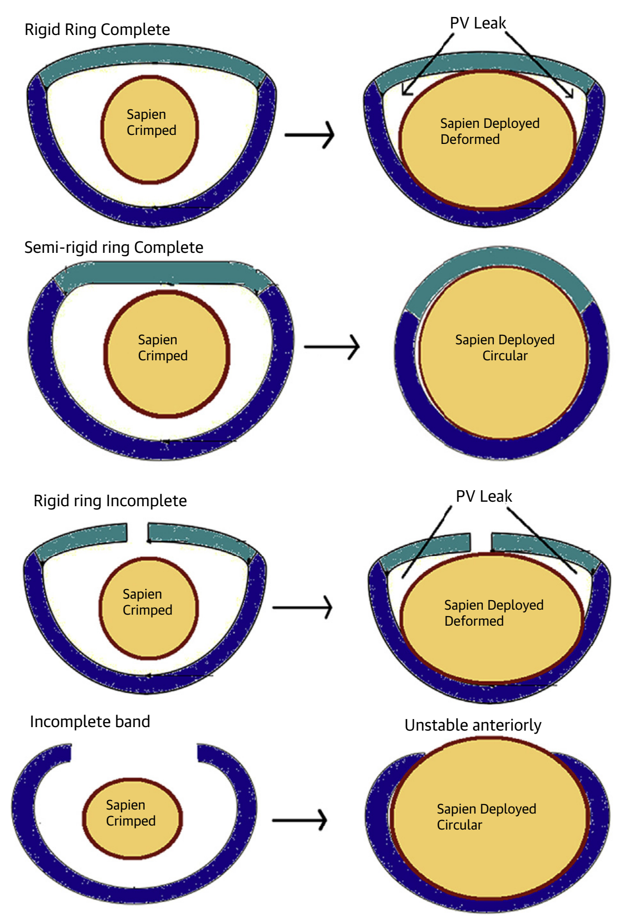
most practical and likely most predictive approach to patient selection involves an imaging-based simulation of the implantation itself. Figure 12 depicts the modeling of an MViV procedure using a simple virtual cylinder to represent the THV, which is overlaid onto patient-specific imaging data for neo-LVOT prediction.

Once high risk of LVOT obstruction is detected (neo-LVOT area <1.9 cm^2), risk-reduction strategies such as alcohol septal ablation in patients with septal thickness >15 mm and good septal targets found on coronary angiography should be considered (9). In patients without favorable anatomy for alcohol septal ablation, percutaneous laceration of the anterior leaflet is possible if the anterior leaflet is not extremely calcified and if the predicted neo-LVOT area is <1.5 cm^2 (10).

MITRAL PARAVALVULAR REPAIR. The preprocedural planning for PVR repair generally uses both contrast multidetector CT and echocardiography imaging. TEE identifies the location of the paravalvular defect and severity of regurgitation. The location of one, or multiple PVR defects can be measured using 2D color Doppler to determine if the site is medial, lateral, anterior, or posterior in relation to the SHV sewing ring. TEE with 3D color Doppler allows localization of 1 or more paravalvular defects in relation to a clock-face orientation around the SHV. This clock-face localization is an important step because it may influence the site of trans-septal puncture; 3D color Doppler methods can also be used to differentiate pathologic PVR from normal washing jets. Washing jets are usually relatively small color jets that originate near the hinge points of a mechanical SHV, and are eccentrically directed toward the center of the valve (Figure 13). Supportive spectral Doppler data (pulmonary vein flow pattern, regurgitant jet density, and Doppler-derived forward stroke volume) can quantify severity of PVR.

The importance of CT contrast imaging for PVR has continued to evolve. CT provides verification of the site of PVR, confirms normal mechanical leaflet motion before PVR repair, and helps with an estimation of closure device design and size (e.g., ventricular septal occluder if a relatively large shelf-like defect is present within the atrial or ventricular landing zone;

FIGURE 7 Suitability of Different Types of Rings/Bands for ViR



Rigid rings, complete or incomplete, will result in suboptimal result due to noncircular expansion of the transcatheter heart valve (THV) and likely paravalvular leaks on both commissures. Semirigid complete ring on the other hand provide a good anchor and can become circular or near circular, making them ideal for valve-in-ring (ViR) procedure. Incomplete bands have no anchor anteriorly and can lead to leakage and embolization.

a vascular occluder for a long serpiginous defect; or ductal occluder for a discrete PVR defect in close proximity to mechanical leaflet hinge points). Increasingly, preprocedural CT datasets are fused with intraprocedural fluoroscopic data to provide trans-septal puncture or PVR repair targeting within the fluoroscopic image. Optimal fluoroscopic viewing angles can be prespecified by interrogation of a contrast multidetector CT dataset (11).

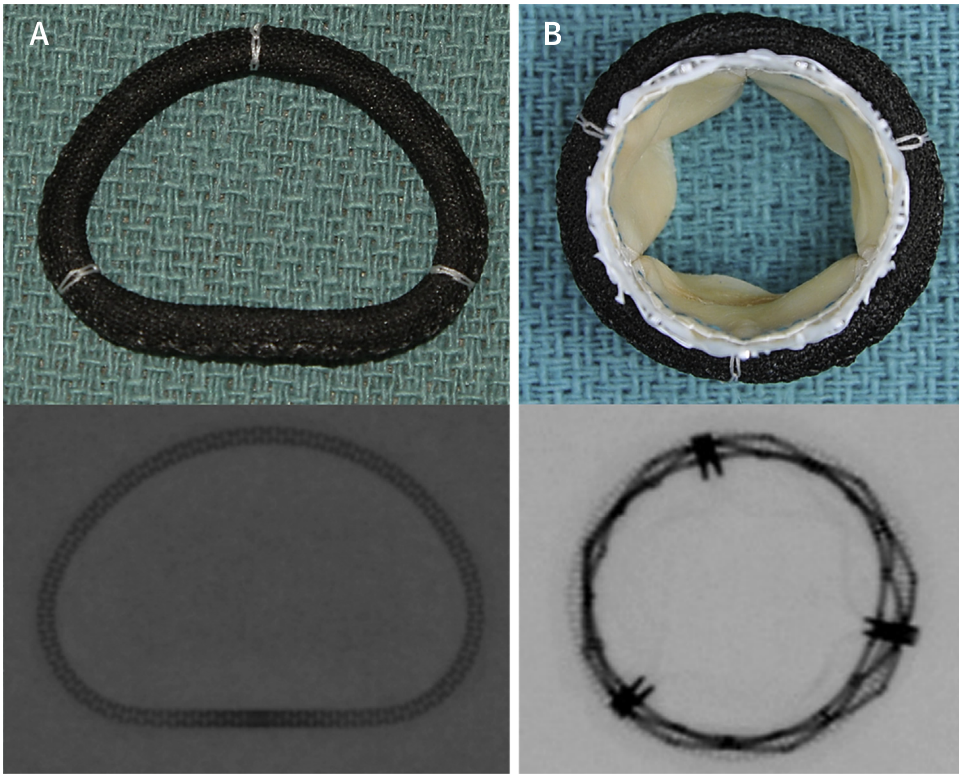
INTRAPROCEDURE

TRANS-SEPTAL PUNCTURE. The trans-septal procedural step requires imaging guidance. The interventional cardiologist delivers the appropriate catheter to the septal area using fluoroscopy with a transition to guidance by echocardiography for precise septal puncture. Optimally both 2D and 3D TEE are used. 3D TEE allows use of multiplane 2D images, bi-plane images at fixed or variable multiplanar angles, as well as enface 3D images viewed from either the left atrium (LA) or the right atrium perspective (Figure 14). The perpendicular distance between the fossa ovalis and the landing zone is assessed with intraprocedural TEE, which can identify challenging anatomy (Figure 15). Previously acquired CT images can simulate the potential puncture site by providing reformats in TEE standard views, such as the bi-caval, 4-chamber, and short-axis view.

When viewed from the LA using 3D echocardiography, the fossa ovalis can be referenced as a clock face with the superior and inferior margins at the 12 o'clock and 6 o'clock positions. The typical target for trans-septal puncture of a MitraClip procedure is the superior/posterior rim of the fossa ovalis represented by the 12 to 2 o'clock position (Figure 14). In most patients, this target region will be 4 to 4.5 cm superior to the plane of the anterior mitral annulus, positioned directly superior to the medial commissure of a native mitral valve, to avoid the aorta anteriorly, and the atrial free wall posteriorly (12). The anatomic target for the trans-septal puncture varies by procedure (13). In general, the preferred trans-septal site for MViV, MViR, and ViMAC procedures is often relatively inferior and posterior to the center of the fossa ovalis. For paravalvular repair along the lateral annulus a more superior and posterior trans-septal puncture site may be preferred for delivery catheter angulation. In contrast, PVR repair along a medial (adjacent to the intra-atrial septum) SHV sewing ring may be adequately accessed by a more inferior trans-septal puncture site or a transapical LV puncture.

CATHETER ALIGNMENT. 3D echocardiography provides a rapid and accurate method to evaluate catheter and guide-wire positioning within the LA, and across native valves, prosthetic valves, or paravalvular defects. Although catheters are initially being manipulated and repositioned within the LA, a relatively large 3D volume that encompasses the entire LA volume is generally preferred. From this top-down imaging perspective, the catheters or wires that enter a pulmonary vein, LA appendage, or ventricle can be easily identified by both the imager and interventionalist. The distal tip of the guide-wire or catheter needs to be accurately tracked and displayed within this 3D volume. The tip of a catheter or guide-wire that traverses out of the imaging volume may be erroneously interpreted because of a distal "tapering" of the device. The true tip of a catheter

FIGURE 8 **Example of a Semirigid Ring**



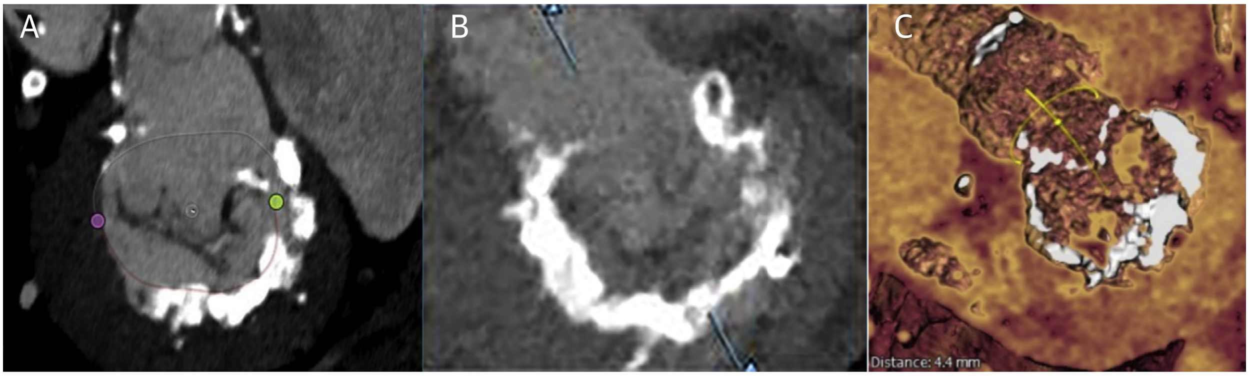
Sorin Memo 3D ring has geometric shape but after transcatheter heart valve implantation, the ring assumes a circular shape.

will often display symmetrical features and move in synchrony with hand motions of the interventionalist. The distal tip of any straight guide-wire is difficult to confidently visualize by either 2D or 3D TEE methods. For this reason, a pig-tail-shaped wire configuration is preferred. Depending on the specific procedure, the trajectory that the catheter follows between the trans-septal puncture site and the transvalvular target may be important. A paravalvular defect along the lateral annulus may be more easily crossed by a catheter-looping within the LA appendage to create a parallel approach angle as an example (Figure 16).

DEVICE DEPLOYMENT. The imaging guidance required during the deployment of a device is specific to the procedure being performed. Common steps include the following: 1) guide-wire positioning across the native valve, prosthetic valve, or paravalvular defect; 2) advancement of the guide-catheter over the guide-wire; 3) datheter-based delivery of the device within the target zone; 4) expansion of the THV device; 5) detachment of the device from the delivery catheter or balloon; and 6) retraction of the delivery catheter (Central Illustration).

During deployment of a THV within a surgical ring, bioprosthetic valve, or MAC, the principal imaging concerns are device depth in relation to the plane of the annulus, coaxiality of device in relation to mitral annulus, and complete expansion of the THV within the constraining tissue (native or prosthetic). Rapid pacing is generally recommended during MViR, MViV, or ViMAC procedures, although not as fast as the one used for transcatheter aortic valve replacement (140 beats/min is usually adequate). Implant depth can be guided by echocardiography but is more often guided by fluoroscopy, as the targeted prosthetic tissue or native annular calcification are well visualized. The goal is to implant the THV approximately 80% in the ventricle and 20% in the atrium. A final position as ventricular as possible may provide the best hemodynamic performance with the least amount of valvular gradient, similar to aortic valve-in-valve procedures in which a higher implant (more aortic) provides better valvular gradients; however,

FIGURE 9 Examples of Distribution of MAC

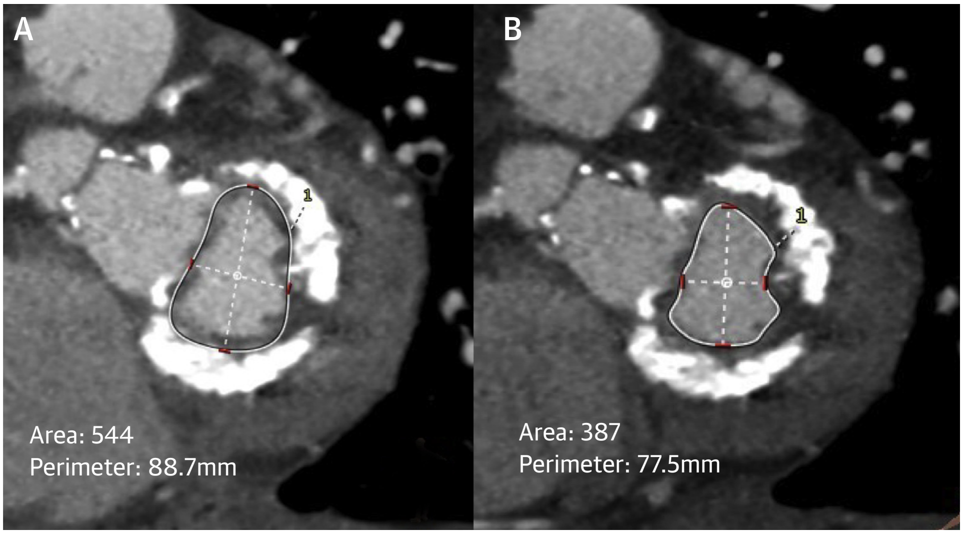


(A) Mitral annular calcification (MAC) extends partially over the posterior annulus. **(B)** MAC extends over the entire posterior annulus and commissure. **(C)** MAC extends over the entire circumference of the mitral annulus. ViMac will not be possible in **A** but possible in **C**. In **(B)**, a detail modeling will be needed to assess feasibility.

the risk of LVOT obstruction, which may be greater with THVs in a more ventricular position, particularly when the anterior leaflet has not been previously resected, should be noted. Flaring the ventricular edge of the balloon-expandable THV is important to reduce embolization or migration to the LA. Evaluation of the degree of THV flaring within the LV may be done using TEE or fluoroscopy.

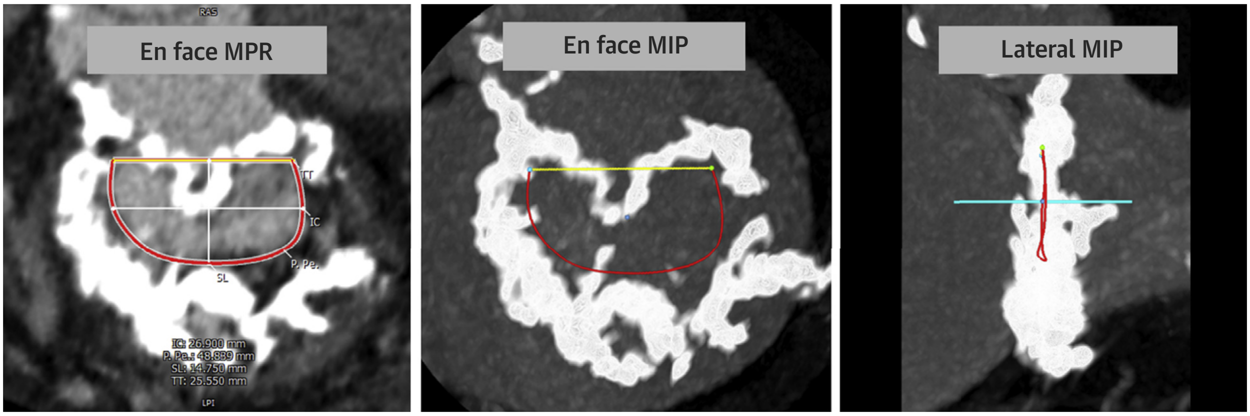
MITRAL VALVE-IN-VALVE. For the intraprocedural guidance during MViV within a radiopaque SHV, fluoroscopic imaging must be optimized so that replication of this simulated ideal THV implant depth can be achieved. From a "surgical" perspective, bovine leaflets descend farther than porcine leaflets compared with the SHV posts. However, on CT only the radiopaque components of the posts are

FIGURE 10 THV Sizing in MAC



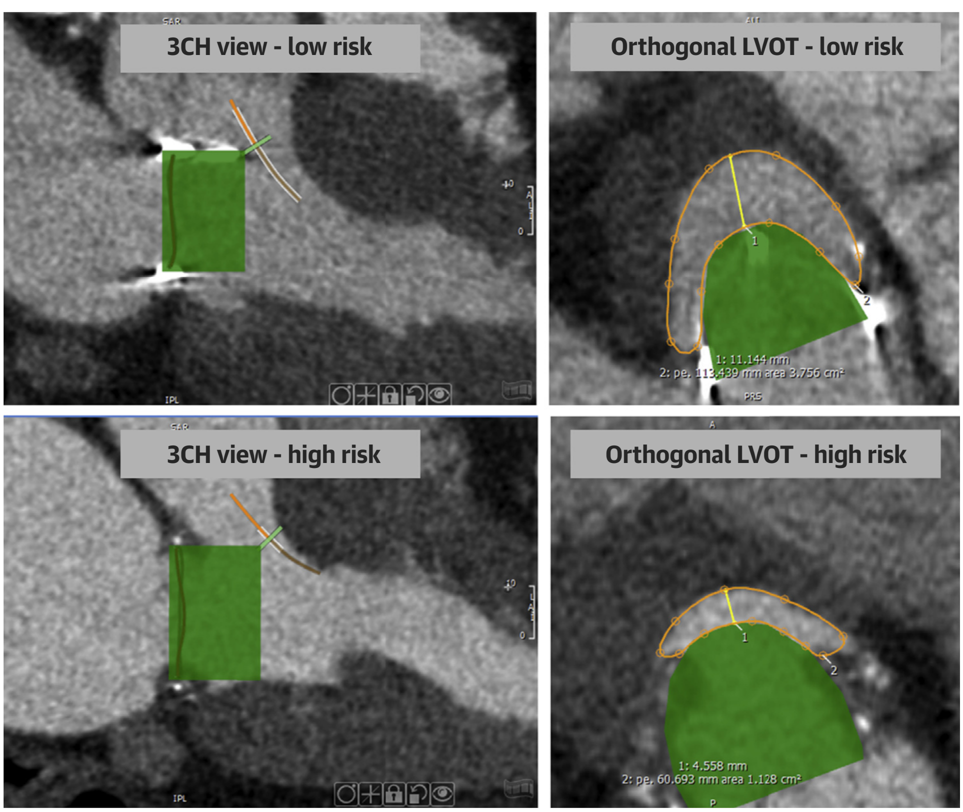
(A) Measurement of neo-annulus area performed at inside margin of mitral annular calcification (MAC). **(B)** Measuring contrast contour may underestimate the annular area.

FIGURE 11 Landing Zone Segmentation in Calcific Mitral Valve Disease Using Both Thin-Sliced MPR and Thick-Slab MIP



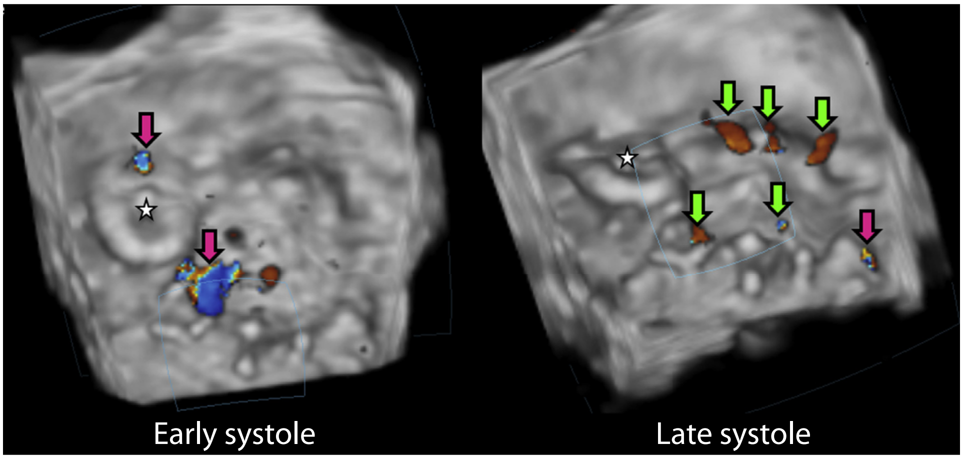
The example shown demonstrates near circumferential MAC which is best appreciated on the en face multi-intensity projection (MIP). The posterior segmentation is drawn in a harmonic fashion along the anticipated site of contact. Small spurs are included into the segmentation. A large spur at A2 which is anticipated to be partially displaced in included into the anterior segmentation. The lateral MIP demonstrates the 3-dimensionality of the MAC. MPR = multiplanar reformat.

FIGURE 12 Simulation of a Valve-In-Valve Procedure to Predict the Neo-LVOT Dimension Using a Centerline Technique on a 3-Chamber View With Correlating En Face LVOT Views Oriented Orthogonally to the Centerline



The virtual cylinder is simulated to reach the tip of the posts. The upper example demonstrates sufficient predicted neo-left ventricular outflow tract (neo-LVOT) dimensions at end-systole while the predicted neo-LVOT dimensions in the lower example are well <2 cm^2, placing the patient at high risk for relevant neo-LVOT obstruction. 3CH = 3-chamber.

FIGURE 13 Identification of Paravalvular MR and Normal Mechanical Valve Washing Jets



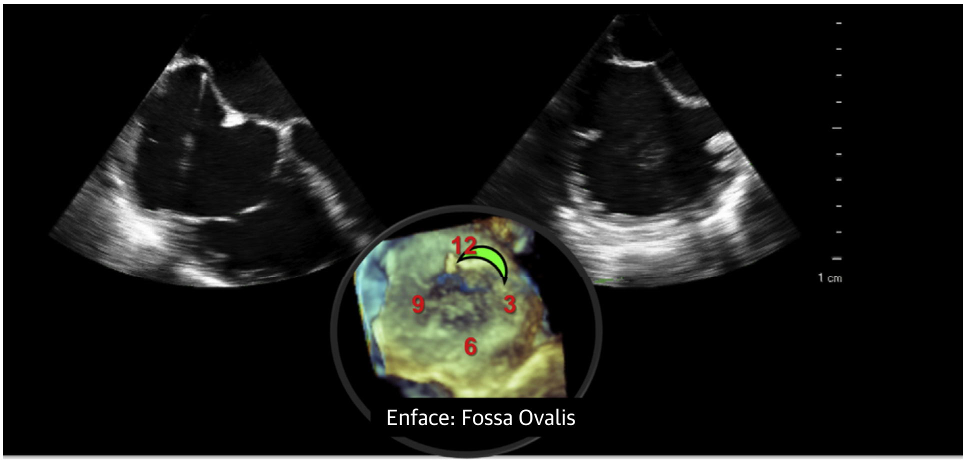
Three-dimensional color Doppler transesophageal echocardiography can be used to identify residual paravalvular mitral regurgitation (MR) **(pink arrows)** after paravalvular prosthetic leak (PVL) plug deployment **(star)** and the normal small washing jets **(green arrows)**.

visualized but not the overlying fabric. Thus, although the porcine leaflet may not reach the tips of the macroscopic post, they may reach the tip of the CT-visualized posts. A case of MViV is depicted in Video 1.

SHVs vary by the degree to which the sewing ring can be visualized by fluoroscopy. MViV into a non-radiopaque SHV is more challenging since surrogate landmarks must be used to localize the THV landing zone. Left ventriculography may visualize the annular plane or 3D TEE can guide valve position and deployment (Figure 17).

MITRAL VALVE-IN-RING. Most surgical rings are visible using fluoroscopy; however, there is some variability. One can start with an "open ring" view and then slowly obtain the optimal "closed ring or coaxial" view (Figure 18). As opposed to valve-in-

FIGURE 14 TEE Guidance of the Trans-Septal Puncture



A combination of 2-dimensional and 3-dimensional imaging is used to ensure adequate puncture site height relative to the mitral target (annulus, surgical ring, or paravalvular prosthetic leak [PVL] location) and to target the puncture relative to the superior, posterior rim (clock-face location) of the fossa ovalis. TEE = transesophageal echocardiography.

valve procedures, annuloplasty rings provide less guidance with respect to the final orientation of the transcatheter heart valve, and the anterior mitral leaflet is still intact. When referencing a preprocedure CT, the virtual THV cylinder simulation should match the final positioning and ventricular implantation depth to reliably predict the neo-LVOT dimensions. A case of MViR is depicted in Video 2.

VALVE-IN-MAC. Similar to MViR planning, the virtual cylinder simulation in ViMAC must resemble the final implantation position, which can be difficult to predict in cases with heterogeneous calcium distribution. MAC is essentially a calcified ring around the mitral annulus and hence a similar fluoroscopic approach can obtain coaxial views during deployment. Any calcification along the anterior annulus or anterior mitral leaflet is at risk for being displaced into the outflow tract, thereby reducing the size of the neo-LVOT. A case of ViMAC is depicted in Video 3.

PARAVALVULAR REGURGITATION REPAIR. The intraprocedural imaging guidance of PVR repair focus on real-time TEE imaging (2D and 3D) of the guide-wire crossing the PVR defect, advancing the delivery catheter across the defect, and successful deployment of the selected occluder device. The variable elements reflect patient-specific troubleshooting issues, which may include wire or catheter entanglement within the submitral apparatus, occluder interference with systolic or diastolic function of the prosthetic mitral valve, and rapid identification of residual mitral regurgitation (MR) location and severity. During paravalvular repair procedures, a second guide-wire may sometimes be positioned across the defect in anticipation of

FIGURE 15 Assessment of Fossa Ovalis Height in 2 Patients With Perpendicular Linear Measurements From the Annular Plane to the Upper and Lower Margin of the Fossa Ovalis

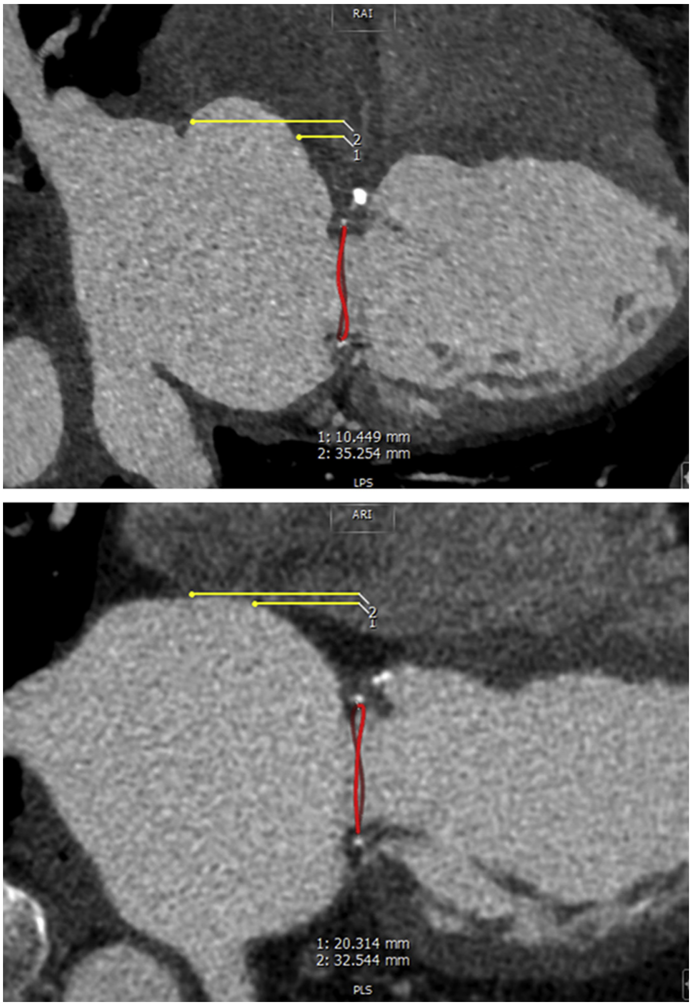
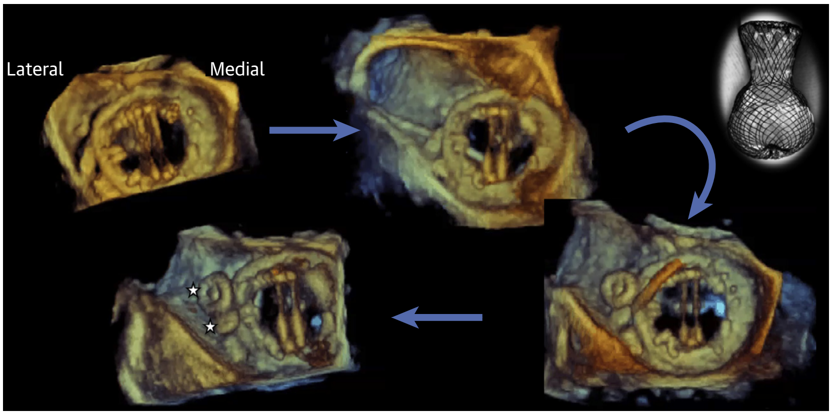
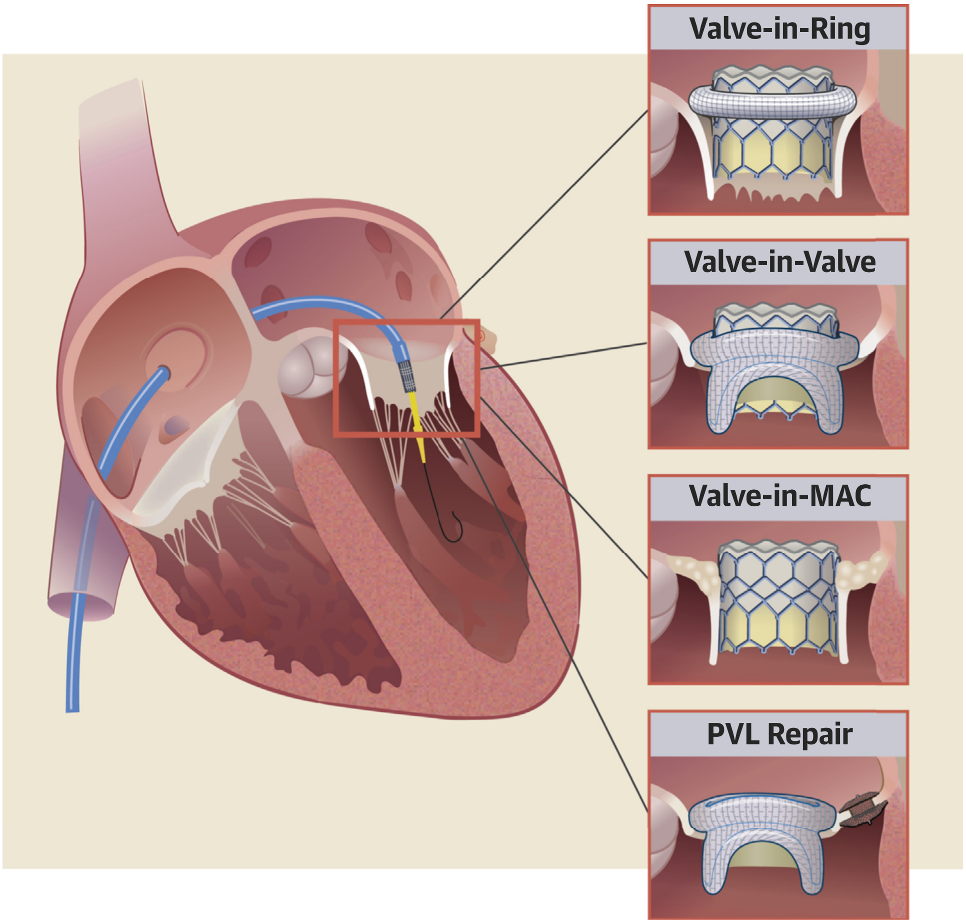


FIGURE 16 Performance of Mitral Paravalvular Repair With a Plug



The guide-wire is intentionally looped within the left atrial appendage to create the wire trajectory to cross a lateral paravalvular defect. Following wire access, 2 paravalvular plugs **(stars)** are deployed.

CENTRAL ILLUSTRATION A Spectrum of Interventions for Prosthetic Mitral Valves, Rings, and Annular Calcification



Little, S.H. et al. J Am Coll Cardiol Img. 2020;■(■):■-■.

Imaging guidance requires a common approach, with procedure-specific concerns.

requiring a second paravalvular prosthetic leak plug. This second guide-wire may impact the configuration of the deployed device. If residual paravalvular leak is significant, the guide-wire itself should be visually interrogated (applying 2D or 3D imaging as needed) to ensure noninterference with the occluder device (Figure 19). A case of transcatheter paravalvular prosthetic leak repair is depicted in Video 4.

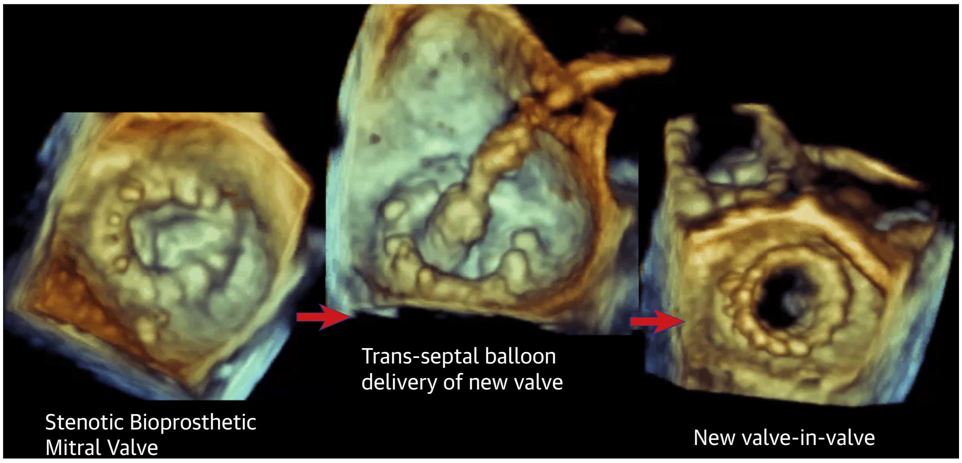
POST-PROCEDURE

Priorities for acute functional evaluation immediately following these procedures include the following: review for new structural complications, determination of diastolic flow pressure gradient, residual MR severity, assurance of LVOT patency, and evaluation of new changes in global or regional LV wall motion.

MITRAL VALVE-IN-VALVE. When a balloon-expandable THV with a sealing skirt is used for MViV, the sealing skirt must be positioned within the level of the SHV sew ring. An implant depth is generally defined by the ratio of THV within the LV and the LA. A ratio of 80:20 (ventricle:atria) takes full advantage of the sealing skirt of the THV. This ratio may be adjusted when a small LV is present, or for MViR and ViMAC procedures when an intact anterior mitral leaflet may compromise LVOT systolic flow patency.

Significant PVR may be reduced or eliminated by further balloon expansion of the deployed device. If the deployed device is at the larger range of the sizing

FIGURE 17 **TEE Guidance of a MViV Procedure**



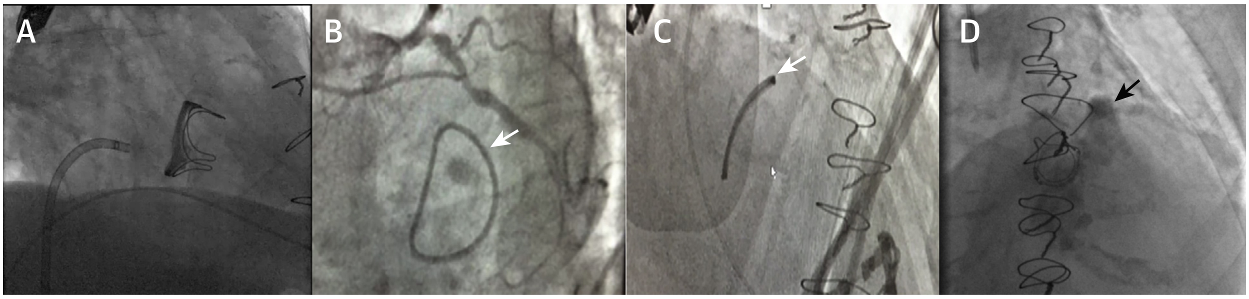
Two-dimensional/3-dimensional transesophageal echocardiography (TEE) is used to guide the trans-septal puncture, to assist in orientation of the catheter trajectory, and to evaluate acute postdeployment function of the transcatheter heart valve (THV). The imaging guidance during device deployment is usually provided by fluoroscopy.

spectrum, some degree of relative "overexpansion" may be required to achieve sufficient device anchoring and to minimize the risk of PVR. This may come at the expense of central transvalvular MR as the cooptation zone of the prosthetic leaflets may be reduced during frame expansion.

MITRAL VALVE-IN-RING; VALVE-IN-MAC. The acute post procedure concerns for MViR, and ViMAC are similar. Immediate concerns are LVOT patency and PVR severity. For PVR, the results with MViR and ViMAC are variable because the sealing skirt of the THV may not eliminate PVR along such irregular contact surfaces (Figure 20). There is a paucity of information on the assessment of MR severity after any form of THV in the mitral position. The assessment of residual MR and prosthetic stenosis, as well as PVR is similar to postsurgical mitral valve replacement or repair.

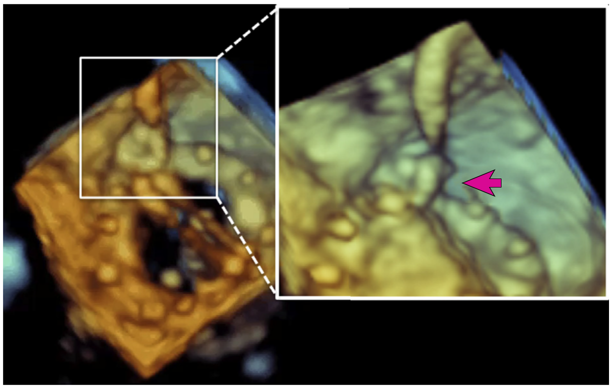
LVOT patency should be evaluated after MV interventions; 2D and 3D TEE images may identify prosthetic or native MV tissue within the LVOT. If any valve elements are highly mobile or in direct contact with the LV septum, then rupture of a chordae

FIGURE 18 **How to Obtain Best Fluoroscopic Angle for Deployment**



(A) During valve-in-valve (ViV), fluoroscopic portion of surgical heart valve (SHV) is used to get best alignment. **(B)** In case of valve-in-ring (ViR), best is to start with a view where the ring is "open." **(C)** C-arm is then rotated so that the ring is now "closed," which gives the best view for deployment, especially in multiplanar mitral rings. Example shown is the St. Jude Rigid Saddle ring **(white arrow)**. **(D)** Mitral annular calcification (MAC) is treated in the same way as mitral ring **(black arrow)**. This helps to identify correct reference level for transcatheter heart valve deployment.

FIGURE 19 Guide-Wire Visualization During Paravalvular Repair



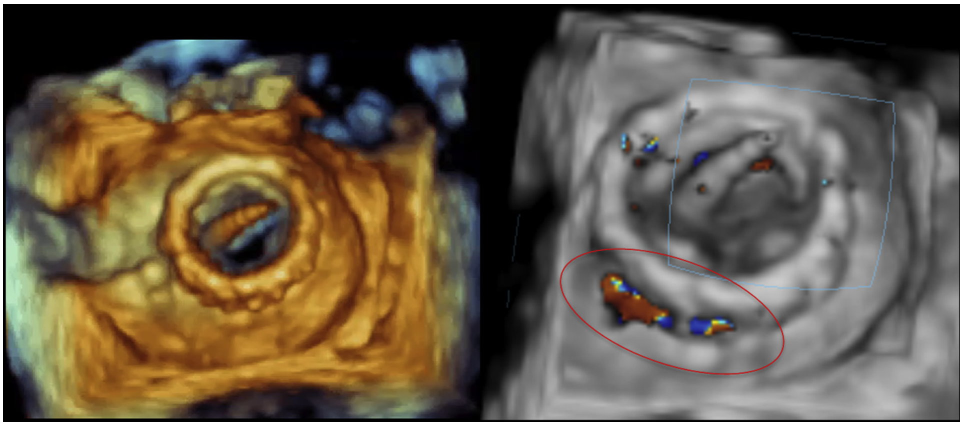
A double-wire technique had been used to cross the paravalvular defect in anticipation of requiring the deployment of 2 plugs to adequately seal the defect. Three-dimensional transesophageal echocardiography image shows that the second guide-wire was restricting the configuration of the first plug deployed.

tendineae should be considered. Color Doppler may reveal marked flow acceleration or highly turbulent flow; however, these findings are less specific for significant obstruction. Continuous-wave Doppler imaging accurately identifies a new and significant LVOT obstruction. To ensure adequate Doppler angulation, deep transgastric TEE views or apical transthoracic echocardiogram windows are required. If these are suboptimal, a transthoracic Doppler interrogation can assess the LVOT gradient.

An integrative approach should examine residual MR after any mitral intervention: color Doppler imaging, continuous-wave Doppler of MR jet, pulse-wave Doppler inflow pattern and diastolic gradient, pulmonary vein flow pattern, pulmonary artery systolic pressure, and calculated regurgitant volume and fraction. Accurate and reproducible grading of native valve MR is difficult. After valve repair or replacement, MR grading is even more challenging because of distortion of normal anatomy and eccentric or multiple jets. Dense shadowing from devices may limit accurate detection of the jet, its trajectory, and size. The presence of mitral annular calcium can complicate imaging the MR jet (Figure 21). TEE is often necessary to identify and quantify residual MR, as well as to exclude PVR. Color Doppler is essential for assessment of residual MR. It is used to assess the number of jets as well as to localize the origin of MR. The standard 3 components of the MR jet (flow convergence, vena contracta, and jet area) should be assessed.

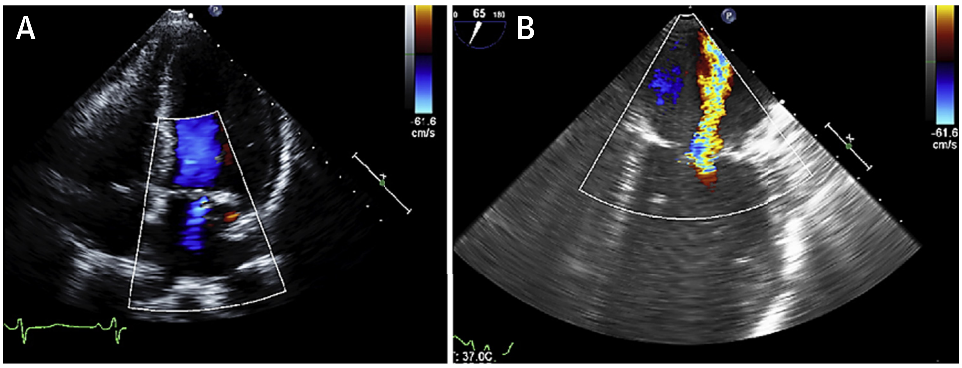
Because of the presence of the valve repair device or prosthesis and the associated acoustic shadowing, it can be difficult to identify the residual jet(s), let alone all 3 flow components. To further complicate postintervention assessment of MR, the jets are often multiple, eccentric, and wall-hugging. Color Doppler is useful in certain scenarios, especially with small

FIGURE 20 Identification of Acute PVL After MViR Procedure



After transcatheter heart valve (THV) implantation into a mitral band (partial ring), there is paravalvular leak noted along the posterior-lateral region. This is not unexpected due to the relatively unsupported anterior region devoid of prosthetic annular tissue for the THV device to push against. The paravalvular defect was effectively treated with a second balloon inflation of the THV device. MViR = mitral valve-in-ring; PVL = paravalvular prosthetic leak.

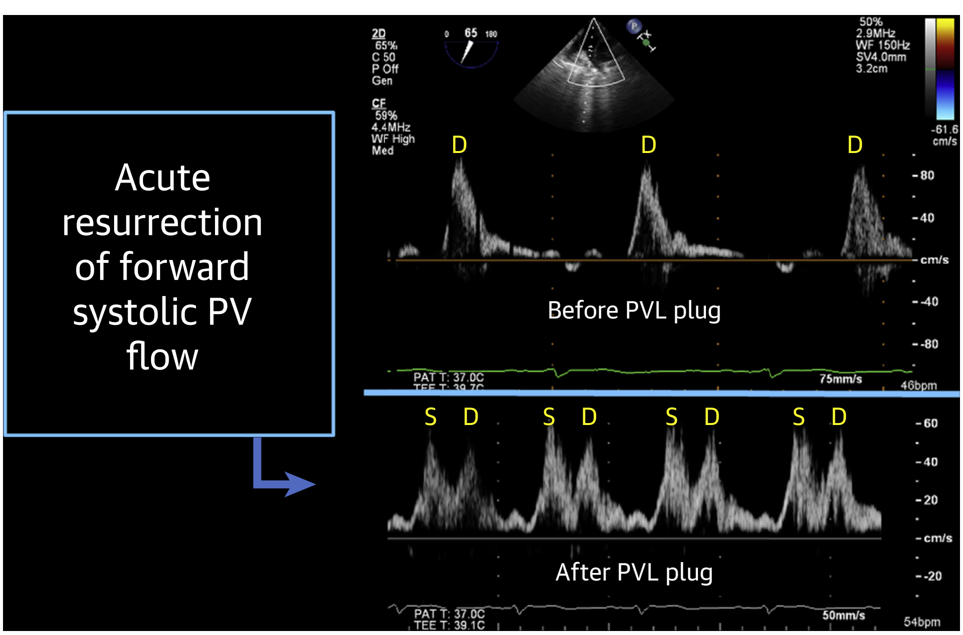
FIGURE 21 **Assessment of MR in the Presence of MAC**



(A) Apical 4-chamber transthoracic echocardiogram where there appears to be only mild mitral regurgitation (MR) by color Doppler due to shadowing from heavy MAC obscuring the color flow Doppler jet in the left atrium. **(B)** In the same patient, from a transesophageal view, the MR color flow jet appears significant as the color flow Doppler is not shadowed by the dense MAC and the color jet extends to the back wall of the left atrium. MAC = mitral annular calcification.

thin color jets, where there is little or no flow convergence indicative of mild MR. Conversely, Doppler patterns consistent with severe MR include large color jets that penetrate deep into the LA or occupy >40% of LA area, large proximal flow convergence, and eccentric jets with a wide vena contracta that extends along the LA wall to the pulmonary veins. Parasternal short-axis views at the level of the mitral valve as well as off-axis views may be needed to identify residual MR.

FIGURE 22 **Pulmonary Vein Flow Response to Paravalvular Repair**



At baseline, the antegrade systolic flow wave (S) is absent from the left upper pulmonary vein. Immediately after paravalvular prosthetic leak (PVL) plugging the systolic wave is present. This Doppler finding indicates acute hemodynamic improvement.

An elevated diastolic pressure gradient along with a high pulsed-wave Doppler E-wave reflect severe postprocedural MR rather than stenosis. Conversely, a change in the MV inflow pattern from a high (>120 cm/s) E-wave-dominant mitral inflow, to an A-wave-dominant pattern postprocedure indicates a substantial decrease in MR. An A-wave-dominant pattern generally precludes severe residual MR. Postprocedure normalization of the pulmonary vein flow pattern indicates reduction in MR, and is highly predictive of improved clinical symptoms (14) (**Figure 22**). A dense holosystolic jet on continuous-wave Doppler postintervention suggests severe residual MR.

DIASTOLIC MITRAL VALVE FUNCTION. After MViV, MViR, or catheter-based plugging of paravalvular leaks, mitral inflow is determined using continuous-wave Doppler to assess the peak mitral E velocity, its deceleration rate, and mean transvalvular pressure gradient. The goal of a transcatheter MV repair or replacement is to eliminate MR and/or to improve diastolic flow if the prosthetic valve is stenotic. Even when correctly sized, a ViMAC, MViV, or MViR procedure will not restore normal native MV diastolic area (4 to 6 cm^2). A directly planimetered mitral valve area of >1.5 cm^2 is reassuring but difficult to visualize after any form of THV implantation in the mitral position.

The hemodynamic condition of a normal prosthetic valve that is relatively undersized with an increase in transvalvular pressure gradient is referred to as patient-prosthesis mismatch. Because of the inherit limitations of transcatheter THV delivery to the mitral position, a mildly stenotic residual pressure gradient is often expected even with a normally functioning THV (i.e., patient-prosthesis mismatch). Post-procedural mitral stenosis may be problematic, but a mean gradient of <5 mm Hg at a normal heart rate is acceptable. Additional outcome studies are required to define the prognostic significance of residual diastolic gradient between 6 and 10 mmHg. Severe stenosis (>10 mm Hg) is unlikely to be associated with improvement in morbidity and may actually worsen the symptom burden.

For this review, the focus has been on the intra-procedural guidance and acute functional evaluation of each mitral intervention. Additional baseline transthoracic Doppler characterization of valve function is appropriate within the first few days or weeks after THV implant or SHV repair. Because catheter-based mitral interventions may not restore ideal hemodynamic function, it is reasonable to re-evaluate valve function on an annual basis.

HIGHLIGHTS

- Computed tomography is an essential imaging modality for patient selection and procedural planning of catheter-based mitral valve interventions on a prosthetic valve or calcified native annulus.
- Echocardiography and limited fluoroscopy are principal imaging tools for intraprocedural guidance. Echocardiography is well suited for immediate post-procedure functional evaluation.
- Accurate prediction of left ventricular outflow tract patency is a specific imaging challenge for these interventions.
- Functional evaluation of residual mitral regurgitation and paravalvular regurgitation post procedure are important tasks for the echocardiographer.

In summary, transcatheter mitral valve intervention on prosthetic valves, surgical rings, and annular calcification is highly dependent on anatomic and functional information provided by noninvasive imaging to plan, perform, and evaluate each intervention.

COMPETENCY IN PATIENT CARE AND PROCEDURAL SKILLS. Transcatheter mitral valve intervention on prosthetic valves, surgical rings, and annular calcification is highly dependent on anatomic and functional information provided by noninvasive imaging to plan, perform, and evaluate each intervention. Those providing the imaging guidance for such procedures should be familiar with the common procedural elements as well at the specific functional concerns associated with each procedure.

Key take home messages:

1. Transcatheter mitral valve repair and replacement procedures are complex. For adequate patient selection and technical success, procedural planning and guidance with multimodality imaging approach is key.
2. Transthoracic and transesophageal echocardiogram are essential imaging tools to select patients with favorable anatomy for transcatheter mitral valve repair of paravalvular defects.
3. For MViV, MViR, and ViMAC procedures, cardiac CT is essential in preprocedure planning: mitral

annular sizing, estimating risk of LVOT obstruction, determining landing zone of the THV, and predicting risk of paravalvular regurgitation.

4. Precise sizing of the landing zone decreases valve embolization or migration. Cardiac CT is the main tool for annular sizing, particularly in MAC. Although neo-annulus dimensions come from the manufacturer in MViV and MViR cases, CT may be more accurate.
5. Compared with echocardiography, cardiac CT discerns risk of LVOT obstruction after transcatheter mitral valve replacement contributes to improved outcomes for patients.
6. Transseptal puncture location can be planned using cardiac CT. However, final location choice is guided by TEE. For transcatheter mitral valve repair procedures, trans-septal location depends on device technology and underlying pathology.
7. Fluoroscopy is the main imaging tool for THV placement within a radiopaque prostheses or ring. TEE is valuable for guiding THV deployment within nonradiopaque devices.
8. 2D and 3D TEE are essential to evaluate the acute result of THV intervention on the mitral valve. MR quantification is challenging due to prosthetic shadowing, mitral annular calcification and/or eccentric MR jets.
9. An integrative approach to MR quantification relies on color and spectral Doppler, as well as valve morphology.
10. Quantification of mitral valve diastolic function after transcatheter valve implantation is critical. Diastolic valve area is challenging to directly measure; however Doppler-derived mean pressure gradient is feasible and predictive of clinical response.

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KEY WORDS mitral valve, paravalvular repair, transcatheter, valve-in-mitral annular calcification, valve-in-ring, valve-in-valve

APPENDIX For supplemental videos, please see the online version of this paper.