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STATE-OF-THE-ART PAPER

3D TEE During Catheter-Based Interventions

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3D TEE During Catheter-Based Interventions

Guidance of catheter-based procedures is performed using fluoroscopy and 2-dimensional transesophageal echocardiography (TEE). Both of these imaging modalities have significant limitations. Because of its 3-dimensional (3D) nature, 3D TEE allows visualizing the entire scenario in which catheter-based procedures take place (including long segments of catheters, tips, and the devices) in a single 3D view. Despite these undeniable advantages, 3D TEE has not yet gained wide acceptance among most interventional cardiologists and echocardiographists. One reason for this reluctance is probably the absence of standardized approaches for obtaining 3D perspectives that provide the most comprehensive information for any single step of any specific procedure. Therefore, the purpose of this review is to describe what we believe to be the most useful 3D perspectives in the following catheter-based percutaneous interventions: transseptal puncture; patent foramen ovale/atrial septal defect closure; left atrial appendage occlusion; mitral valve repair; and closure of paravalvular leaks. (J Am Coll Cardiol Img 2014;7:292–308) © 2014 by the American College of Cardiology Foundation

Advances in technology and human skill have made possible the adoption of percutaneous catheter-based procedures in a wide spectrum of structural heart diseases that over the past 2 decades would have required open-heart surgery. Typically, guidance of these catheter-based procedures is performed using fluoroscopy and 2-dimensional (2D) transesophageal echocardiography (TEE). Both of these imaging modalities have significant limitations. Fluoroscopy is limited by its 2D projections of a complex 3-dimensional (3D) heart, and its inability to delineate soft structures precisely; 2D TEE, because of its tomographic nature, needs multiple planes and adjustments to visualize the course of intracardiac catheters and their complex relationship with cardiac structures.

3D TEE has the unique ability to depict cardiac structures as they are in reality (1,2). Moreover, because of its 3D nature, long segments of catheters, tips, and the devices can easily be intersected by the pyramidal ultrasound beam and displayed without excessive probe manipulations. Finally, the entire scenario in which most of the catheter-based procedures take place (i.e., atrial septum, left atrial appendage [LAA], left atrium, and mitral valve) can be shown in a single 3D view (3–5). Theoretically, 3D TEE should be the ideal guidance-imaging tool for catheter-based procedures. Despite its undeniable advantages, 3D TEE has not yet gained wide acceptance among most interventional cardiologists and among those echocardiographists involved in catheter-based procedures.

Several reasons may explain the reluctance to shift from 2D to 3D TEE. Historically, 2D TEE was used to guide these procedures, thus interventional cardiologists and echocardiographists became accustomed working with 2D TEE imaging. Because of its tomographic nature, 2D TEE needs multiple planes and adjustments to accurately track catheters moving in a 3D environment. For this reason, its use, especially during some complex catheter-based interventions, has been carefully standardized and both echocardiographists and interventional cardiologists have a clear notion of which plane(s) must be used for each step of the procedure (6).

The use of 3D TEE as guidance imaging modality during catheter-based procedures was first described by Perk et al. (3), who collected data from 5 institutions with great expertise with this new imaging tool. However, this first experience was not followed by an effort to select (and hence standardize) those 3D views that might provide the most useful data for each step of any specific procedure. Even when 3D TEE is described as a useful tool for guiding interventional procedures (4,7–10), there are no systematic descriptions of how to acquire those perspectives that can provide the best images of catheters, devices, and their relationships with target structures. The need to provide specific 3D views derives from the fact that the "volumetric" acquisition includes many cardiac structures that, in turn, can be imaged from countless perspectives. However, only a few of them are very innovative and useful, others are redundant and useless, and some are just confusing. Moreover, from some viewpoints, target structures may be covered by surrounding tissue that needs to be removed. Finally, reverberations (i.e., multiple reflections) and

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shadowing (i.e., lines of dropout beyond catheters similar to tears in the tissue) both caused by the specific material of the catheters may further complicate the selection of the most appropriate perspectives. The only way to select those views that best match the requests of interventionalists and to remove the presence of redundant tissue and avoid reverberations or dropout artifacts, is to manipulate the volumetric data set (i.e., cropping, rotating, and adjusting the acquired images) during the procedure.

This review aims to provide practical guidance for echocardiographists who, working in institutions performing catheter-based interventions, are involved in these procedures. We describe how to obtain those 3D perspectives that, to our minds, are the most useful in the following procedures: transseptal puncture, patent foramen ovale (PFO)/atrial septal defect (ASD) closure, LAA occlusion, mitral valve repair (mitral clip), and closure of mitral paravalvular leaks.

ABBREVIATIONS AND ACRONYMS

ASD = atrial septal defect

IAS = interatrial septum

LAA = left atrial appendage

PFO = patent foramen ovale

TEE = transesophageal echocardiography

2D = 2-dimensional

3D = 3-dimensional

Basic Technical Aspects of Imaging Acquisitions

The use of 3D TEE for guidance during catheter-based procedures depends exclusively on the generation of 3D images in real time. Currently, with the 2 available 3D TEE technologies (i.e., Philips, Medical Systems, Andover, Massachusetts; and Vivid 9, GE Healthcare, Milwaukee, Wisconsin), there are 2 modalities for real-time image acquisition:

1. 3D zoom modality: This modality can display a truncated but magnified pyramidal dataset of variable size. After sizing the zoom sector over the area of interest, the volume dataset is acquired. Minimizing sector width is important for increasing temporal resolution and image quality. Both GE and Philips 3D TEE technologies have similar 3D zoom modality acquisition.
2. Single beat: With Philips technology, a pyramidal set 60° × 30° is displayed in real time. This acquisition modality generates high-quality 3D images at a volume rate up to 25 Hz. New technical developments allow electronic steering, in both lateral and elevation planes of the pyramidal dataset, thus avoiding transducer manipulations. Single-beat acquisition of a larger area (60° × 60°) produces images at a volume rate of 9 to 10 Hz. With GE technologies, the single-beat modality has 3 pre-defined acquisition modalities with increasing angles: bird's eye view, medium modality, and large modality. The angle of these pre-configured volume datasets can also be manually changed according to specific needs.

Transseptal Puncture

The transseptal crossing is the common entry point for many left-side catheter-based procedures. Experienced operators may safely perform a transseptal puncture using only fluoroscopy (11,12). However, in catheter-based procedures, this maneuver is usually performed under fluoroscopy and 2D TEE. The use of an imaging guide may avoid complications related to inappropriate puncture sites, especially in high-risk patients (i.e., those with a previous transseptal crossing failure or severe kyphoscoliosis, septal aneurysm, or aortic root dilation). When the catheter is against the fossa ovalis and the interventional cardiologist applies pressure, the site of the puncture may be identified by the "tenting" seen in 2D TEE images.

3D TEE shows the "authentic" anatomical deformation of the interatrial septum (IAS) during the puncture (i.e., a configuration similar to a "conic tent"), yet many echocardiographists still prefer to use 2D TEE. Indeed, with 3D TEE, the atrial septum is usually displayed in an en face perspective (2). However, this perspective is not as effective as 2D TEE in showing the tenting. Difficulties in interpreting 3D tenting in an en face view perspective are shown in Figures 1A and 1B.

Even when echocardiographists manipulate the image online to obtain a view similar to that of 2D TEE, interventional cardiologists remain reluctant to maneuver under 3D guidance because the borders of the tenting may be difficult to distinguish against a background of a similar color (Fig. 1C).

The safest site for septal puncture is across the fossa ovalis (11). The various steps needed to acquire 3D imaging of the fossa ovale en face from a right perspective using Philips technology are described elsewhere (2). Table 1 summarizes technical details of image acquisition with both Philips and GE technologies.

The en face view from the right atrial perspective is particularly appreciated by interventionalists because it matches the fluoroscopic right anterior oblique projection. They can follow the catheter tip (part of the body usually remains out of volumetric dataset) from the superior vena cava to the fossa ovalis, associating their tactile feedback with the

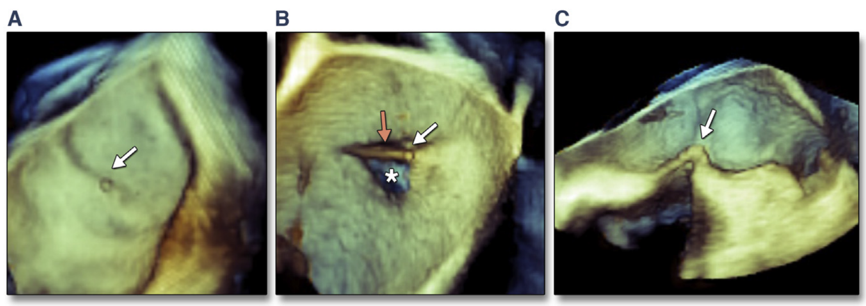

Figure 1. Difficulties in Recognizing Tenting With 3D TEE

(A) A nonprominent tenting **(arrow)** is difficult to recognize from an en face perspective: the visual perception of a protrusion is obtained through different nuances of blue/beige color; when tenting is not prominent, this difference may be elusive, and the protrusion is difficult to distinguish. **(B)** Reverberations **(pink arrow)** and dropout artifacts **(asterisk)** may complicate the immediate recognition of tenting **(white arrow). (C)** Using a perspective similar to a 2-dimensional transesophageal echocardiography (TEE) bicaval view, the tenting is projected against a background of similar color, which may make immediate detection difficult.

visualization of the movement of the catheter through these structures (Fig. 2).

Once the catheter has been moved into the fossa ovalis, tenting can best be viewed from a lateral perspective. This view can be obtained quite simply by rotating the volumetric dataset left-to-right around the y-axis (Fig. 3, Online Video 1). The source of light (created by a specific algorithm) illuminates the tenting, laterally enhancing its edges against the background and facilitating recognition. Moreover, both dropout artifacts and reverberations are covered by the tenting itself. We found that this perspective is very effective in imaging the tenting and, more importantly, was well accepted by our interventional cardiologists.

PFO/ASD Closure

Percutaneous closure of PFO/ASD is usually performed via the right femoral vein. The septal crossing and the other steps of the procedure can be easily guided by 3D TEE visualizing the IAS from both oblique and lateral perspectives, which enhance catheter imaging and disk expansion (Fig. 4, Online Videos 2 and 3). Technical details on how to acquire these perspectives are described in Table 2.

LAA Occlusion

Specific 3D perspectives are needed for guiding the correct positioning of the guide catheter inside the LAA and following the expansion of the occluder (Figs. 5 to 8, Online Video 4). Details on how to acquire these perspectives are described in Table 3. Figures 5 to 8 and Online Video 4 refer to the deployment of the Amplatzer cardiac plug (AGA Medical, Plymouth, Minnesota) (13).

Mitral Clip Procedure

The catheter-based edge-to-edge mitral clip repair (mitral clip) consists of bringing the anterior and posterior leaflets together with a metallic clip (14). The procedure is complex and embraces several steps. None of them can be made without TEE guidance. Because of the complexity, the use of 2D TEE has been strictly standardized and at least 4 key basic views are recommended, each of them crucial for any specific step (6).

The role of 3D TEE as the guidance imaging modality during a mitral clip procedure has been

Table 1. 3D TEE Visualization of the Fossa Ovalis—Technical Details

Steps	Suggested Perspectives
Step 1	3D TEE imaging of the left side of the IAS is obtained with a 2D bicaval view using a zoom modality.
Step 2	A 90° clockwise rotation around the x-axis of the acquired dataset shows the left side of IAS in en face perspective. A further counterclockwise 90° rotation around the z-axis displays the IAS in an "anatomically correct" orientation.
Step 3	A further 180° rotation around the y-axis shows the right side of the atrial septum with the fossa ovalis, the surrounding muscular rim and the entrance of the superior vena cava (Fig. 2). This perspective is similar to the fluoroscopic right anterior oblique projection view and precisely delineates the spatial relationship between the fossa ovalis and the aortic bulge.

IAS = interatrial septum; TEE = transesophageal echocardiography; 2D = 2-dimensional; 3D = 3-dimensional.

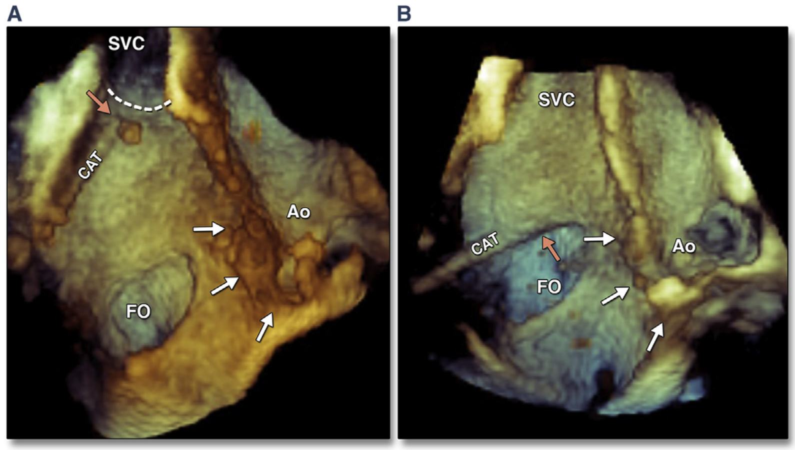

Figure 2. 3D TEE Imaging of Right Side of the Atrial Septum

(A) Three-dimensional (3D) TEE cropped imaging of the right side of the atrial septum. The imaging shows the fossa ovalis (FO) and its relationship with the aortic bulge **(white arrows)**. The **dotted line** marks the border between the superior vena cava (SVC) and right atrial cavity; while passing this border, interventionists perceive the tactile feedback of a jump. The **pink arrow** points to the tip of the catheter (CAT). **(B)** The catheter is withdrawn until it falls (second jump) into the FO **(pink arrow)**. Ao = aorta.

recently explained (5,15). During the septal crossing, the site of the septal puncture is of particular relevance: a distance not inferior to 4.0 to 4.5 cm between the septal tenting and mitral valve orifice provides an adequate space for maneuvering the mitral clip delivery system into the left atrium; a lateral perspective of IAS enables the visualization in a single image of the tenting and the mitral valve

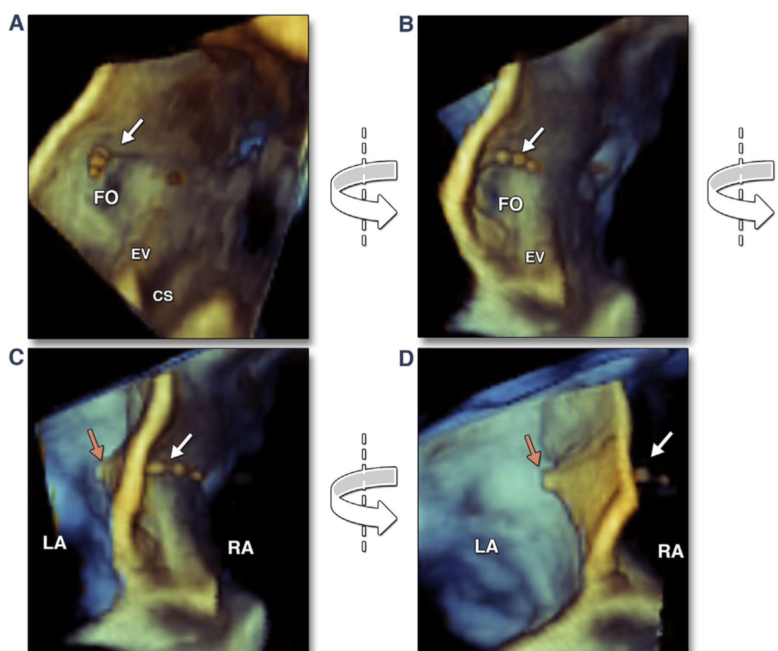

Figure 3. 3D TEE Imaging of the Tenting in Lateral Perspective

(A) A 3D TEE image of the right side of the septum with the needle **(white arrow)** pushing against the FO. **(B to D)** A left to right rotation **(curved arrows)** around the y-axis progressively displays the tenting **(pink arrow)** protruding into the left atrium (LA). CS = coronary sinus ostium; EV = Eustachian valve; RA = right atrium; other abbreviations as in Figures 1 and 2. See Online Video 1.

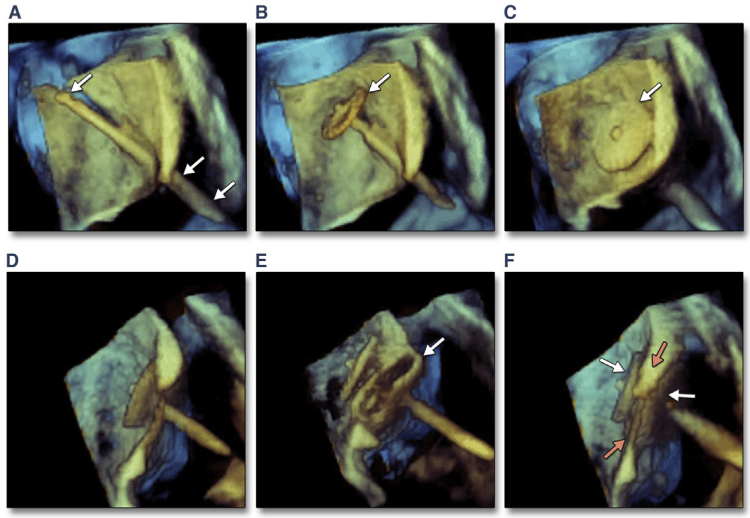

Figure 4. 3D TEE Sequential Imaging of PFO Closure

(A) 3D TEE imaging of an "oblique" view of the atrial septum. The guide catheter is clearly visible across the atrial septum **(arrows); (B)** expansion of the left disk **(arrow); (C)** the disk is pulled back toward the atrial septum; **(D)** a further slight rotation of the volume dataset enables the visualization of the expansion of the right disk; **(E)** the right disk is pushed against the atrial septum **(arrow); (F)** this perspective enables one to see septal tissue **(pink arrow)** entrapped between the disks **(white arrows)**. PFO = patent foramen ovale; other abbreviations as in Figures 1 and 2. See Online Videos 2 and 3.

plane. How to obtain this perspective is described in detail in Table 4 and shown in Figure 9A.

The advancement of the mitral clip delivery system into the left atrium and its steering toward the mitral valve requires 3D views that display the spatial relationship of the delivery system with the atrial wall and IAS. An oblique perspective of IAS satisfies these requirements (Figs. 9 and 10). Such a view is particularly appreciated by interventionalists because they can safely maneuver (advancing, pulling back, and steering) catheters while maintaining the entire delivery system in the left atrium and avoiding hurting the atrial walls. Details on how to acquire these perspectives are described in Table 4.

Orienting the clip arms perpendicular to the coaptation line is of paramount importance for the success of the procedure because lack of perpendicularity may result in a failure to capture or inadequately grasp 1 or both leaflets. The overhead perspective, which enables imaging the open arms, and in a deeper plane, the mitral valve coaptation line, has been the first 3D view fully accepted during the procedure (3). Even the most reluctant adopters of 3D modality should admit that this unique perspective is by far preferable to the 2D TEE

Table 2. Details on How to Acquire Effective 3D Perspectives During PFO/ASD Closure

Steps	Suggested Perspectives
Step 1. Visualization of the catheter passing through the PFO/ASD	Obtain an image of the left side of the IAS in an anatomically correct orientation. A slight right-to-left rotation around the y-plane provides a view of the left side of atrial septum from an oblique perspective. From this viewpoint, the guide catheter crossing the PFO/ASD is visualized (Fig. 4A)
Step 2. Visualization of the left disk expansion	The same view allows one to visualize the expansion and withdrawal of the left disk (Figs. 4B and 4C).
Step 3. Visualization of the right disk expansion	Visualize the IAS from a lateral perspective. This view allows the operator to guide the deployment of the right disk and to clearly image the septal tissue between the 2 disks (Figs. 4D to 4F).

ASD = atrial septal defect; PFO = patent foramen ovale; other abbreviations as in Table 1.

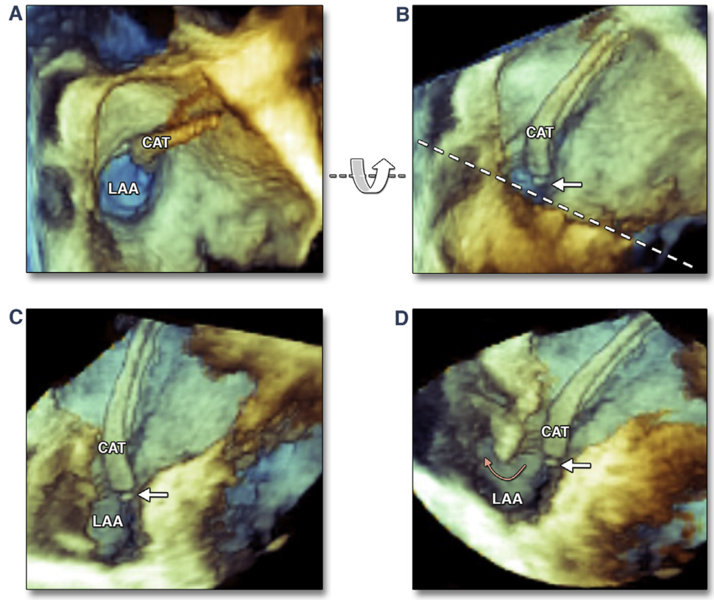

Figure 5. 3D TEE Images of Catheter in LAA

(A) An overhead perspective of the left atrial appendage (LAA) orifice. The CAT is clearly seen in the LAA. However, the tip is not visible. **(B)** A slight rotation around the x-axis **(curved arrow)** shows the catheter's tip **(arrow)**. **(C)** Cropping through the plane indicated by the **dotted line** in **B** reveals a long-axis aspect of the LAA. The tip is clearly seen adjacent to the LAA wall **(arrow)**. **(D)** A deeper cut along the same plane displays an anterior lobe **(curved pink arrow)**. Abbreviations as in Figures 1 and 2.

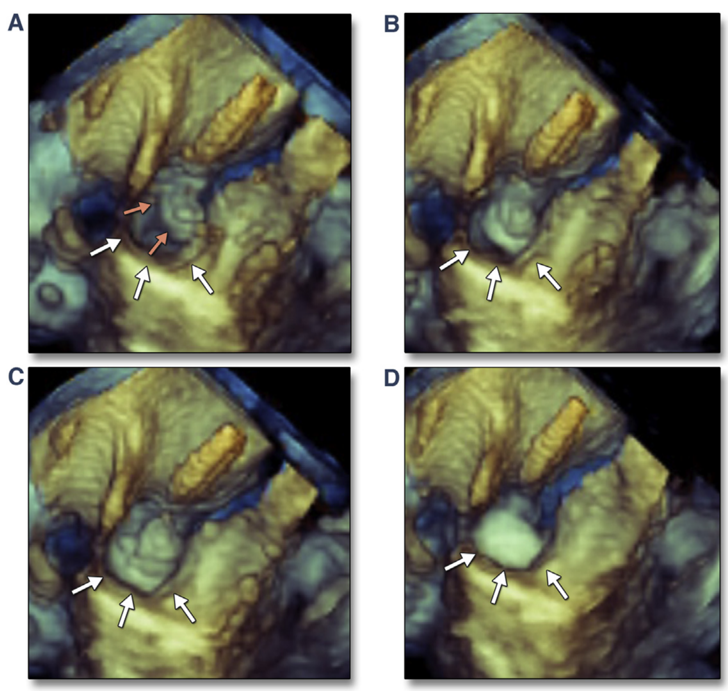

Figure 6. 3D TEE Imaging of Opening of the Lobe in LAA Occlusion Procedure

(A to D) Sequential 3D TEE images showing the opening of the lobe. The perspective is from above with a slight angulation to ensure that both the edges of the lobe **(pink arrows)** and the border of the orifice **(white arrows)** can be seen. Abbreviations as in Figures 1, 2, and 5.

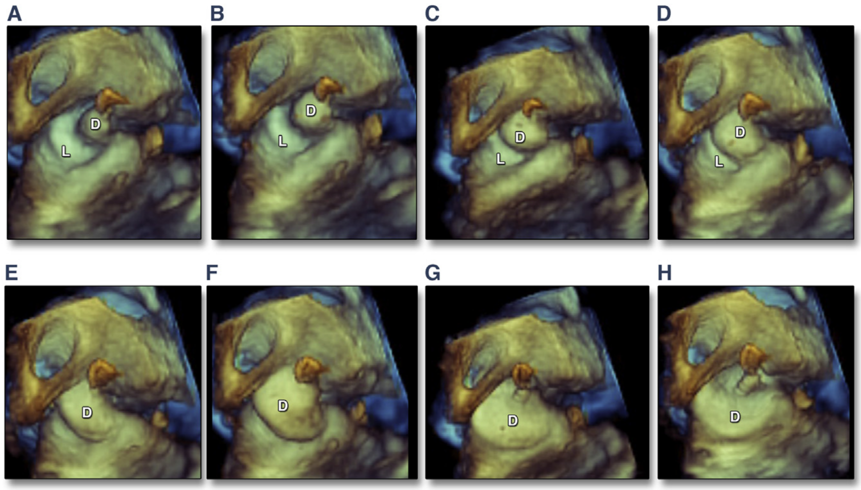

Figure 7. 3D TEE Imaging of Opening of the Disk in LAA Occlusion Procedure

(A to H) Same perspective as in Figure 6 showing the sequential 3D images of the opening of the disk (D). L is the lobe. Abbreviations as in Figures 1, 2, and 5. See Online Video 4.

transgastric short-axis view (6), allowing fine adjustments until the clip arms are perfectly perpendicular to the coaptation line (Fig. 11, Online Video 5, Table 4).

The most relevant step of the procedure is the act of grasping the leaflets. Currently, this step is exclusively guided by 2D TEE because the spatial resolution of 3D imaging is not sufficiently adequate to image the thin leaflets between arms and grippers. Once captured, however, among the most challenging issues is evaluating the adequacy of the insertion of the leaflets into the clip. Because the clip is inserted from below, we found the 3D perspective from the left ventricle to be particularly valuable. This perspective allows one to evaluate the adequacy of the insertion, residual orifices, and the number and position of clip(s) (Fig. 12, Table 4). The 3D views that allow monitoring of the clip

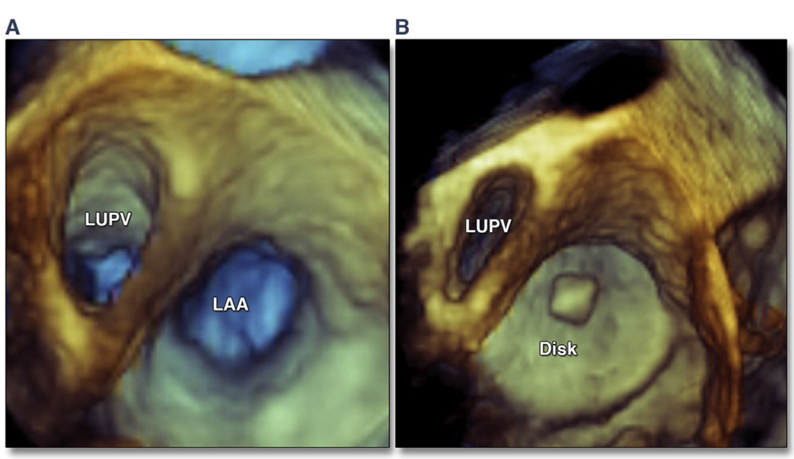

Figure 8. 3D TEE Imaging Final Result in LAA Occlusion Procedure

(A) The LAA orifice before and **(B)** after the procedure. The entire LAA orifice is covered by the disk. LUPV = left upper pulmonary vein; other abbreviations as in Figures 1, 2, and 5.

Table 3. Details on How To Acquire Effective 3D Perspectives for LAA Occlusion

Steps	Suggested Perspectives
Step 1. Transseptal crossing	Obtain 3D visualization of tenting of the atrial septum and transseptal puncture from a lateral perspective.
Step 2. Position of the catheter inside the LAA	Obtain an en face view of the LAA orifice from an overhead perspective (Fig. 5A). A slight angulation displays the tip of the catheter inside the LAA (Fig. 5B). A "long-axis view" of the LAA allows the visualization of the tip of the catheter, its spatial relationship with the LAA wall, and its distance from the cul-de-sac of LAA (Figs. 5C and 5D).
Step 3. Expansion of the lobe	The same perspective as in Fig. 5B allows simultaneous imaging of the edges of the lobe in the LAA and the borders of the LAA orifice.
Step 4, Expansion of the disk	Maintain the same perspective (Figs. 7A to 7H).
Step 5. Final control	An overhead perspective of LAA (Fig. 8A) confirms that the disk covers the entire LAA orifice (Fig. 8B).

LAA = left atrial appendage; 3D = 3-dimensional.

deployment and the removal of the delivery system are shown in Figure 13 and described in Table 4.

Mitral Paravalvular Leak

3D TEE allows a "panoramic" view of the suture ring from an overhead perspective (the surgical view) with the aortic valve at the top of the mitral ring (12 o'clock), and the LAA at approximately the 9-o'clock position. Within this virtual clock, the location of any mitral paravalvular leak may be reported as a single hour, if localized or, as a range of hours if the defect is larger or has a crescent-shaped configuration. The same view may be maintained during the entire procedure of mitral valve leaflet closure. The main advantage of this perspective

Table 4. Details on How to Acquire Effective 3D Perspectives for Mitral Clip

Steps	Suggested Perspectives
Step 1. Transseptal puncture	Obtain an image of the left side of atrial septum from a lateral perspective. A slight counterclockwise rotation of the probe shows the tenting and the mitral valve in the same image allowing a direct measurement of the distance (Fig. 9A).
Step 2. Advancement of the guide catheter and the mitral clip delivery system	A slight rotation around the y-axis of the volumetric dataset shows the atrial septum from an oblique perspective. This perspective allows following the advancement of the mitral clip delivery system (Figs. 9B to 9D) and the safe withdrawal in case of blockage against the atrial wall (Figs. 9E to 9H).
Step 3. Steering the mitral clip system toward the mitral valve	This step may be guided by maintaining the same perspective (Figs. 10A to 10C) or using an overhead perspective (Figs. 10D to 10F).
Step 4. Opening the arm perpendicularly to the coaptation line	Maintain the same overhead perspective. From this view, the opened arms are exactly displayed over the mitral leaflets. This perspective allows imaging the rotation of the clip until the arms are perfectly perpendicular to the coaptation line (Fig. 11, Online Video 5).
Step 5. Capturing leaflets	This step is usually guided by 2D TEE because of its higher temporal and spatial resolution, as described by Silvestry et al. (6).
Step 6. Evaluating adequacy of the insertion of the leaflets into the clip	A ventricular perspective (Figs. 12A and 12B) allows the visualization of the amount of tissue captured from each clip, the residual valve orifices, and the positions and number of clips inserted (Figs. 12C and 12D).
Step 7. Clip deployment and withdrawal of the guide catheter from the left atrium	A slight clockwise rotation around the x-axis from an overhead perspective allows monitoring the detachment of the delivery system (Figs. 13A to 13D), whereas an oblique perspective of the atrial septum allows monitoring the catheter withdrawal (Figs. 13E to 13H).

Abbreviations as in Table 1.

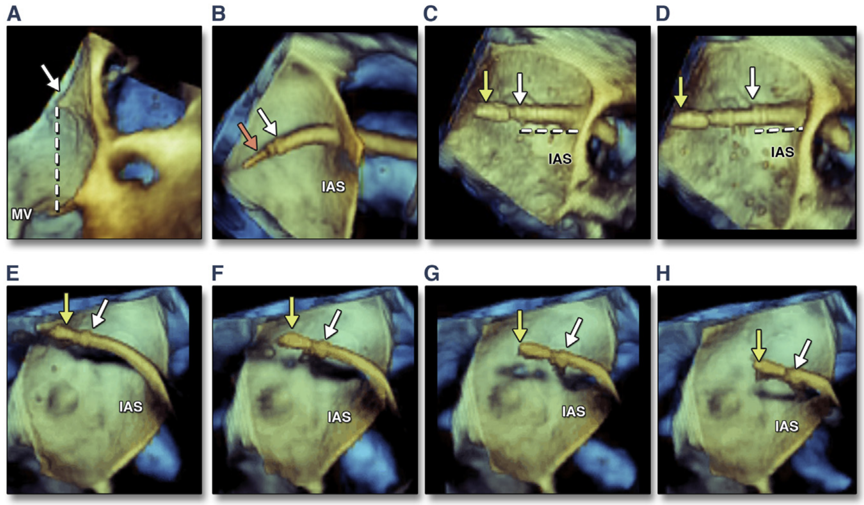

Figure 9. 3D TEE Imaging of Mitral Clip Delivery System in the Left Atrium

A composite 3D TEE figure showing how the same lateral perspective can visualize both transseptal puncture and the mitral clip delivery system positioning. **(A)** 3D TEE enables measuring directly on the 3D image the distance between the tenting **(arrow)** and the mitral valve (MV). **(B)** A slight rotation around the y-axis (similar to that used in PFO/atrial septal defect closure) shows the atrial septum in an oblique view. This oblique perspective clearly shows the guidewire **(pink arrow)** and guide catheter in the left atrium. The **white arrow** points to the tip of the guide catheter, which shows a small circular protrusion owing to the radiopaque ring. **(C, D)** Two sequential images showing the advancement of the mitral clip delivery system **(yellow arrow)**. The distance between the tip of the guide catheter **(white arrow)** and the interatrial septum (IAS) can be easily visualized and measured on the 3D image **(dotted line). (E)** The tip of the mitral clip delivery **(yellow arrow)** is against the lateral wall. **(F to H)** The entire assembly can be safely withdrawn. The **white arrow** points to the tip of the guide catheter, which must remain in the left atrial cavity. Abbreviations as in Figures 1, 2, and 4.

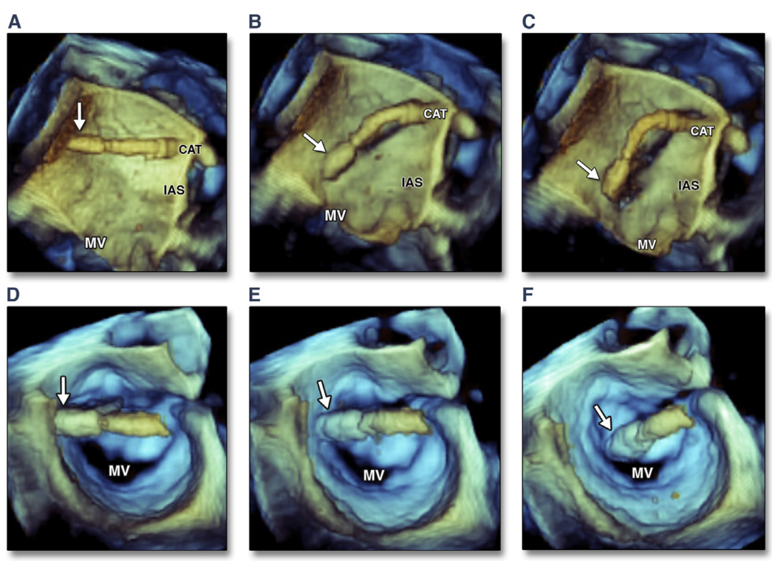

Figure 10. Perspectives Showing the Steering of Mitral Clip Delivery System

3D TEE sequential images showing the progressive steering of the mitral clip delivery system **(arrow)** toward the MV maintaining the same perspective as in Figure 9 **(A to C)** and the overhead perspectives **(D to F)**. The oblique perspective allows the visualization of the entire mitral clip delivery system from the guide CAT crossing the IAS to the clip **(arrow),** while it is being steered. From the overhead perspective, the clip delivery system is seen projected on the entire mitral valve circumference. Abbreviations as in Figures 1, 2, and 9.

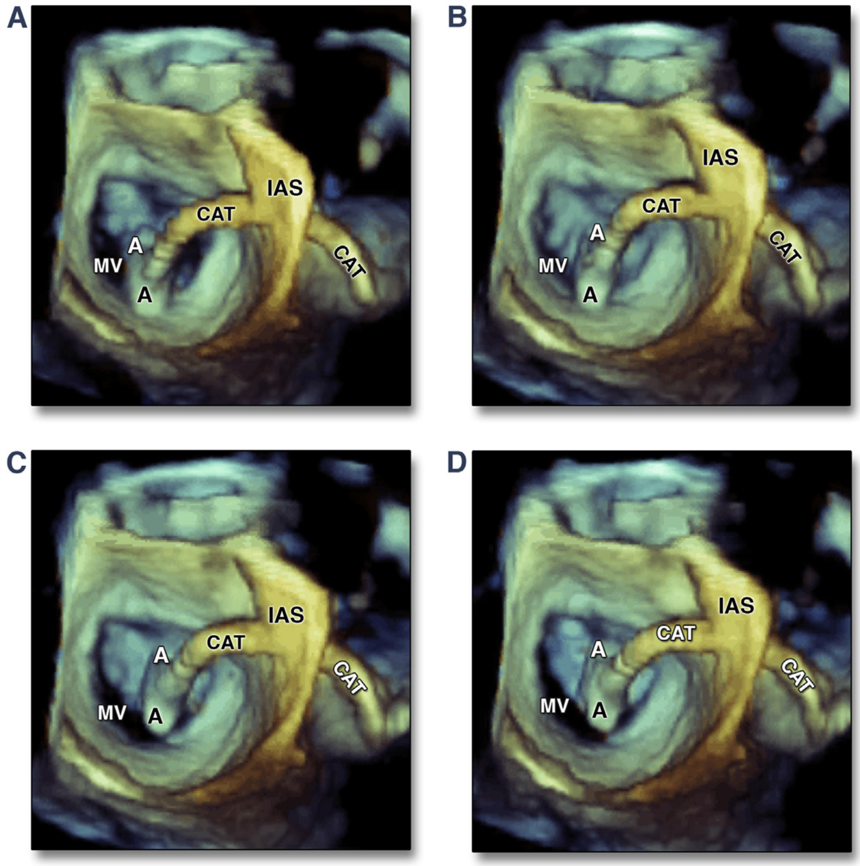

Figure 11. The Overhead Perspective

The overhead perspective can show the whole scenario where the procedure takes place. The guide CAT is seen passing through the IAS, steering toward the MV, and searching for an optimal alignment with its arms (A) opened. Abbreviations as in Figures 2 and 9. See Online Video 5.

is that it facilitates observation of the spatial relationship between catheter tip, target leak, and surrounding anatomical structures, providing a 3D anatomical environment, where interventionalists can safely maneuver the catheter, observing its movement toward the leak (Figs. 14A to 14C). Moreover, the device itself can be visualized during expansion from the same perspective (Figs. 14D and 14E); once deployed, the exact location and shape of the device can be appreciated (Fig. 14F, Table 5).

Study Limitations

Most of the images shown in this review are obtained by a single ultrasound machine that uses its own technology (i.e., Philips technology). This is no longer the only machine in which 3D TEE is available. A second ultrasound machine that uses a different technology, acquisition modalities, and imaging processing (i.e., GE technology) is currently available. However, once the most appropriate perspectives have been established, similar perspectives can be obtained with both ultrasound machines, although with different imaging acquisition and processing algorithms (Fig. 15).

We did not include in this review the role of 3D imaging in transcutaneous aortic valve replacement. Indeed, whereas 3D TEE is useful pre-procedurally for annulus measurements, its role during the procedure is limited, being the mainstay of intraprocedural imaging fluoroscopy and angiography. Currently in our institution, 2D/3D TEE is performed in the post-implant assessment.

Certainly, we do not advocate the use of 3D TEE as the sole imaging technique. We are aware that many limitations remain. In particular, the frame rate,

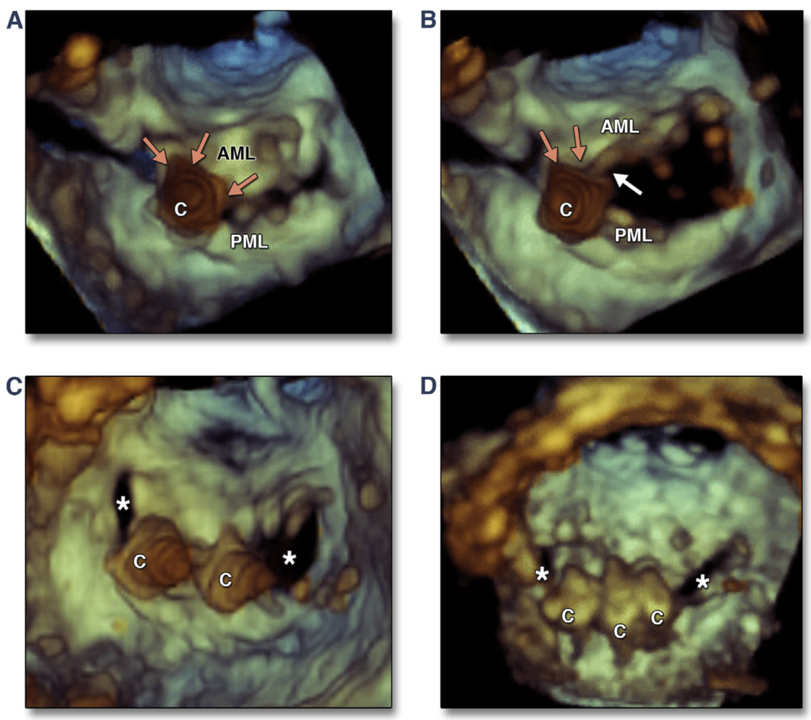

Figure 12. Perspective From Left Ventricle

(A, B) 3D TEE images from the left ventricle. This view shows clearly the amount of tissue captured. Although in **A,** an adequate grasp seems to have been achieved in systole **(pink arrows),** in **B** (diastole), part of the anterior mitral leaflet (AML) can be seen to be still detached **(white arrow)**. This view is particularly valuable for visualizing the orifices and clip(s). **(C)** Two and **(D)** 3 clips (C) are shown creating a doubled orifice valve **(asterisk)**. See Online Video 6. Abbreviations as in Figures 1 and 2.

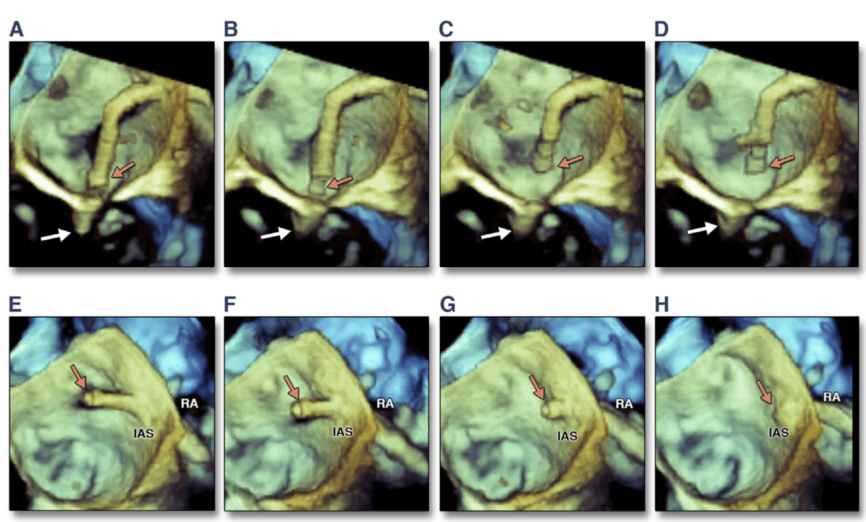

Figure 13. Perspectives Showing the Detachment and Retreating of the Clip Delivery System

(A to D) Sequential 3D TEE images showing the detachment of the clip delivery system **(pink arrow)** from the clip **(white arrow). (E, F)** Sequential images from an oblique perspective showing the guide catheter **(pink arrow)** retreating into the RA through the IAS. Abbreviations as in Figures 1, 2, 3, and 9. See Online Video 7.

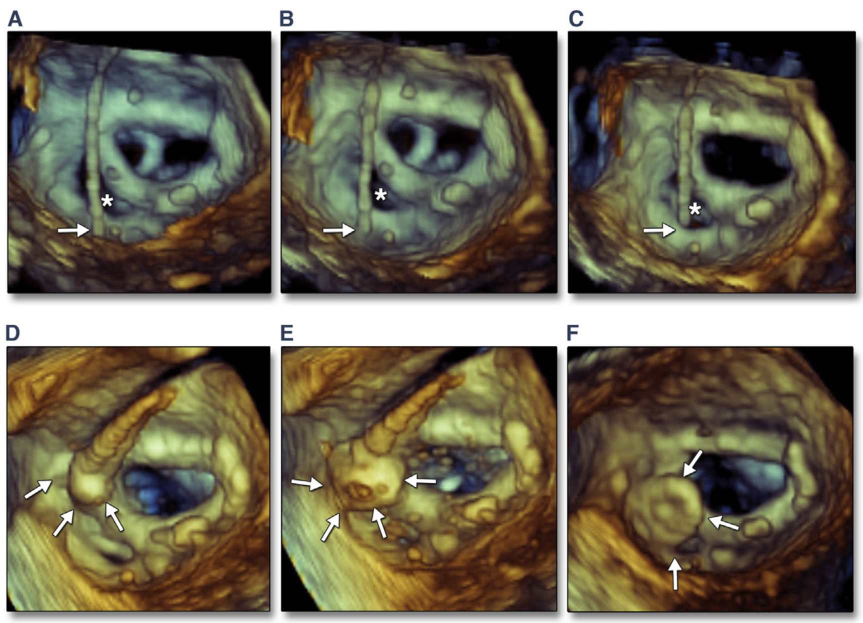

Figure 14. 3D TEE Images of Paravalvular Leak Closure

(A to C) The motion of the guidewire toward the leak **(asterisk);** the arrow point at the tip; **(D, E)** expansion of the occluder **(arrows).** **(F)** Deployment. The arrows point to the final shape of the occluder (see also text). Abbreviations as in Figures 1 and 2.

though acceptable (Online Videos 2 to 7), is still not optimal; the spatial resolution is inferior when compared with that of 2D TEE, and there is also the issue of the lack of real-time acquisition of the 3D color Doppler. These limitations may affect the use of 3D TEE in several steps of any interventional procedure and create difficulties in interpreting 3D images. The most frequent limitations and difficulties that we experienced in interpreting 3D images are listed in Table 6 and shown in Figure 16.

Ongoing technological improvements (such as the 3D color Doppler in real time with an adequate frame-rate and better temporal and spatial resolutions in large panoramic images) will further facilitate the use of this novel technique.

Specific 3D artifacts may occur when the pyramidal ultrasound beam intersects the metallic structures of catheters and devices. These artifacts when displayed in 3D format may appear more "realistic" and may lead to misinterpretation. Dropout artifacts in the atrial septum, for instance, resembling "real" holes, may cause misinterpretation in patients scheduled for ASD closure. Shadowing from catheters may create the impression of real

Table 5. Details on How To Acquire Effective 3D Perspectives for MVL Closure

Steps	Suggested Perspectives
Step 1. Transseptal approach	Obtain an image of the left side of atrial septum from a lateral perspective (as for the other procedures requiring transseptal crossing).
Step 2. Positioning the guidewire across the leak	Obtain an overhead perspective of the prosthesis or sutured ring (Figs. 14A to 14C).
Step 3. Deployment and expansion of the device	Maintain the same perspective (Figs. 14D to 14F). With the Amplatzer device, the expansion of the ventricular disk may be monitored from a ventricular perspective or from a lateral perspective.
Step 4. Final assessment	Maintain an overhead perspective (Fig. 14F).

MVL = mitral valve leaflet; 3D = 3-dimensional.

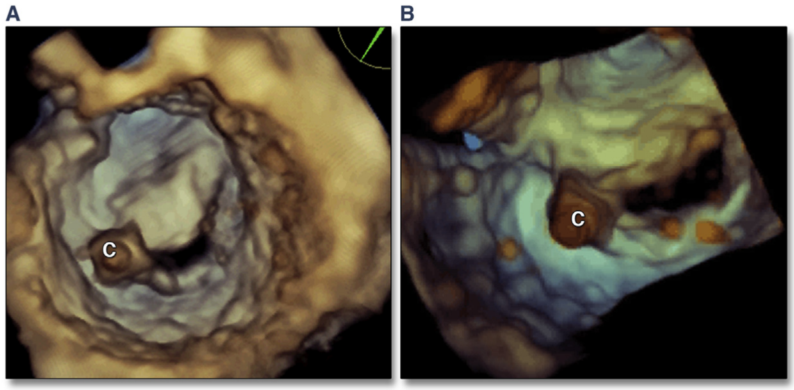

Figure 15. 3D TEE Images Obtained With 2 Different Vendors

Same 3D perspective from below (ventricular perspective) showing a mitral clip (C) located in proximity to the medial commissure obtained **(A)** with GE and **(B)** Philips technologies. Abbreviations as in Figures 1 and 2.

tears in the cardiac tissue behind catheters. Selecting those specific perspectives that are effective in guiding the procedure and, at the same time, minimize these artifacts (thus avoiding that they might have any impact on the procedure) requires experience and practice.

Conclusions

The main goal of this review is to provide practical suggestions on how to obtain specific views that, in our minds, may have additional value over conventional 2D TEE in specific steps of the above-mentioned catheter-based procedures. Searching

Table 6. Limitations and Difficulties in Interpreting 3D Imaging

Interventions	Limitations
Transseptal puncture	• When seen in an en face view, the protrusion (tenting) of IAS may be difficult to distinguish (Fig. 1A). • When stretched by the needle, the IAS becomes oblique to the ultrasound beam and confusing dropout artifacts may appear (Fig. 1B). • Reverberations produced by the metallic needle may make interpretation of the 3D image difficult (Fig. 1B).
PFO/ASD closure	• Very low frame rate (5 Hz) occurs when an extensive area of the IAS is scanned. • Poor spatial resolution may prevent imaging of the atrial tissue between the disks (Figs. 16A and 16B). • The device may have an oblique position. The resulting dropout artifacts of the atrial tissue may create difficulty in correctly evaluating the position of the device (Figs. 16C and 16D).
LAA occlusion	Poor spatial resolution may prevent imaging the spatial relationship between device and circumflex artery (Figs. 16E and 16F).
Mitral clip	• Absence of 3D color Doppler in real time makes it difficult to guide the clip directly onto the regurgitant jet. • Poor 3D spatial and temporal resolution make it difficult to guide the capture of the leaflet with a 3D image. • A large mitral valve may preclude the obtaining of the entire panoramic view in a single perspective with an acceptable frame rate. • Reverberations/shadowing caused by catheter/devices may cover or cancel parts of the mitral leaflets.
Paravalvular leak closure	The flexible guide may move too fast to be followed by 3D imaging especially in large volume datasets.

Abbreviations as in Tables 1, 2, and 3.

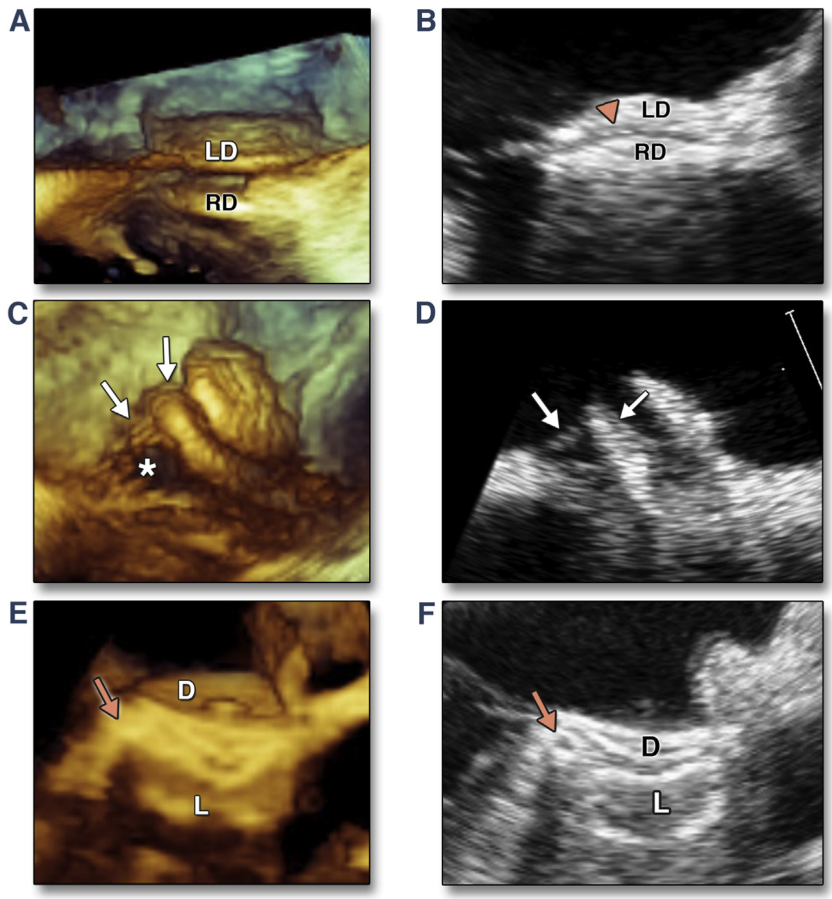

Figure 16. Limitations of 3D TEE Imaging

(A) A 3D TEE image showing the final assessment of PFO closure. Due to the poor spatial resolution the atrial tissue between the left disk (LD) and right disk (RD) is not clearly visible. **(B)** Conversely, the higher spatial resolution of 2D TEE allows one to identify the atrial tissue **(pink arrow)** between the disks. **(C)** Because of the oblique position of the device, the thin atrial tissue around the device remains oblique or parallel to the direction of the ultrasound beam with consequent dropout artifacts **(asterisk)** that may lead to a misdiagnosis or dislocation of the device. **(D)** Conversely, using 2D TEE, the atrial tissue is well visible outside and in between disks **(arrows). (E)** Final assessment of LAA occlusion. The circumflex artery should be positioned between the disk (D) and the lobe (L) of the device. The poor spatial resolution of 3D imaging prevents a clear visualization of the coronary artery, which, on the contrary, is clearly visible **(F)** using 2D TEE **(pink arrow)**. Abbreviations as in Figures 1, 2, 4, and 5.

for these perspectives during the procedure requires time that many interventionalists may be unwilling to concede. However, in our experience, recognizing in advance those perspectives that would meet the needs of interventionalists could eventually speed acquisition and online processing. In the future, the most effective perspectives might be pre-defined to be immediately available during the procedure.

It should be emphasized that our findings are based on the experience of a single center. Other echocardiographers working in hemodynamic laboratories performing structural interventions, may have found different but equally (or even more) effective perspectives. Table 7 shows the most significant manuscripts on the use of 3D TEE for interventional procedures and the perspectives shown by different investigators. Because in the future the technique is expected to be widely used during catheter-based procedures, this review might be considered an encouragement for professional associations such as the American and European Society of Echocardiography to generate appropriate recommendations in this specific field. Finally, following in real time what interventional cardiologists are doing in a 3D panoramic environment may be very attractive. But to be completely accepted by interventional cardiologists, we need to provide clear evidence that the use of 3D

Table 7. Literature on the Use of 3D TEE for Interventional Procedures

First Author (Ref. #)	Intervention	Perspectives Used
Lee et al. (7)	Closure of ASD/PFO	En face perspective of the IAS used for visualizing ASD and occluder.
	LAA occlusion	En face perspective used for visualizing the LAA orifice and occluder. Lateral perspective (after a longitudinal crop) used for visualizing LAA.
	Transseptal puncture	En face perspective of IAS used for visualizing the site of tenting.
	Mitral clip	Lateral perspective used for positioning the device. Oblique perspective (with the aorta positioned at 6 o'clock) used for showing the double orifice.
	Closure of periprosthetic leak	En face perspective used for visualizing the leak.
Cavalcante et al. (8)	Mitral clip	En face perspective of IAS used for visualizing the guide catheter in the LA. Overhead perspective used for visualizing alignment of the clip arms. Lateral perspective used for visualizing the capture of leaflets. En face perspective used for visualizing the double orifice.
	Closure of periprosthetic leak	En face perspective used for valve prosthesis to visualize the leak and the guiding catheter and occluder(s).
Balzer et al. (9)	Closure of ASD/PFO	En face perspective used for visualizing the ASD and catheter crossing. Lateral perspective used for visualizing the expansion of the left disk. Oblique perspective used with different rotations for confirming that left and right disks are opened. Lateral perspective used for visualizing the IAS entrapped between the 2 disks.
	Mitral clip	Overhead perspective of the mitral valve used for visualizing the relationship between the delivery system and the mitral valve and for the alignment of the arms. Lateral perspective used or visualizing the capture of leaflets.
Altiok et al. (4)	Mitral clip	Overhead perspective used for clip positioning and visualization of the double orifice.
Biner et al. (10)	Mitral clip	Lateral perspective used for visualizing the clip delivery system in the LV. Overhead perspective used for visualizing alignment of the arms perpendicular to the coaptation line.

LA = left atrium; LV = left ventricle; other abbreviations as in Tables 1, 2, and 3.

TEE instead of 2D TEE generates practical advantages such as avoiding potential complications, reducing radiation exposure, and/or shortening procedural times.

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Key Words: catheter-based percutaneous interventions ■ 2-dimensional transesophageal echocardiography ■ 3-dimensional transesophageal echocardiography.

APPENDIX

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