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REVIEW ARTICLE

The growing role of echocardiography in interventional cardiology: The present and the future

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Abstract As structural heart disease interventions continue to evolve to a sophisticated level, accurate and reliable imaging is required for pre-procedural selection of cases, intra-procedural guidance, post-procedural evaluation, and long-term follow-up of patients.

Traditionally, cardiovascular procedures in the catheterization laboratory are guided by fluoroscopy and angiography. Advances in echocardiography can overcome most limitations of conventional imaging modalities and provide successful completion of each step of any catheter—based treatment. Echocardiography's unique characteristics rendered it the ideal technique for percutaneous catheter-based procedures.

The purpose of this review is to demonstrate the use of the most common and up-to-date echocardiographic techniques in recent non-coronary percutaneous interventional procedures, underlining its inevitable and growing role, as well as illustrating areas of weakness and limitations, and to provide future perspectives.

1. Introduction

Over the past two decades, percutaneous catheter-based procedures have increased dramatically for a wide spectrum of structural heart diseases. A large number of patients who in the past would have required open heart surgery can now be treated with alternative, non-surgical therapies performed in cardiac catheterization

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laboratories. Today, a new field of cardiology, called interventional cardiology, has been developed.[1]

This rapid expansion in non-coronary cardiac interventions can be attributed to improvements in available devices, techniques, operator skills and, more importantly, innovations concerning imaging techniques, such as echocardiography.

Traditionally, cardiovascular procedures in the catheterization laboratory are guided by fluoroscopy and angiography. Both of these imaging techniques have important limitations, such as radiation exposure, 2D projection of a three-dimensional organ, lack of accurate tissue differentiation and use of radiographic contrast agents. On the other hand, advances in echocardiography can overcome most of the limitations mentioned above and provide successful completion of almost any catheter − based treatment.[1]

Although many contemporary imaging techniques have already been utilized (CT scan, MRI), echocardiography's unique characteristics render it the ideal technique for percutaneous catheter-based procedures. It is portable, offers real-time imaging, provides accurate anatomic and physiologic assessment of the target structure and facilitates appropriate patient selection. The application of 3D echocardiography allows preciseness in procedural guidance. Additionally, it is conducive to early identification of complications and post-procedural close patient follow-up. All of these characteristics of echocardiography increase the likelihood of a successful post-procedural outcome.[2]

Two-dimensional (2D) or three-dimensional (3D) transthoracic echocardiography, 2D or 3D transesophageal echocardiography and intracardiac echocardiography (ICE) are different imaging modalities that are utilized in catheterization laboratories.

Sometimes, the 2D TEE multiple imaging planes may be unfamiliar to interventionalists, leading to misinterpretation. In such cases, 3D images obtained with RT 3D TEE resolve the misunderstanding because they are similar to real anatomy and are better recognized by interventional cardiologists. Moreover, during 3D catheter wires, adjacent structures can be anticipated in a single volumetric data set, avoiding the use of multiple planes.[3]

Currently, percutaneous interventional procedures that are performed under echocardiographic guidance include[2,4,5]:

1. Closure of congenital and acquired septal defects
   a. Atrial septal defect (ASD)
   b. Patent foramen ovale (PFO)
   c. Ventricular septal defect (VSD), especially post infarction VSD
2. Valvular heart disease
   a. Balloon mitral valvuloplasty
   b. Mitral valve repair (edge to edge repair with a mitral clip)
   c. Aortic valve implantation
   d. Prosthetic paravalvular leak closure
   e. Valve in valve implantation for a degenerative bioprosthetic valve
   f. Tricuspid valve repair (functional tricuspid regurgitation with use of the Mitralign System)
3. Left atrial appendage device occlusion
4. Pulmonary vein ablation for atrial fibrillation.
5. Ventricular pseudoaneurysms, post-infarction
6. Pericardiocentesis
7. Myocardial biopsy
8. Alcohol septal ablation
9. Suction of right heart clots
10. Placement of percutaneous left ventricular support devices
11. Laser lead extraction of pacemaker and defibrillator leads
12. A diverse array of other congenital heart diseases that will not be discussed further in this review
    a. Patent ductus arteriosus closure with coil
    b. Stenting of aortic coarctation
    c. Valvulopasty for congenital aortic and pulmonary stenosis
    d. Narrowed baffles opening

The purpose of this review is to demonstrate the use of the most common and up-to-date echocardiographic techniques in non-coronary percutaneous interventional procedures, underscoring its unavoidable and growing role, illustrating areas of weakness and limitations and providing future perspectives.

2. Transseptal puncture

Transseptal puncture of the interatrial septum is the first step for many left-side percutaneous interventions.

Well-educated interventionalists may successfully perform a transseptal puncture guided only by direct fluoroscopy. However, the limited resolution of soft tissue on fluoroscopy makes the procedure extremely difficult, especially in high-risk patients (e.g., those with septal aneurysm, aortic root dilation, thorax deformities, or unsuccessful previous transseptal catheterization). Complementary use of echocardiography, 2D TEE or, more recently, 3D TEE and ICE facilitates the puncture and eliminates complications related to incorrect puncture sites.[6]

TEE offers excellent visualization of the interatrial septum. Understanding the complex septal anatomy is crucial for the procedure. The safest target area to cross the septum is the fossa ovalis.[6]

The recommended TEE views are the mid-esophageal short axis view at the aortic valve level (30−60°) and bicaval view (90−110°).[7,8] Simultaneous visualization of these views is achieved using 3D TEE. When the needle is against the fossal ovaris, a slight tenting is created. Once that tenting is recognized, the needle of the puncture system can be advanced safely. The tenting is usually confirmed from an "en face" view of the right atrial perspective because this view is suitable for the fluoroscopic right anterior oblique projection.[6,7]

3D TEE offers a reliable, anatomic view of the tent−shaped septum. Moreover, with the biplane mode of 3D TEE image acquisition, one can simultaneously observe the 2 recommended plane views (the aortic and bicaval views), allowing quick and easy guidance of the catheter (Figure 1). Despite the unique characteristics of 3D imaging, it is not well-received by operators. Conversely,

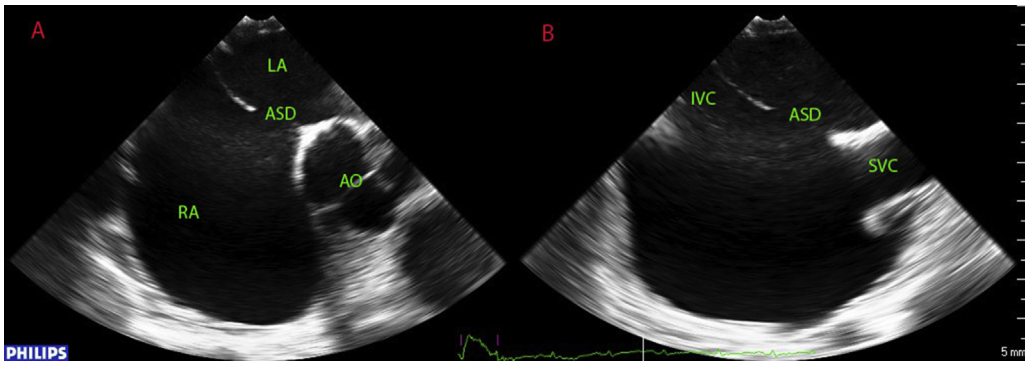

Figure 1 Biplane acquisition with the 3D TEE probe simultaneously showing the atrial septal defect at the aortic (A) and bicaval view (B). ASD = atrial septal defect, LA = left Atrial, LA = left atrial, RA = right atrial, AO = Aorta, SVC = superior vena cava, IVC = inferior vena cava.

operators still prefer to be guided by 2D TEE, and this preference might be ascribed to the fact that recognizing tenting in an "en face" view is not always an easy task in a background with subtle shades of similar colors, dropout artifacts and reverberations. What is traditionally suggested is the use of a narrow pyramidal data set because the frame rate is higher and the instant of puncture is well-visualized.[7,8]

3. Atrial septal defect and patent foramen ovale closure

Transcatheter percutaneous device implantation is the therapy of choice for closing anatomically suitable secundum atrial septal defect (ASD) and patent foramen ovale (PFO) with clinical indications.[9]

Currently, morphological criteria require a secundum atrial septal defect to be closed and include that the stretched diameter of the defect be less than 38 mm with a sufficient rim of 5 mm, except towards the aorta.[9]

Echocardiography has an instrumental role in this procedure and must be used before, during and after device implantation.[1]

First, echocardiography provides a diagnosis of the defect as well as its hemodynamic consequences.

Before device closure, echocardiography (2D or 3D TEE) evaluates the size of the defect, residual septum's morphology, rim size and quality, and presence of additional defects, as well as confirms the normal pulmonary venous connection and estimates the pulmonary artery pressure (PAP) and tricuspid regurgitation (TR). The additional value of 3D techniques is to display the septum "en face" from both the right and left sides and to allow evaluation of the dynamic geometry (systole and diastole) of the defect and its surrounding rims, facilitating selection of the appropriate closure device.[1,10]

During an ASD closure procedure, TEE and ICE are utilized in combination with fluoroscopy. Echocardiography, along with 3D TEE, has the ability to precisely display the long segments of the catheter and wires as well as their relationship to adjacent and surrounding anatomical structures, aiding the manipulation by the interventionalist. Echocardiography enables real time assessment of closure device sizing and deployment and provides imaging of the septum both from the oblique and lateral perspectives. It allows the operator to visualize left and right disk expansion. Furthermore, it gives immediate information regarding the adequacy of closure, such that modifications can be made, if necessary, prior to final implantation.[7,10,11]

After ASD closure, echocardiography is used to assess post-procedural results and presence of any residual shunts, as well as to detect potential complications, such as pericardial effusion, thrombus formation, device erosion, migration, and others. For long term follow-up, TTE is suggested on a regular basis, and evaluation should include assessment of a residual shunt, device stability, RV size and function, TR and PAP.[8]

All echocardiography imaging modalities can be used in ASD closure, but TEE and ICE are the most preferred. Each has its own advantages and disadvantages.

TEE offers a detailed assessment of the inter-atrial septal anatomy. Additionally, the advent of 3D TEE further assists in the definition of the septal anatomy and improves the visualization of catheters, wires, and devices depicted as they are in reality. The drawbacks of TEE are the requirement of general anesthesia with endotracheal intubation due to the risk of aspiration, which increases the cost and procedure time.[10,11]

ICE provides better visualization of the inferior rims and can be performed by the interventionalist without requiring an additional echocardiographer. It does not necessitate general anesthesia and is also an alternative technique when there are contraindications to performing TEE. On the other hand, one of the drawbacks of ICE is that it has a limited far-field view, single-use catheters are expensive, there is no 3D capability, supplementary training is required and handling of the catheters is difficult due to the instability and provocation of atrial arrhythmias or other vascular complications.[10,11]

In conclusion, echocardiography has an essential role in ASD-PFO percutaneous closure and numerous factors should be taken into account when choosing the proper echo-imaging modality.

4. Percutaneous mitral valve repair

Several percutaneous techniques have been developed to treat mitral regurgitation in patients who are at high

surgical risk. These techniques can be classified into four general categories, and most of them are under development and/or in early stages of clinical trials[4]:

(i) Indirect annuloplasty-coronary sinus techniques
(ii) Direct annuloplasty
(iii) Leaflet repair
(iv) Ventricular remodeling

To date, the most commonly used technique is leaflet repair based on mitral clipping. The Percutaneous Mitral Clip system is currently the only mitral valve procedure approved by the FDA, and it mimics the Alfieri surgical technique, creating edge to edge repair. It delivers a two-armed, V-shaped clip that grasps the tips of the middle portions of the anterior and posterior mitral leaflets, creates a double orifice mitral valve and restores coaptation to reduce the degree of MR.[4]

Everest I and II trials and a continued access Realism registry have published the clinical results of this procedure.[12–14]

Echocardiography is the key imaging modality to first select patients who are amenable for this treatment, then guide the procedure and finally evaluate post procedural mitral regurgitation.

a. Pre-procedural Transcatheter edge to edge repair (TEtoE) imaging

A basic factor for a successful outcome is appropriate case selection, which heavily relies on echocardiography as the MV leaflets are not visible by fluoroscopy. The echo study has to determine the mitral regurgitation mechanism, severity, and suitability for clipping.

This method is applicable in two categories of patients[4,12–15]:

1. Those with degenerative MR (prolapse or flail of the A2 and/or P2 scallops) Carpentier type II. The flail gap must be <10 mm and flail width <15 mm, and there must be no calcification of the grasping area.
2. Those with functional MR, either due to dilated cardiomyopathy or to ischemic LV remodeling, provided that the regurgitant jet arises from the A2-P2 portion. The coaptation length must be at least 2 mm and coaptation depth <11 mm.

Another essential role of pre-procedural echo imaging is to quantitate the severity of mitral regurgitation using parameters based on current guidelines.

Carpentier Classification is used to assess the mitral valve anatomy to optimize communication regarding the MV morphology among echocardiologists and interventional cardiologists.

Some worthwhile views that may help identify which leaflet is moving abnormally include the Zero-degree views in which the A1 and P1 segments can be seen in the superior position, A2 and P2 segments in a more central position, and A3 and P3 segments in an inferior position of the probe. The Inter commissural (60–70) views make the P1, A2, and P3 scallops visible, whereas an anterior (clockwise) rotation of the probe exposes the A1, A2, and A3 segments of the anterior leaflet and a posterior (counter clockwise) rotation presents the P1, P2, and P3 segments of the posterior leaflet. A long-axis or LVOT view (90) shows the A2 and P2 segment. In the transgastric short-axis views, all segments of the anterior and posterior leaflets can be identified.[8,15]

Moreover, with 3D TEE, putting the aortic valve at 12 o'clock, the left atrial appendage can be seen at 9 o'clock, anterior commissure can be seen at 9 o'clock with the adjacent A1 & P1 mitral segments and posterior commissure can be seen at 3 o'clock (A3 & P3 segments). With 3D imaging, all mitral segments can be illustrated more precisely and accurately than 2D TEE, and 3D TEE has the unique advantage of identifying prolapse of the mitral commissure, which is a rare occurrence (Figure 2).[10,11]

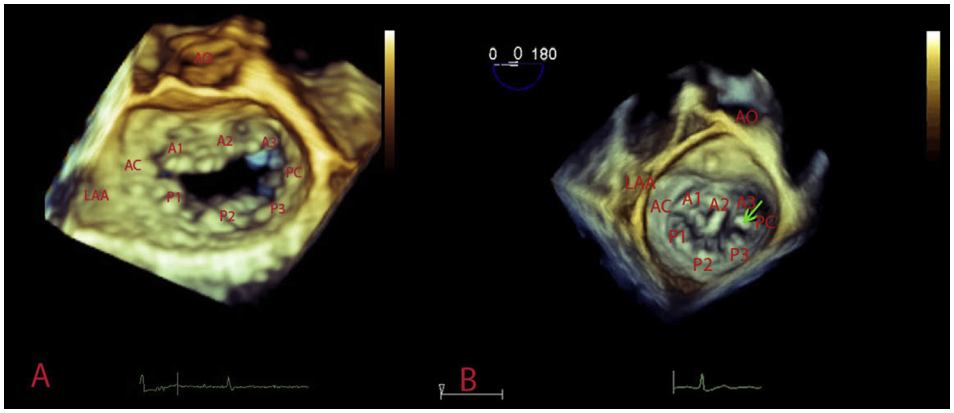

Figure 2 A. 3D echo imaging of the mitral valve. With the position of the aortic valve at 12 o'clock, the left atrial appendage can been seen at 9 o'clock, anterior commissure can be seen at 9 o'clock (and the adjacent A1 &P1 mitral segments) and posterior commissure can be seen at 3 o'clock (A3&P3 segments). B. Green arrow indicates prolapse of the posterior commissure. LAA = Left atrial appendage, AO = aorta, AC = Anterior commissure, PC = posterior commissure, A1-2-3 = segments of the anterior mitral leaflet, P1-2-3 = segments of the posterior mitral leaflet

5. Procedural monitoring

The procedure is complex and has 5 steps that require real-time echocardiographic guidance complemented with fluoroscopy.

Standardized 2D planes can be used as the primary imaging method for guidance during the Mitral Clip procedure.

5.1. Step 1: Transseptal puncture

As mentioned above, the target area for crossing is the fossa ovalis with a posterior mid-approach and in a posterior and superior direction, facilitating the clip delivery system to reach the middle of the mitral orifice parallel to the antegrade mitral flow. The site of optimal puncture varies among degenerative and functional regurgitation and can be assessed with the 4 Ch (0) imaging plane. In degenerative MR, the puncture site must be 4—5 cm above the mitral annulus, whereas functional MR requires a puncture site 3.5 cm above the annular plane due to extensive tethering.[15]

5.2. Step 2: Advancement of the Clip Delivery System (CDS) towards the mitral valve

Once the correct transseptal crossing has been achieved, the delivery catheter is turned down and monitoring with TEE begins towards the mid portion of the mitral leaflets (A2-P2), avoiding contact with the left atrial appendage and left atrial wall.

The inter-commissural (55—75°) view and LV outflow (100—160°) view are particularly helpful at this step by showing the medial—lateral alignment and posterior—anterior alignment, respectively. A single 3D en face view (3D zoom) shows whether the approaching clip is directed optimally.[15]

5.3. Step 3: Positioning the mitral clip above the mitral leaflets

The clips' arms need to be placed perpendicular to the commissure line, above the largest regurgitant jet, as indicated by the PISA effect. Using the RT3D surgeon's view is valuable in this step, and where 3D is not available, the transgastric 2D short axis view is recommended as an alternative.[4,15]

5.4. Step 4: Advancement of the Clip Delivery System (CDS) into the left ventricle

The CDS system crosses the mitral leaflets, passes into the left ventricle under fluoroscopy and TEE guidance, and can be viewed from the LVOT position (100—160). Advancement of the CDS can be monitored best in X—plane imaging based simultaneously on LVOT using an inter-commissural view. A rapid reassessment of the perpendicular clip orientation and position using the transgastric 2D short axis or 3D en face views is mandatory to be sure that the CDS system has not rotated as it is advanced in the LV.[4,15]

5.5. Step 5: Grasping of the leaflets and evaluating adequate leaflet insertion

Once the mitral clip is at an optimal position, the open device is pulled up to grasp the leaflets. Assessment of proper leaflet insertion into the clip is usually performed using 2D LVOT and inter-commissural views. 3D imaging has limited value at this step of the procedure. If either leaflet has not been adequately grasped, a replacement is necessary.[4,15]

5.6. Step 6: Clip release and assessment of the result

Once both leaflets are successfully clipped, the MitraClip can be closed and an evaluation is made of the residual MR. If the result is not sufficient, the clip is brought back into the LA and the process is repeated. Sometimes, a second Clip should be placed.

After implantation of the clip, it is essential to evaluate the grade of mitral regurgitation and mitral stenosis.

Due to the newly created double mitral orifice, the estimation of residual regurgitation is not easy because there are many limitations to conventional parameters. Currently, there are no recommendations for the best way to evaluate the MR in the presence of a double orifice. Generally, utilization of multiple parameters is valuable in assessing the MR after mitral clip implantation.

It is well-known that this procedure is very demanding on both the echocardiographer and interventionalist. Although 2D TEE is used primarily to guide the mitral clip procedure, 3D TEE can supplement 2D TEE and provide unique, additional, anatomic information. It is recommended for guidance of interventional mitral valve procedures.[10,11] With real-time 3D TEE, full volume data sets can be acquired, which allow en-face views of the MV, either from the atrial or left ventricle perspectives. These unique 3D views facilitate the precise assessment of the MV structure and pathology, which is crucial for the selection of patients. During the procedure, 3D TEE enables visualization of the mitral valve, left atrium, interatrial septum, delivery catheters, wires, and devices in a single view that is easily understandable in 3D space.[4,15]

Notably, 2D TEE plays an essential role in transseptal puncture, optimal clip alignment and evaluation of mitral regurgitation pre- and post-clip implantation. Unfortunately, the lack of real-time 3D color and low frame rate limit the use of 3D TEE in the main procedural steps, such as the positioning of the delivery system to the origin of the regurgitant jet and grasping the leaflet.[4,15,16]

As all imaging modalities have their own limitations, it has been demonstrated that the combined use of 2D TEE, 3D TEE and fluoroscopy facilitates the procedure and increases the likelihood of a successful result.

6. Transcatheter closure of periprosthetic regurgitation (TCPPR)

Paravalvular regurgitation is a recognized complication that affects from 5% to 17% of all surgically implanted prosthetic

heart valves. Most patients are asymptomatic, but sometimes they present with heart failure, hemolytic anemia or both. In those patients who have a significant re-operative risk, percutaneous techniques may allow successful treatment of paravalvular regurgitation.[4,10,17–23]

The role of echocardiography (Figure 3) is essential in this procedure and can be summarized as below:

1. Making a diagnosis of the periprosthetic defect and assessing the severity of paravalvular regurgitation. Evaluation of prosthetic valve regurgitation is technically more demanding than that of native valves, especially for aortic prosthetic PVR.
2. Localization of defects, describing the whole number and shape as well as providing accurate sizing of the hole. Real–time 3D TEE using 3D color Doppler is the preferred imaging modality for MV leaks, but it is not very helpful in aortic leaks.
3. Assessment of other structures (chambers, valves and pericardial space) and an analyses of the relationships between the defects, aortic valve, left atrial appendage and interatrial septum.
4. Ruling out the presence of thrombus, vegetation and significant dehiscence involving more than one-fourth of the valve ring because these are considered to be contraindications for percutaneous repair.
5. Guiding access either antegrade, venous transseptal, or retrograde approach via aortic valve or transapical valve.
6. Guiding the wire across the defect and catheter placement.
7. Assessing the decrease in paravalvular regurgitation during balloon inflation.
8. Evaluating proper positioning and stability of the closure device.
9. Assessing possible complications (pericardial effusion, prosthetic leaflet entrapment).
10. Re-evaluating of the severity of residual paravalvular regurgitation and estimating whether a second occlusion device is needed (Figure 4).

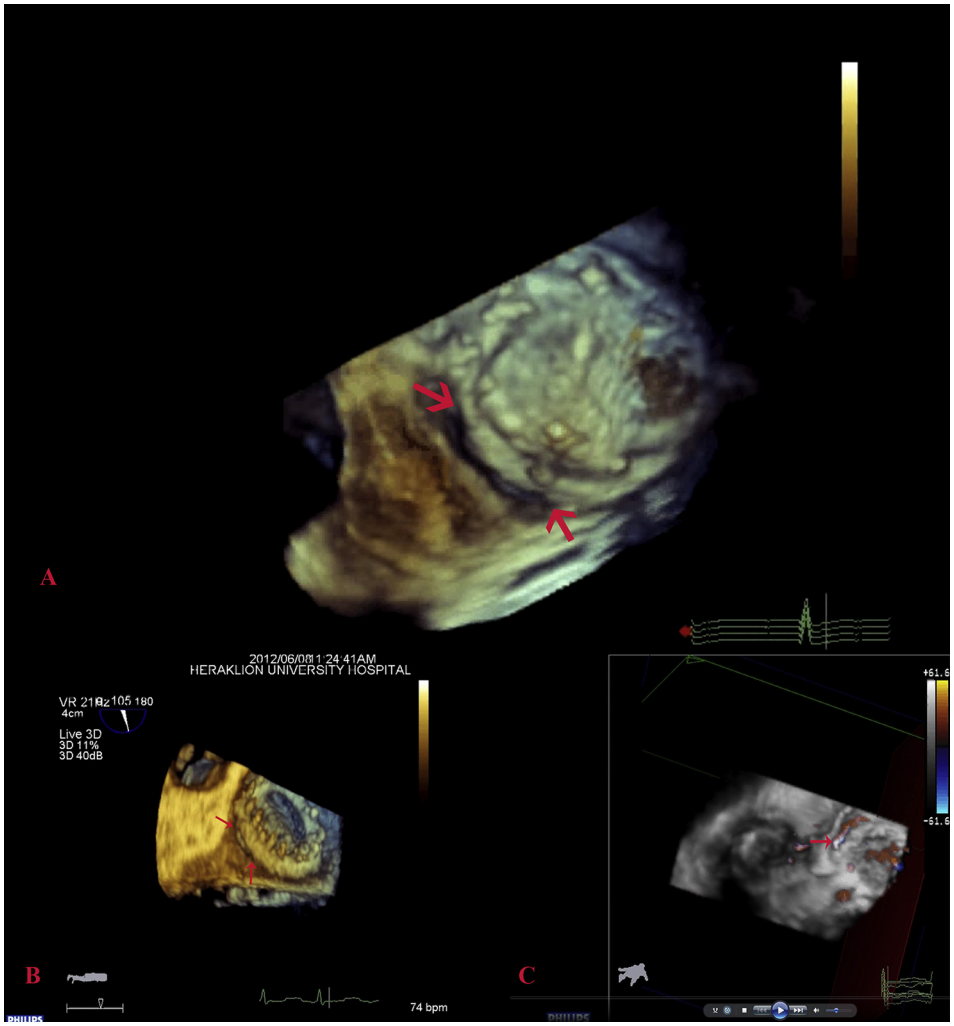

Figure 3 A&B. Prosthetic mitral valve in 2 different patients with a large dehiscence of the valve from the mitral annulus. The two edges of the defect are illustrated with red arrows. In figure C, the red arrow shows the mitral paravalvular regurgitation via 3D color Doppler.

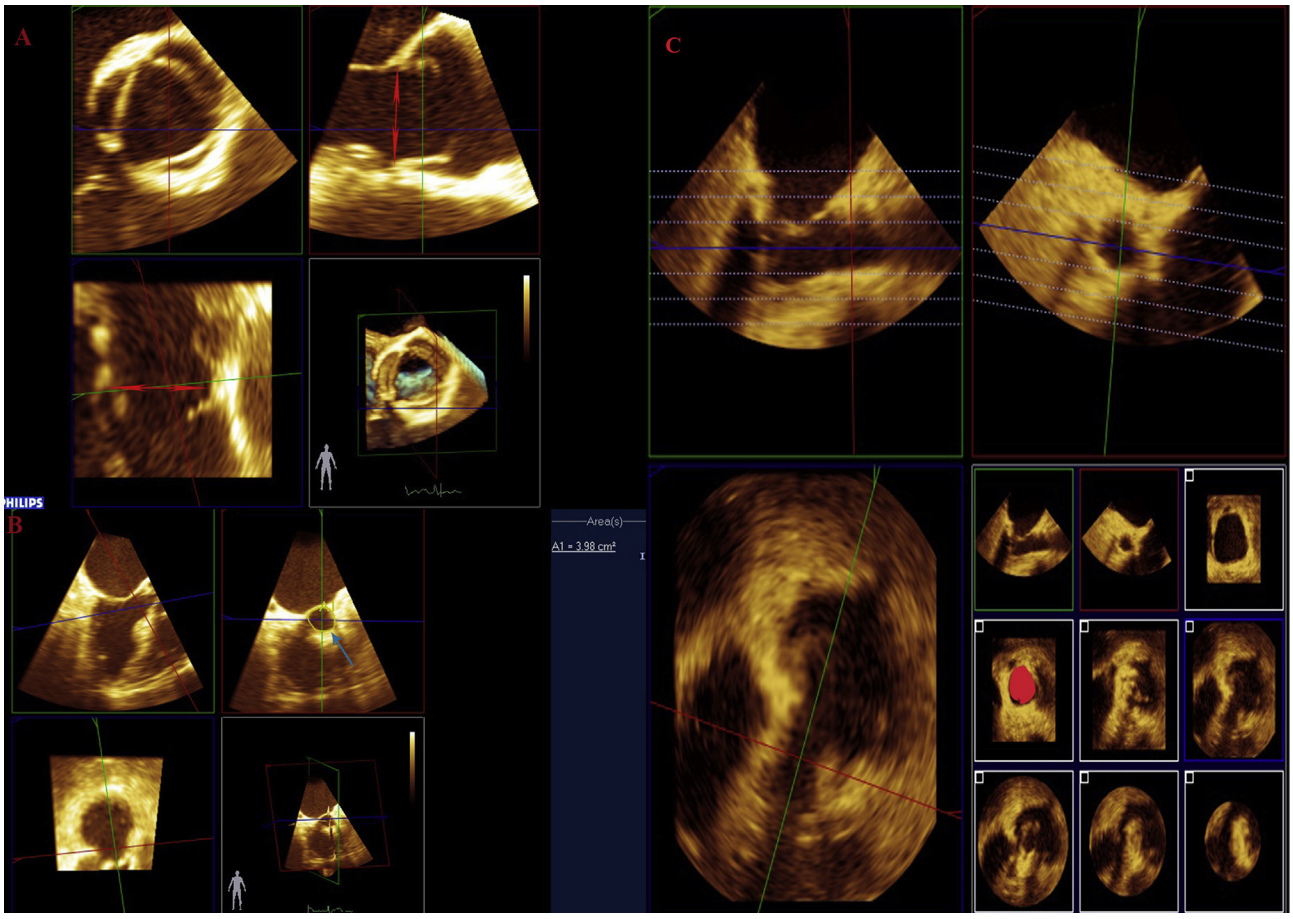

Figure 4 In a patient with bileaflet mitral prosthesis, severe paravalvular regurgitation has been observed and a closure device has been inserted. The red arrows in figures A and B show the edge of the ovale closure device. In figure C, triplane mode arrows show the device at the red and blue levels, and in figure D, a residual mild to moderate periprosthetic regurgitation through the closure device was recorded.

7. Transcatheter aortic valve implantation (TAVI)

Currently, transcatheter aortic valve implantation is considered to be an alternative therapy to conventional surgery for severe, symptomatic aortic valve stenosis (AS) in patients who are inoperable or at high surgical risk.

At the moment, two devices with different characteristics, the Edwards SAPIEN and CoreValve, are approved prostheses for TAVI.[24]

A multidisciplinary approach including interventional cardiology, cardiac surgery, vascular surgery, cardiac anesthesia and obviously cardiac imaging is needed for a successful outcome. Echocardiography, angiography, fluoroscopy, multislice computed tomography (CT) and, rarely, CMR are the imaging modalities for TAVI procedures.[25,26]

Many studies, new guidelines for 3D echocardiography and TEE, and recent recommendations for interventional echocardiography have been published supporting the critical and expanding role of echocardiography either pre-implantation, intra-procedural or post-TAVI implantation assessment.[4,8,11]

A. A comprehensive echo study prior to a TAVI procedure is important for patient selection and should include assessment of[4]:
   1. The severity of aortic stenosis:
      Transthoracic echocardiography (TTE) is the primary imaging modality to estimate the severity of AS and provide a differential diagnosis between true severe AS and pseudo-severe AS.
   2. The aortic annulus size:
      The decision of the aortic prosthetic size is crucial, and it is related to the aortic valve annulus dimensions. Due to the elliptical shape of the annulus, accurate sizing is not always easy. It is well-known that both TTE and TEE undersize the annulus diameter, assuming annular circularity. The 3D echo overcomes the limitations of the annulus shape and provides a more accurate assessment of the LV outflow tract and annular diameter (Figure 5). Currently, CT has been recommended as the gold standard for aortic annulus evaluation.[4,11]
   3. The aortic valve and root morphology:

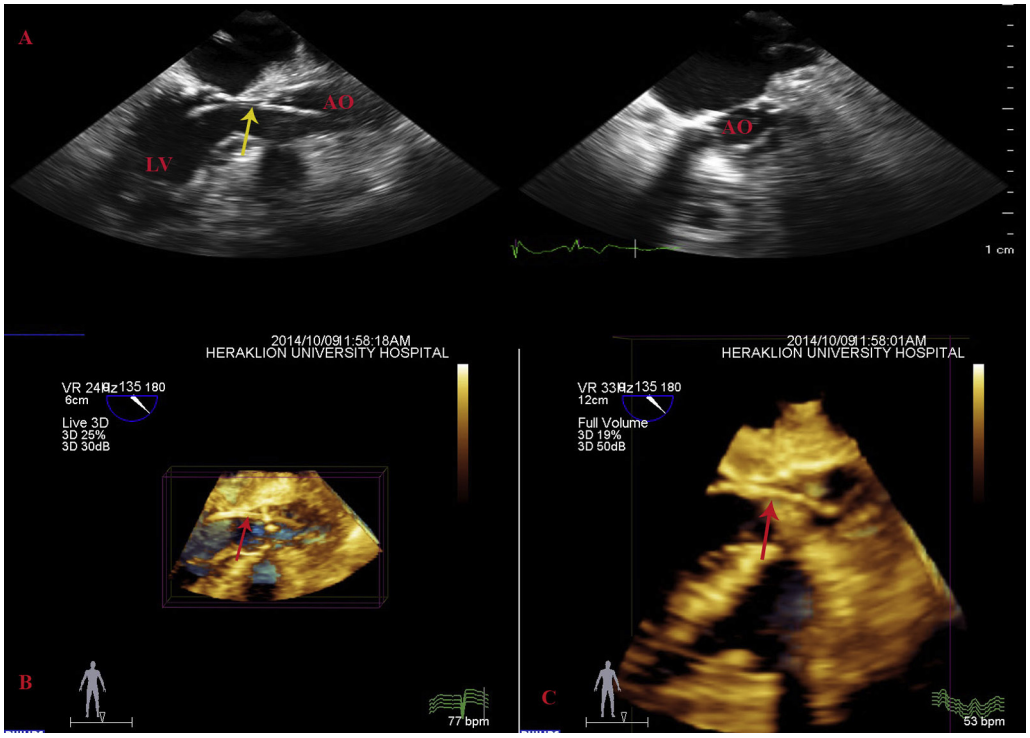

Figure 5 Triplane mode shows the aorta and aortic annulus in 3 different saggital planes. The red, green and blue lines show the orientation and angle of the interception of the planes. The red arrows in figure A show the measurement of the aortic annulus. Figure B shows the planimetry of the aortic annulus. Figure C illustrates the aortic valve and aortic root in triplane mode and after cutting them into multiple slices (Multislice mode), thus making the planimetry of the annulus more precise. (Red area)

Echocardiography has to describe the number of cusps, leaflet thickening and fusions, mobility and calcification, and geometry and symmetry of the aortic valve opening, sinus of Valsalva and sinotubular junction. A bicuspid aortic valve is a relative contraindication for TAVI due to the risk of severe paravalvular regurgitation, aortic dissection and embolization. Severe calcification is related to post-TAVI paravalvular regurgitation, coronary artery ostium compression and occlusion.[24]

4. The coronary ostium height:
   Measuring the distance between the annular plane and coronary ostia is of paramount importance, and a minimum distance of 10—11 cm is required to minimize the risk of coronary occlusion. Usually, this measurement is performed by CT, but 3D echocardiography can also provide accurate sizing.[26]
5. The thoracic aorta:
   A significant aneurismal dilatation is a contraindication for CoreValve, and severe aortic arch calcification leads to a transapical approach.
6. The additional structures:
   Mitral regurgitation is a common finding in patients with AS, and the degree of MR usually decreases after the TAVI procedure. Aorto-mitral continuity was recently described with 3D TEE, and the anatomy and function of the mitral valve should be evaluated either pre- or post-TAVI because both valves are interdependent. Additionally, the presence of the LV thrombus and significant LVOT obstruction due to basal septal hypertrophy should be excluded as they are contraindications prior to TAVI. The existence of a patch in the LV and the presence of severe pericardial calcification discourage a transapical approach.[11,26]

A. Echocardiography during the TAVI procedure.

It is a well-established fact that fluoroscopy is the gold standard for procedure guidance, and the role of echocardiography is limited compared with its major role in the selection of patients for TAVI. The disadvantages of using peri-procedural TEE include the requirement of general anesthesia as well as the partially concealed and shackled fluoroscopic view caused by the TEE probe. Sometimes, to have a clearer view, the probe must be removed during prosthesis implantation and positioned post-deployment. Occasionally, some interventionalists prefer purely fluoroscopic guidance during TAVI.[11,25,27]

However, echocardiography is the primary imaging modality for a wire's guidance and the assessment of complications. In addition, TEE may be helpful in cases in which the stenotic valve does not have much calcification and the fluoroscopic view alone is limited.

The most important procedural steps are:

1. Crossing the aortic valve.
   Traditionally, passing a guidewire through the aortic valve is manipulated by fluoroscopy. Nevertheless, this step may be difficult in patients with aortic root distortion and dilatation. In such cases, the use of real-time 3D TEE can safely guide the wires through the aortic valve orifice (Figure 6). Additionally, 3D TEE, due to its better spatial resolution, provides sufficient imaging of the pacing wire and left ventricular stiff wire.[4,25–27]
2. Balloon dilatation and positioning
   TEE, as a supplemental imaging method to fluoroscopy, confirms the optimal site for balloon inflation and provides information about the efficacy of inflation in aortic cusps as they are moved back toward the coronary ostia. Accidentally, the balloon may not remain stable during inflation and may migrate, especially in cases with severe subaortic septal hypertrophy and a narrow sinotubular junction.[4,25–27]
3. During deployment of the prosthesis
   Therefore, TEE in combination with fluoroscopy secures the ideal position of the valve. The appropriate localization for the Edwards SAPIEN valve is 2–4 mm below the aortic annulus, and the appropriate location for the CoreValve is 5–10 mm below the plane of the annulus.

Immediately after deployment, it is important to ensure via TEE that the aortic cusps of new prosthesis function well, the valve stent has a circular configuration (3D TEE), there is no contact with adjacent structures (such as the anterior mitral leaflet) and severe paravalvular regurgitation is absent. Severe paravalvular regurgitation is related to an inappropriate position or undersized prosthesis and inadequate balloon inflation. In this case, the balloon may be re-inflated or a second prosthesis may be needed. It is well-known that a small degree of valvular regurgitation due to guidewires and mild paravalvular regurgitation is a common finding.[4,25–27]

The criteria for a successful implantation are assumed to be an optimal anatomical position of the prosthesis, aortic valve area >1.2 cm^2, mean gradient <20 mmHg, Vmax <3 m/sec and absence of moderate or severe regurgitation.[26]

A. Echocardiography after the TAVI procedure.

Following the TAVI procedure, repeated echocardiograms must be performed. After the first 24 h, an echo study is recommended at 1, 6, and 12 months and then on an annual basis. Assessment of aortic prosthesis function, left ventricular function and evaluation of aortic regurgitation is of paramount importance. Moreover, complications related to the TAVI procedure include migration or misplacement of the prosthesis, mitral valve damage, coronary ostium occlusion, cardiac tamponade secondary to left and/or right ventricular rupture, and dissection or tear of the aortic root.[28]

8. Percutaneous left atrial appendage (LAA) closure

The percutaneous LAA closure is an alternative treatment option for the prevention of stroke in a selected group of

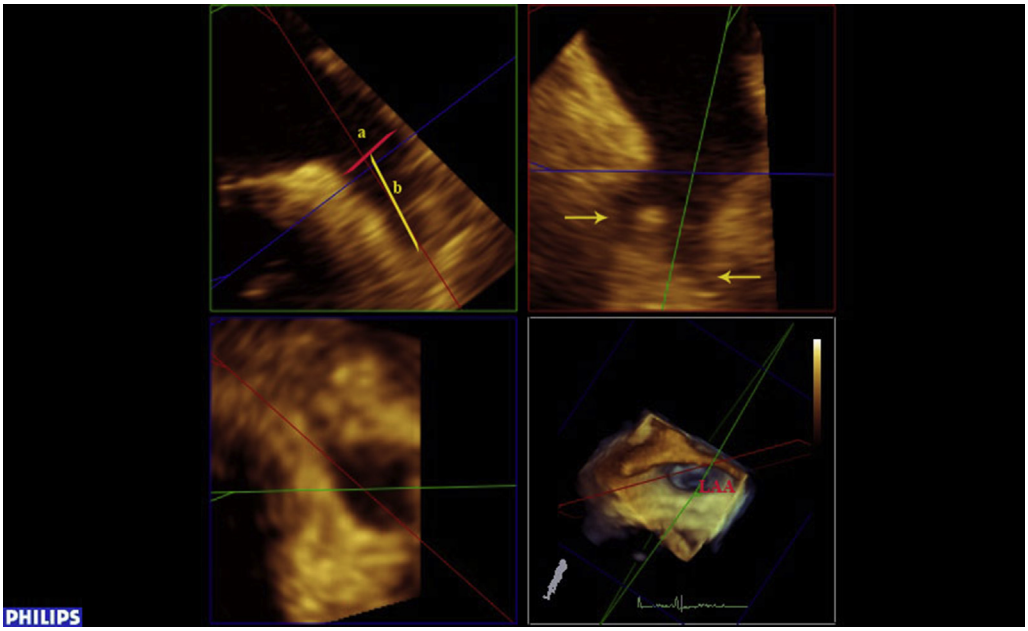

Figure 6 (A) Biplane mode shows the wire of the prosthetic aortic valve (yellow arrow) passing throughout the aortic valve (AO) into the Left Ventricle (LV) after deflating the valve. B&C. Live 3D (B) and full volume (C) reveal the wire of the prosthetic aortic valve (red arrow) passing through the calcified aortic valve (AO) into the left Ventricle (LV).

patients with atrial fibrillation who cannot receive an anticoagulation regimen.[29,30]

Currently, two different devices are available in clinical practice: the WATCHMAN device (Atritech, Plymouth, MN) and Amplatzer Cardiac Plug (ACP; AGA, St Jude Medical, Minneapolis, MN).[31]

TEE assessment is the best cardiac imaging for the selection of patients who are suitable candidates for device closure of the LAA. LAA is a complex anatomic structure that commonly has 2 lobes, but might be up to 4 lobes, and 4 morphologic variants have been described. 3D TEE provides additive information in cases of complex morphology. Multiple views from 2D and 3D TEE are required to reveal the full extent of the LAA (Figure 7). ICE is an acceptable alternative to TEE during implantation of the device occluder with similar results to those reported for TEE-guided implantation.[32]

The role of echocardiography in the LAA occlusion procedure is essential throughout all phases of the procedure, and it is used in the following ways[33–35]:

1) To exclude the presence of LAA thrombus. Spontaneous echo contrast and significant valve disease that could interfere with the procedure should be taken into account.
2) To identify the ostial width and length dimensions of the dominant LAA lobe. The diameter of the LAA, by measuring the transverse diameter 10 mm below the ostium, is called the landing zone. Occluder device sizing is crucial, and selecting a device with a diameter larger than the LAA ostium is preferred to achieve optimal sealing and to minimize the risk of leakage, which could provide a new source of thrombus.
3) To guide the transseptal puncture.
4) To confirm the delivery sheath position.
5) To ensure the position and stability of the device before and after deployment. Optimal localization is considered when the axis of the device is in alignment with the major axis of the LAA. A color-flow Doppler must be used to detect any peri-device flow into the LA. Angiographic grading, as well as an echocardiography color Doppler

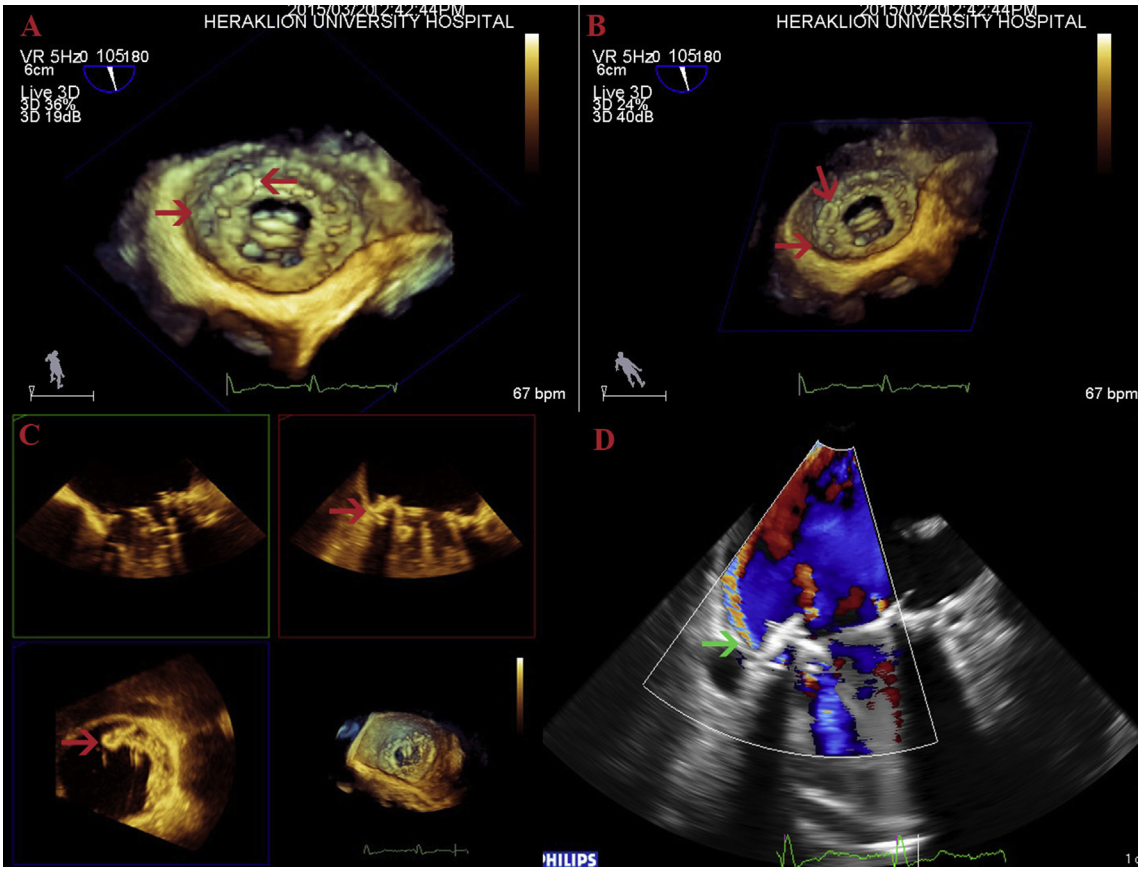

Figure 7 Triplane mode displays the left atrial appendage (LAA) in 3 different sagittal planes. Measurements of the LAA (crucial for the size of the implantation device) are made at 0°, 45°, 90°, and 135° and include the maximal LAA ostium diameter (a), width (b), and length of the LAA primary lobe. At 0°, the LAA ostium measurement is taken at a point approximately 1–2 cm from the tip of the left upper pulmonary vein (LUPV) limbus. At other angles, the LAA ostium measurement is confirmed to the plane from the top of the MV annulus to a point approximately 1–2 cm from the tip of the LUPV limbus. The yellow arrow in the red plane shows the 2 lobes of the LAA.

flow grading, have been suggested to assess LAA device sealing as follows: Successful LAA occlusion is defined as Grade 3 or higher.

Grade 1: Severe leak with multiple jets of free flow.
Grade 2: Moderate leak, >3 mm diameter jet is noted.
Grade 3: Mild leak, with a 1−3 mm diameter jet.
Grade 4: Trace leak, with <1 mm diameter jet.
Grade 5: No leak is present.

6) To check for disruptions of transmitral and pulmonary vein flow.
7) In the end, echocardiography assesses procedural complications, such as tamponade, thrombus associated with implantation and device migration or embolization.

9. Electrophysiology-pulmonary vein ablation

Pulmonary vein ablation is an established, new treatment for symptomatic drug refractory paroxysmal atrial fibrillation (AF) that has emerged over recent years. Current guidelines underscore the importance of noninvasive, multimodality imaging through this procedure. Echocardiography is instrumental in every stage of the ablation work-up.[34]

Pre-procedural TEE can exclude the presence of left atrial or LAA thrombus, which is a contraindication for the procedure. Additionally, TEE provides valuable information on any underlying cardiac or valvular disorder that may be related to the success of the intervention, such as mitral stenosis.[35]

During the procedure, TEE and/or ICE facilitates transseptal puncture, determines pulmonary vein (PV) anatomy, confirms proper catheter location and tip-tissue contact and monitors complications, such as development of pericardial effusion, clot formation and microbubble formation related to tissue over-heating.[35,36]

Post procedure, TEE and/or ICE is essential in the detection and management of complications, including esophageal injury, PV stenosis, LA hematoma, pseudoaneurysm, or AV fistula.[36]

10. Tricuspid valve repair (Mitralign system)

It is well known that uncorrected severe functional tricuspid regurgitation has serious long-term morbidity and mortality and is highly related to poor prognosis.

Transcatheter tricuspid valve repair could become an attractive alternative treatment for high-surgical risk patients who do not respond to optimal medical therapy.

Recently, the first-in-human transcatheter repair for functional tricuspid regurgitation was reported with the use of Mitralign's Percutaneous Tricuspid Valve Annuloplasty System (PTVAS).[37]

This percutaneous tricuspid valve repair mimics a surgical repair procedure (Kay bicuspidization) based on tricuspid bicuspidization by plicating the annulus along the posterior leaflet using sutures.

The Mitralign system (Mitralign, Inc., Tewksbury, Massachusetts) plicates the tricuspid annulus by placing pledget sutures, effectively converting the insufficient trileaflet valve into a functioning bi-leaflet one.

Echocardiography is the key imaging modality to first select patients who are candidates for this treatment, to then guide the procedure and to finally evaluate the post procedural tricuspid regurgitation and related complications.

TEE (2D and 3D) was performed at baseline and during and after the procedure. Operators advanced a delivery catheter through a trans-jugular vein across the tricuspid valve and into the right ventricle under echocardiographic guidance. Using the Mitralign system, they positioned 2 sutured pledgets, or anchoring pads, in the annulus around the posterior leaflet (either postero-anterior commisure or septo-posterior commisure). After that, a lock device was used to bring the pledgets together, thereby tightening the annulus. The result was successful "bicuspidization" of the tricuspid valve in a similar way achieved by a surgical technique.[37]

Accurate assessment of the guide catheter is of paramount importance for safe placement of the sutured pledgets. Both 2D and 3D TEE combined with fluroscopy contribute to a successful outcome without complications, such as coronary or chamber perforation.

Currently, the Mitralign System is being investigated and is not available for sale or distribution.

11. Future directions

We are well-aware that despite the great evolution of echocardiography in recent years, especially with the introduction of a 3D echo in catheter laboratories, an ideal echocardiographic modality has not been established.

3D echo is not widely accepted among most echocardiographers and interventionalists due to existing technique-related limitations, such as a low frame rate, dropout artifacts, reverberations and shadowing caused from catheters and a lack of standardized protocols suggesting ways to acquire useful perspectives easily and quickly during the procedure.

Furthermore, some interventionalists seem to be reluctant to introduce not only 3D TEE but even 2D TEE in the laboratory. They feel unfamiliar with the new imaging modalities because they received different training, rendering spatial orientation difficult. X-ray image and Echo image orientation are completely uncorrelated. What is perceived as right on the fluoroscopic view might be left on the Echo image, whereas what is perceived as down on the Echo image might be up on the fluoroscopy view. Each time the interventional cardiologist switches his view from fluoroscopy to echocardiography, he needs to mentally reorient himself.

The solution may be available by the recently introduced integrated 3D Echo-X-Ray navigation system (EchoNavigator, Philips Healthcare, Eindhoven, the Netherlands) whereby 3D TEE imaging is registered automatically in real-

time with live 2-dimensional fluoroscopy images acquired from an X-ray imaging system.[27]

The EchoNavigator live image guidance tool (EchoNavigator), which received 510(k) clearance from the US Food and Drug Administration (FDA)at 3/13, provides an intelligently integrated view of live X-ray and 3D ultrasound images. It automatically registers and aligns X-rays with echo results and enables echocardiographers to identify anatomical targets and mark them as they appear on the X-ray image.

The EchoNavigator system currently has smart technology that automatically localizes and tracks the position of the TEE probe. Every time the interventionalist steps on the fluoro pedal, EchoNavigator will instantly and continuously detect the TEE probe in the image.

The interventional cardiologist can view the 3D echo from any angle, without disturbing what is being seen by the operator of the Philips echo system.

This process essentially means that with the EchoNavigator markers, the interventionist is aware at all times of the relation between the cardiac structures and catheter implants and thus can improve the control, appreciation and communication between invasive and non-invasive cardiologists, ultimately in an attempt to save valuable time and to enhance patient care.

Examples of the echo navigation system in the guidance of atrial puncture (Figure 8), atrial septal defect closure (Figure 9) and mitral clip insertion (Figure 10) are illustrated.

It is likely that echo-navigation will be the standard method in the foreseeable future for the echo-guidance of interventions in the cath lab, although more experience to demonstrate its accuracy is required.

Other future developments that will further extend the role of ICE in the cardiac laboratory may include a reduction in catheter size, improved catheter stability and handling, as well as enhanced image quality and development of real time 3D imaging.

Other potential advances include the integration of ICE into current electro-anatomical mapping systems and also coupling of ICE and ablative therapy into a single catheter.

The recent development of a neonatal TEE probe that is small and flexible enough to allow transnasal insertion in adults may have a potential application in interventional cardiology. The transnasal approach, typically better tolerated by patients, may offer the distinct advantage of enabling some interventional procedures requiring TEE guidance to be performed without general anesthesia. However, acceptable image quality and good patient

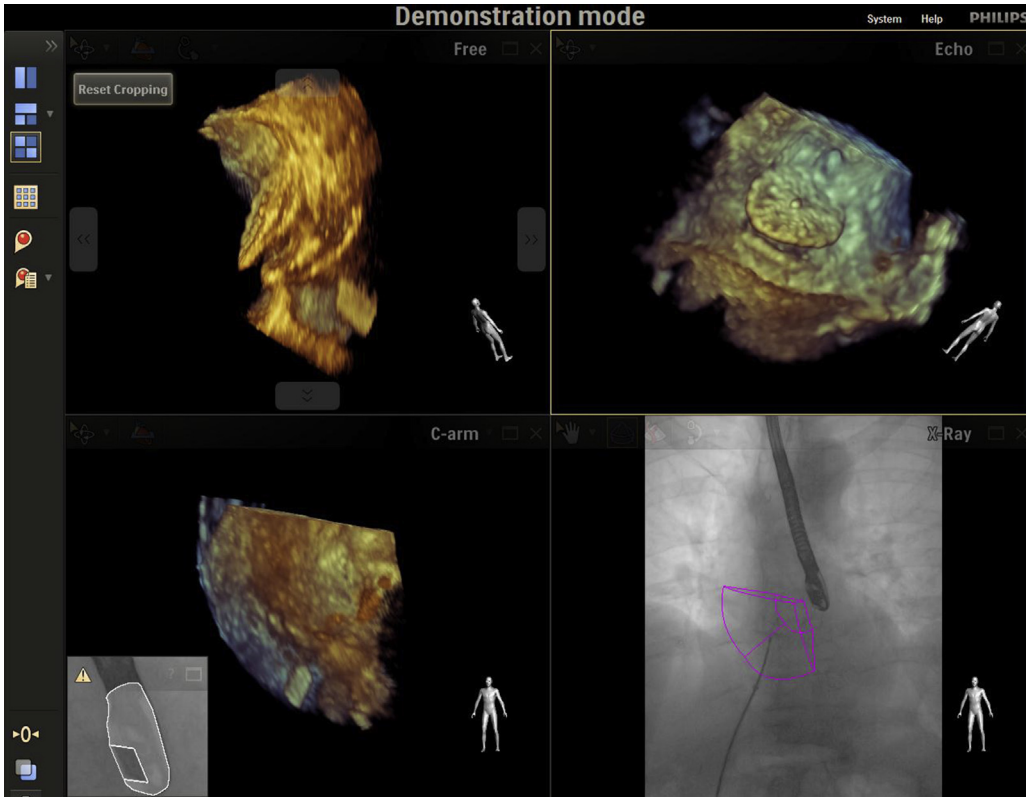

Figure 8 With the Echonavigator, we succeeded in aligning two different imaging modalities, putting the X-ray and echo onto the same coordinate system. With this system, the position of the TEE probe is registered to the X-ray c-arm and 2D/Xplane/3D TEE images are linked and updated with fluoroscopic views. In the present example of atrial puncture, a marker (red plot) is placed at the puncture site. Markings on soft tissue anatomical structures in Echo appear in the X-ray for context and guidance. Echo and fluoroscopic images confirm the marker position. The wire (red arrows) is pulled down to the interatrial septum. X-plane 2D images help identify "tenting of the septum" (thin red arrow).
(Images are courtesy of Philips Healthcare).

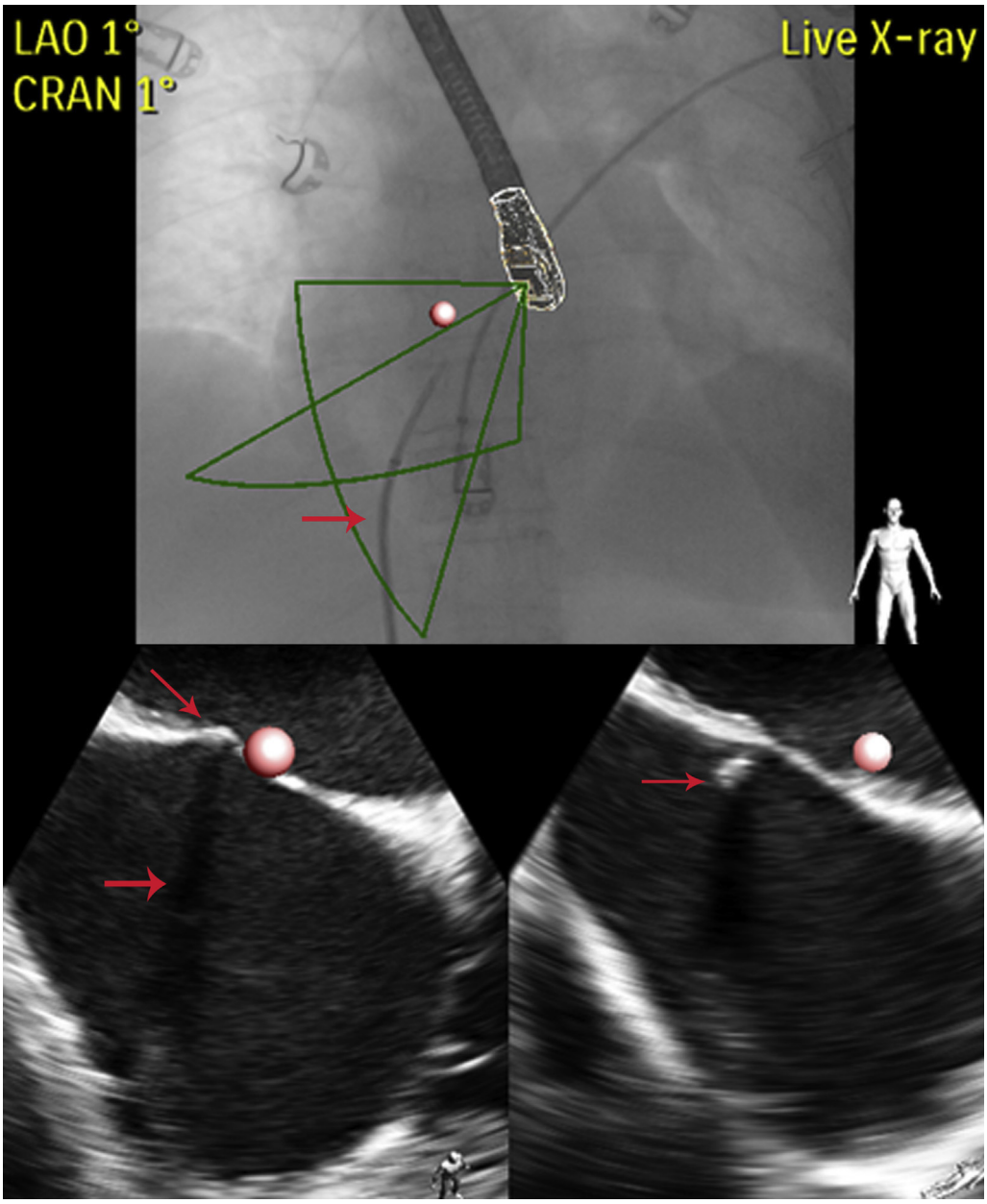

Figure 9 The figure illustrates a typical screenshot of the EchoNavigator live image-guidance tool during a septal defect closure. The technology allows integration and alignment of the X-ray image (lower panel right) with the 3D ultrasound (lower panel left) allowing an easier orientation as well as additional real-time views: the ultrasound view as reconstructed by the echocardiographer (upper panel right) and a free 3D image that can be manipulated by the interventionalist from the table site (upper panel left). (Images are courtesy of Philips Healthcare).

tolerance with this application are yet to be demonstrated in scientific evaluations.

12. Conclusion

Rapid evolution in interventional cardiology demands detailed and accurate imaging of cardiac structures and the guidance of wires. The entrance of echocardiography in almost every stage of all procedures in catheterization laboratories is inevitable, suggesting an important step for echocardiographers.

Despite recent progression in echocardiography, problems still arise, especially concerning the communication between the echocardiographer and interventional cardiologist. Moreover, the clear advantage of the X-ray demonstrating the catheters and implant devices must be merged with the clear advantage of echocardiography demonstrating the soft tissues.

Finally, as technology progresses, it seems that the Echonavigator system and real-time fusion of live X-ray and live echo images will provide intuitive and successful guidance during structural heart disease interventions.

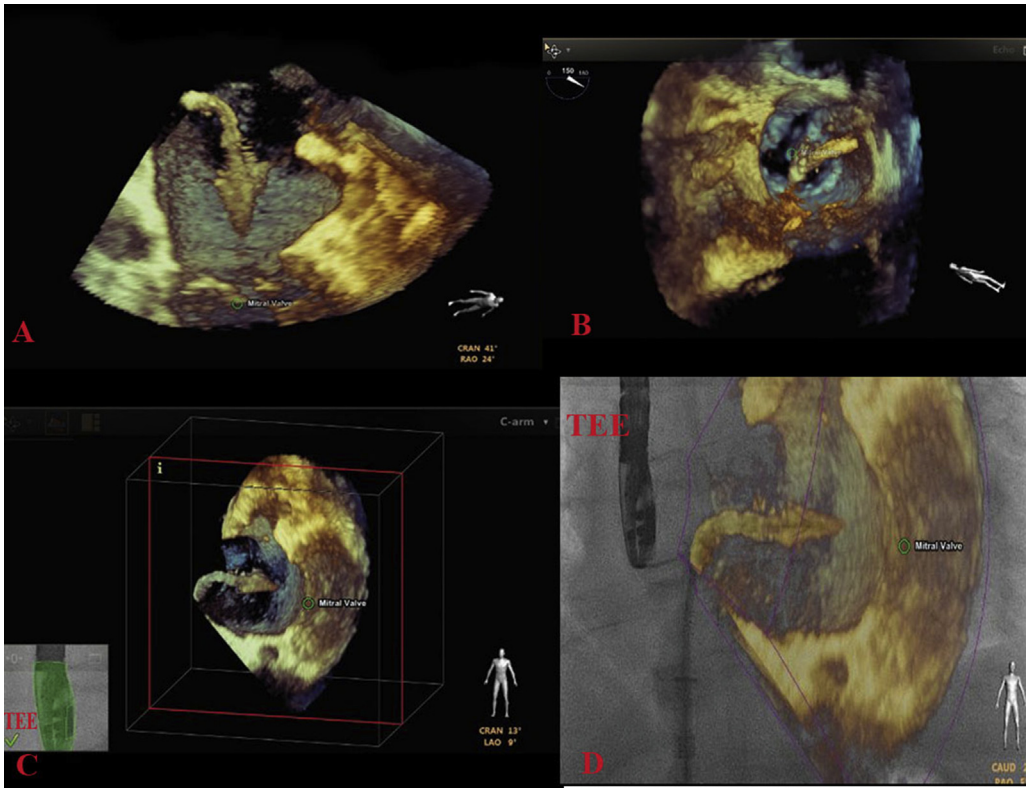

Figure 10 An example of the EchoNavigator live image guidance tool during mitral clip insertion. A. Free 3D image that can be manipulated by the interventionalist from the table site. The mitral valve has been marked (green circle) while the mitral clip guidewire is shown in the left atrial. B. Reconstructed by the echocardiographer 3D image showing the guidewire near the mitral calve (marked by green circle). C. The position of the TEE probe is registered to the X-ray c-arm. The mitral has been marked, and the guidewire appears in the left atrial. D. Merged echo and X-ray imaging. In this image, the 3D echo volume is fused with the X-ray image. The human symbol in the lower right corner of the X-ray and echo image illustrates the different orientations between echo (A, B) and X-ray (D) and how EchoNavigator can orient the Echo view (C) in line with the X-ray image.
(Images are courtesy of Philips Healthcare)

More experimentation with this new system is required at the global scale before it becomes the standard method of care in percutaneous catheter-based procedures.

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