Review

Usefulness of Three-Dimensional Echocardiography in Clinical Practice

Ahmed Abuzaid [1], Aiman M. Smer [2], Navin C. Nanda [3], Ahmed Y. Salama[3] , Ecem R.Akdogan[3] , Hanan Fadala[3] , Mahmoud Abdelsalam[3]
1. Division of Cardiology, University of California San Francisco, San Francisco, California, USA
2. Cardiovascular Department, Creighton University School of Medicine, Omaha, Nebraska, USA
3. Division of Cardiovascular Disease, Department of Medicine, University of Alabama at Birmingham, Birmingham, Alabama, USA
Corresponding author: Navin Nanda
Email: nnanda@uabmc.edu

Abstract

Abstract: Over the last decade, three-dimensional echocardiography (3DE) has become an important diagnostic modality in the evaluation and management of patients with heart diseases. The recent advancements in transducer and computer technologies have been very instrumental in implementing 3D technology in routine clinical practice. Moreover, we anticipate that with further hardware and software improvement, 3D image quality and workflow will continue to improve. For the first time, cardiologists are able to view the heart and its structures in 3D perspective. This unique advantage of 3DE has improved the diagnostic accuracy, clinical decision-making and the success of percutaneous cardiac interventions. The addition of 3DE to conventional 2D imaging adds incremental diagnostic value in several clinical scenarios such as cardiac chamber quantification, valvular heart disease, congenital heart disease, and cardiac masses. 3DE plays an integral role in patient selection for percutaneous cardiac procedures and provides real time guidance and assessment of procedural success. However, further improvement in spatial and temporal resolution of 3D imaging are required to enhance the clinical utility of 3D stress and speckle tracking. To build up a successful 3DE lab, it is important to understand the technical principles of 3DE and train staff in 3D dataset image acquisition, processing and analysis. Guidelines documents are available to provide a practical guide to clinicians on performing 3DE. In this article, will briefly review the main technical principles and common clinical applications of 3DE.

Introduction

The continuous advancement of echocardiography has led to the development of distinctive tools that evaluate cardiac function and morphology in a superior manner. The introduction of three-dimensional echocardiography (3DE) represents a real revolution in cardiovascular ultrasound imaging. Cardiac imagers crave to see the heart in 3D model with satisfactory spatial and temporal resolution to assess the cardiac structures in more realistic anatomical demonstration and accurate quantitative evaluation of cardiac chambers (overcoming 2D geometric assumptions) [1-6]. Advanced cardiac imaging with cardiac magnetic resonance and cardiac computed tomography (CT), are centered on post-acquisition reconstruction of multiple tomographic images of the heart to have a three dimensional image. In contrast, 3DE is a volumetric method that offers real time volumetric sectors of the beating heart and its related structures [1,2,7,8].

Technical overview and modalities display of 3D echocardiography

The 3DE technology relies mainly on the fully sampled matrix array 3D transducer. A conventional 2D transducer is composed of 128 piezoelectric elements, organized in a single row allowing the ultrasound beam to scan the heart in only axial and lateral dimensions [2,7,8] .

On the other hand, 3D matrix-array transducers are constituted of nearly 3000 piezoelectric crystals with the ability to scan the beating heart in 3 dimensions, axial, lateral and elevation dimension. Current 3D transducers generate frequencies ranging from 2 to 4 MHz for transthoracic and 5 to 7 MHz for transesophageal transducers [1-3]. In addition, these 3D transducers provide conventional 2D imaging such as M-mode, X-plane, continuous wave, pulse wave and color Doppler modalities. Further advances in both computer and transducer technologies have led to higher image quality, smaller transducer footprint, increased sensitivity, and adding harmonic technique to 3DE.
Currently, there are four methods of 3D data acquisition: Live or real-time 3D imaging, full volume, 3D zoom and 3D color Doppler data acquisition [9,10]. A detailed description of each technique is beyond the scope of this review.

Clinical applications of 3D echocardiography

Recently, 3DE has become an essential diagnostic tool in clinical practice. It provides superior image quality and accurate assessment of cardiac size and function in patients with cardiomyopathy, valvular lesions and congenital heart disease. In addition, cardiac masses can be characterized and it provides procedural guidance in the cardiac catheterization laboratory. Table 1 summarizes common clinical applications of 3DE.

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Table 1.

Clinical Applications of Three-dimensional echocardiography

1. Chamber quantification	Left and right ventricular volumes and ejection fraction. Left ventricular mass Measurement of left and right atrial volumes
2. Valvular heart disease	Assessment of anatomy of all 4 cardiac valves LVOT and aortic annulus sizing for TAVR Valve area measurement via direct planimetry in mitral, aortic, tricuspid and pulmonary valve stenosis Regurgitant orifice measurement via vena contracta in regurgitant lesions Evaluation of prosthetic valve malfunction and paravalvular leak
2. Intracardiac Masses	Characterization of mass location, size, shape, mobility and spatial relation to the surrounding cardiac structures. Morphologic assessment of the inside structure of a mass and attachment characteristics
3. Congenital heart disease	Anatomic assessment of the site and size of a congenital defect and its relationship to surrounding structures Chamber quantification and function Patient selection for surgery or catheter intervention

4. Interventional cardiac procedures TAVR Mitral Clip LAA occlusion device PFO, ASD, VSD, PDA, fistula and para valvular leak Valve-in-valve Valve-in-ring	Pre-procedure Confirm diagnosis, aortic annulus characteristics • Anatomic assessment • Patient selection Intra-procedural • Trans-septal puncture guidance • Direct catheter and device deployment Post-procedural • Post intervention/ device deployment assessment
Coronary artery disease	Stress test

ASD = atrial septal defect; LAA = left atrial appendage; LVOT = left ventricular outflow tract; PDA = patent ductus arteriosus; PFO = patent foramen oval, TAVR = transcutaneous aortic valve replacement; VSD = ventricular septal defect.

1: Chamber evaluation

- **The left ventricle:**

Unlike conventional 2D methods for left ventricular (LV) quantification, which depend on geometric assumptions of the LV chamber morphology, assessment of 3D volumes has significantly progressed with current newer software incorporating artificial intelligence and automated volumetric analysis which is superior to standard 2D based methods such as Simpson's method; where foreshortening of LV longitudinal axis is a common source of error and volume underestimation [8-13]. Furthermore, 3DE allows for more precise assessment of regional wall motion abnormalities and therefore improves the diagnostic accuracy of stress testing. In addition, more reproducible and accurate ventricular mass measurement can be easily obtained via 3DE [1].

Recent echocardiography society guidelines have provided echocardiographers with a systematic approach to 3DE image acquisition, display and analysis for accurate and reproducible LV chamber quantification (Figure 1) [7, 8].

- **The right ventricle:**

The difficult visualization of asymmetric right ventricular (RV) geometry by 2D echocardiography with highly trabeculated endocardium poses a challenging task for many sonographers and echocardiographers. This may affect the accuracy of 2D obtained RV diameter, size and anatomic landmarks. 3DE unlocked a new era of RV imaging that allows for visualization all RV segments in one 3D dataset with sufficient temporal and spatial resolution [7, 12]. 2D image quality remains the main limitation for accurate 3D volumetric assessment of the RV.

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- Left and right atria:

3D transthoracic echocardiogram (TTE) assessment of left atrium (LA) and right atrium (RA) overcomes the geometrical assumptions often used with 2D imaging (Figure 1). 3DE evaluation of LA size and function is particularly attractive in diagnosis and management of patients with atrial fibrillation, electrophysiological procedures and early detection of diastolic dysfunction. Additionally, 3DE provides better LA mass or thrombus assessment [1, 12].

2: Valve evaluation

- The mitral valve:

The irreplaceable ability of 3DE to image the mitral valve (MV) from an "*en-face*" perspective either from the atrial or the ventricular side provides superb image quality and important diagnostic information of the MV anatomy and pathology. This unique advantage makes transesophageal 3DE a very useful imaging modality for the diagnosis and management of MV diseases and to guide optimal therapeutic decision transcutaneously or surgically (Figure2) [14]. Automated analysis of the annulus and valve morphology allows better understanding of the mechanism and severity of mitral regurgitation (MR). Several parameters such as leaflet tenting height, tenting area, tenting volume, coaptation distance and leaflets surface can be measured and add to the procedural planning. Furthermore, measurement of the vena contracta via 3D color Doppler has identified its non-circular and asymmetric configuration in most cases (Figure 3). Another strength of 3D color Doppler imaging is the accurate delineation of the effective regurgitant orifice area which results in accurate quantification of regurgitant volume [14-18]. 3DE enables accurate planimetry of the MV area in cases of mitral stenosis overcoming the limitations of conventionally used Doppler methods (angle dependence) and 2DE planimetry (improper 2D plane orientation) [19]. Both transthoracic and transesophageal planimetry of the MV area is more accurate with 3D than 2D modality (Figure 4A). Lately a novel 3DE score for mitral stenosis has been recommended for better valve intervention success [20].

- The tricuspid valve:

There is substantial utility of 3DE to obtain high quality *"en-face"* views of the tricuspid valve to identify the leaflet position, size, pathology and relation to commonly encountered pacemaker leads (Figure 5) [21,24].Furthermore, 3DE allows accurate measurement of the tricuspid annulus size and morphology, which are important parameters to consider in case tricuspid annuloplasty is planned for patients with severe tricuspid regurgitation (TR) who are scheduled for MV surgery[1,25-27] . Additionally, 3DE visualizes the position of pacemaker or defibrillator leads in relation to tricuspid valve leaflets which may interfere with the leaflet motion and contribute to TR [12 ,24] .

- The aortic valve:

3DE allows accurate evaluation of aortic valve (AV) morphology and pathology (Figure 6). Similar to mitral stenosis, 3DE measurement of the AV area is more accurate than 2DE [8,12,22,28] . In 2DE method, we assume that the LV outflow tract is circular in shape. However, the true shape of the LV outflow tract delineated by 3DE is not typically circular. Furthermore, 3DE allows exact *"en face"* views of the AV in short axis and allows proper orifice planimetry measurement (Figure 4B) [1,8,22,28,29] .

- The pulmonic valve:

3DE allows simultaneous visualization of the three pulmonic valve (PV) cusps in 'en face' view [1,30]. This can be helpful in quantitative evaluation of PV regurgitation and stenosis [31].

- Prosthetic valves:

3DE is considered an invaluable diagnostic tool in the evaluation of prosthetic valves [23]. 3D transesophageal echocardiogram (TEE) allows accurate assessment of prosthetic valve degeneration, dehiscence and paravalvular regurgitation [12,23,32,33,34]. Color Doppler 3D imaging allows accurate diagnosis and evaluation of paravalvular leak size, location and severity (Figure 7). In addition, 3D TEE is also used to direct percutaneous closure of paravalvular leak (Figure 8).

3: Evaluation of aorta

In patients with adequate acoustic windows, 3DE can provide accurate measurements of the aortic root, ascending aorta and arch measurements [1,12,35] . Aortic aneurysms and aortic dissection can be more accurately characterized as compared to 2D modalities.

4: Intra- cardiac masses

Like 2DE, 3DE can be used to identify the presence of intracavitary thrombi but further it allows more accurate determination of the exact point of attachment and related cardiac valves and /or central lines or device leads and monitor regression response to anticoagulation therapy (Figure 6B)[12] .This can be done by sectioning the thrombus and assessing the size of echolucent areas resulting from thrombus lysis[36] .Thrombi in the LA appendage (LAA), can be challenging and 3D TEE allows direct visualization of the complex LAA morphology and discover hidden lobes (Figure 9)[1] . This is imperative in distinguishing thrombi from prominent pectinate muscles. When 3D TEE is added, diagnostic accuracy is enhanced significantly, especially in complex cases of prosthetic valves or suspected complications such as chordal rupture, leaflet perforation, vegetations, paravalvular abscess, prosthesis dehiscence or paravalvular regurgitation.

Additionally, 3DE adds incremental value for the evaluation of cardiac tumors. 3DE provides better visualization of interatrial septal stalks in atrial myxoma cases, inhomogeneous echogenicity of rhabdomyomas with myocardial attachment, and differentiating fibroelastoma from valve vegetation. Moreover, tumor vascularity and tissue characterization can be detected via 3D color Doppler [37,38].

5. Congenital heart disease

The role of 3DE in patients with congenital heart disease continues to evolve and it has become a crucial diagnostic tool in the diagnosis and management of both simple and complex heart defects [12]. The main applications of 3DE in patients with congenital heart disease are; 1) diagnosis of congenital cardiac defects, viewing the men face to evaluate their size, shape and relationship to surrounding structures 2) chamber quantification and function, and 3) procedural guidance [39] .

6. Interventional echocardiography with 3D imaging

3DE plays a key role in the field of interventional structural heart disease in terms of patient selection and guidance of percutaneous cardiac procedures. As more percutaneous procedures are being performed, cardiologists have recognized the unique utility of 3DE in patients undergoing transcutaneous aortic valve replacement (TAVR), MitraClip and LAA occlusion procedures (Figure 10, 11) [14,15] 3D TEE is considered a good alternative to CT scan for the assessment of aortic annular size, LV outflow tract and coronary ostia locations specially in patients referred for TAVR who are at high risk for CT contrast induced nephropathy [22,40]. The use of 3D TEE in percutaneous repair of severe MR via MitraClip device is indispensable for optimal trans-septal puncture, device delivery and assessment of procedural success [14-16]. 3DE provides precise assessment of the LAA anatomy (number of lobes, orifice shape and size, maximal LAA diameter, minimum LAA diameter, and LAA depth) for patients undergoing LAA occlusion procedures, such as deployment of the Watchman device. Importantly, live 3DE can be used for optimal trans-septal puncture and guide device deployment. 3DE can also provide a comprehensive assessment of atrial and ventricular septal defects type, size and morphology. These defect characteristics are very important for clinical decision making [12].

7. 3DE in stress echocardiography

Both exercise and pharmacological 3D stress echocardiography are still evolving and carry several advantages. Recent studies have demonstrated good sensitivity and specificity to detect underlying severe ischemic heart disease [41,42]. 3D stress echocardiography allows better visualization of the LV apex, fast acquisition of peak stress images and detection of segmental wall motion abnormalities from a single heart beat dataset. However, the relatively lower frame rates and spatial resolution of 3DE remain the main limitations to routinely incorporate 3D stress echocardiography in clinical practice.

In summary, 3DE has become an important diagnostic tool in the evaluation and management of patients with valvular heart disease, cardiac masses and congenital heart disease. Ongoing advancements in stress and speckle tracking 3D technology as well as more robust RV chamber quantification are expected to substantially increase the use of 3DE in clinical practice in the next few years. Another promising area of 3DE is the full integration of 3DE with fluoroscopy in the catheterization lab during percutaneous interventions for structural heart disease.

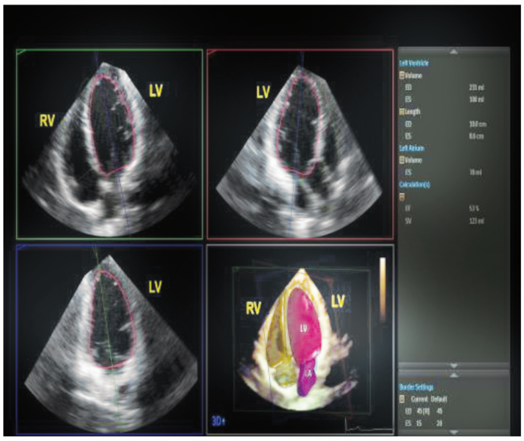

Figure 1. An example of transthoracic three-dimensional Heart-Model dataset with surface reconstruction display of all four cardiac chambers, left atrium volume, left ventricle volumes and ejection fraction. LV=left ventricle; RV=right ventricle.

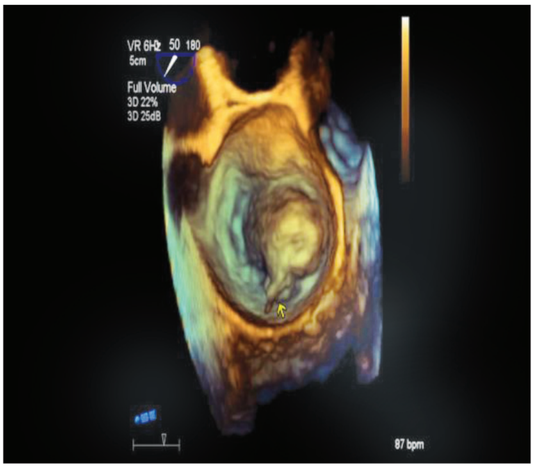

Figure 2. Transesophageal 3D zoom imaging of the mitral valve in en face view from the left atrial side. Arrow points to a flail A2 scallop with a ruptured chord.

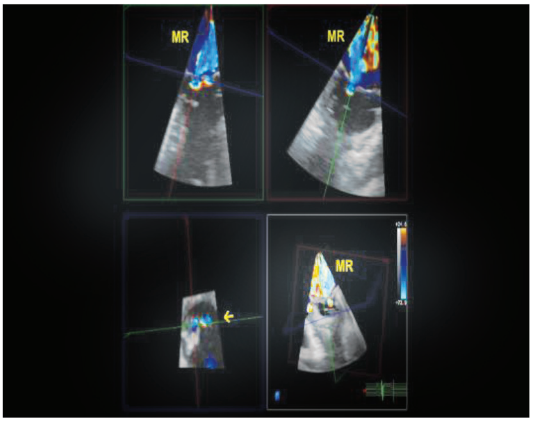

Figure 3. Measurement of vena contracta dimensions from a three-dimensional transesophageal echocardiogram color Doppler data set using three-dimensional analysis software. Note the asymmetric shape of regurgitant orifice.

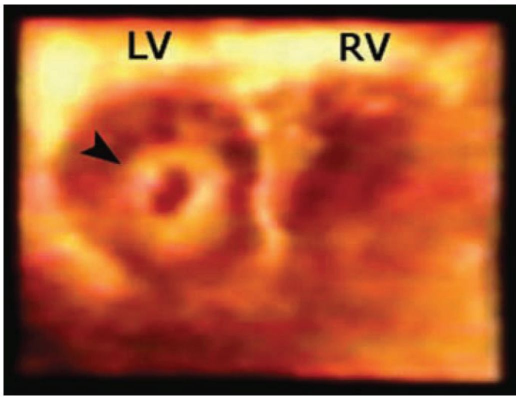

Figure 4A. Live/real time three-dimensional transthoracic echocardiography in mitral stenosis. Arrow head points to the tip of the MV orifice. Abbreviations as in the previous Figure. Reproduced with permission from Singh V, Nanda NC, Agrawal G, et al. Live three-dimensional echocardiographic assessment of mitral stenosis. Echocardiography 2003;20:743-750

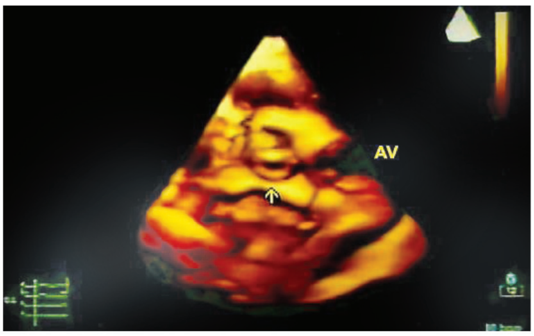

Figure 4B. Live/real time three-dimensional transthoracic echocardiography. Arrow points to severe bicuspid AV stenosis. AV=aortic valve.

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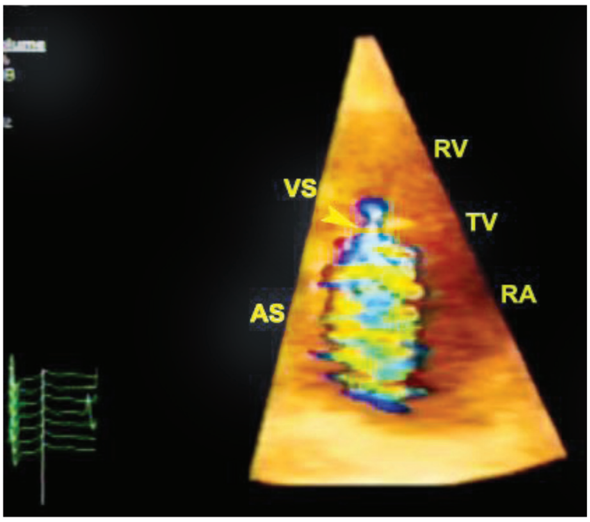

Figure 5A

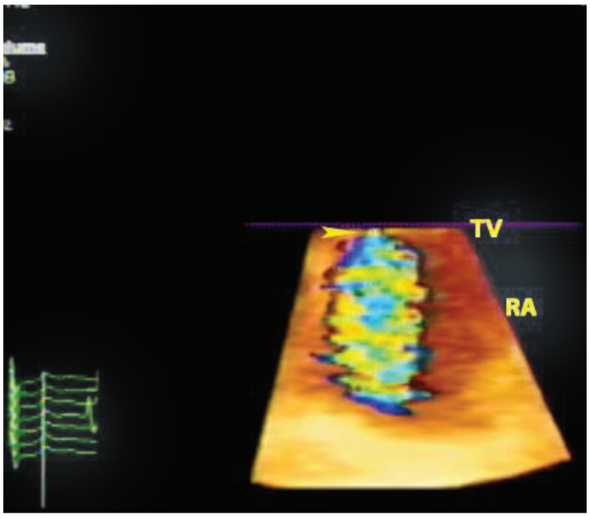

Figure 5B

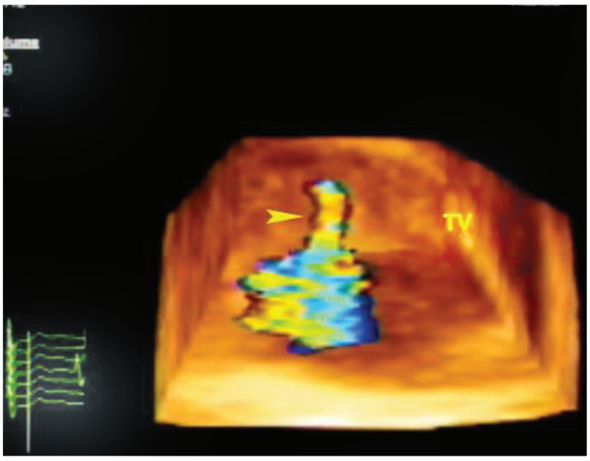

Figure 5C

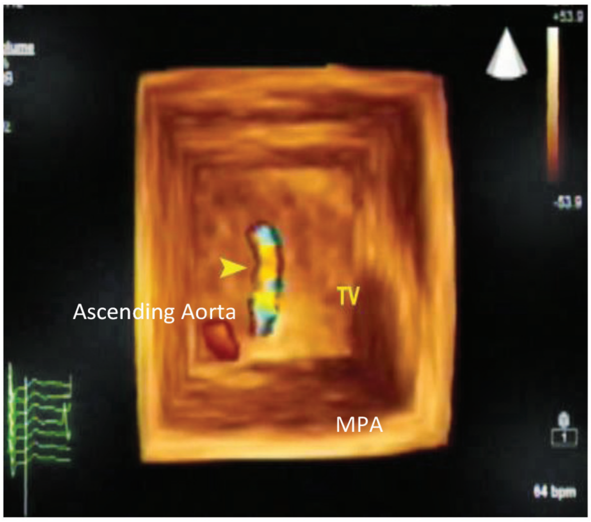

Figure 5D

Figure 5(A-D). Live/real time three-dimensional transthoracic echocardiographic assessment of tricuspid regurgitation vena contracta. A. The three-dimensional data set was first cropped posteroanterior to detect the tricuspid regurgitation jet, flow acceleration (PISA) and the vena contracta (arrow head). B. The cropping plane was then moved from the top towards the bottom and placed at the level of the vena contracta making sure it is parallel to it. C, D, the data set was tilted to view the vena contracta enface. The size of the vena contracta can then be measured by planimetry.AS=atrial septum; RA=right atrium; TV=tricuspid valve; VS=ventricular septum. Other abbreviations as in previous Figures.

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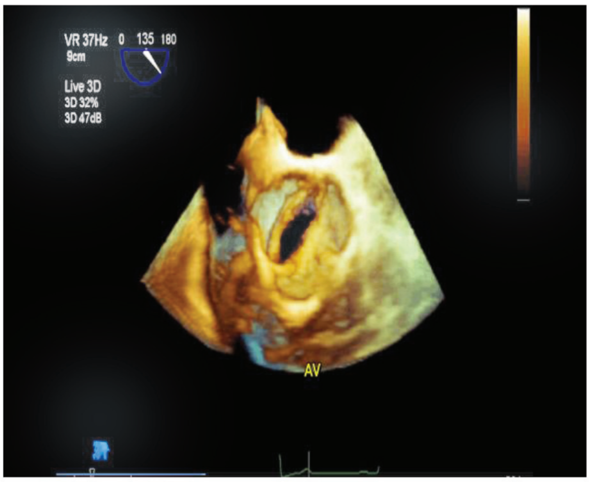

Figure 6A. Live three-dimensional transesophageal echocardiogram showing enface view of a bicuspid aortic valve with fusion of the right and left coronary cusps.

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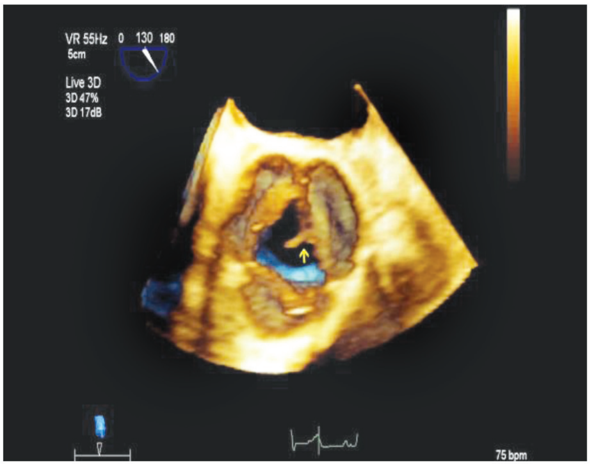

Figure 6B. Live three-dimensional transesophageal mid-esophageal short axis view of the aortic valve. Arrow points to a linear mobile echodensity at the tip of the left coronary cusp consistent with a Lambl's excrescence.

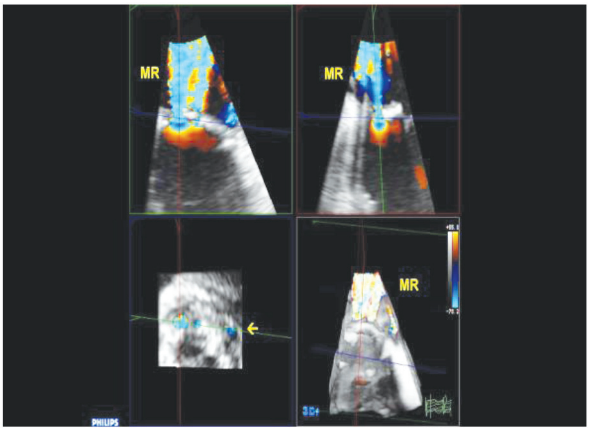

Figure 7. Three-dimensional transesophageal color Doppler en face view of a mitral valve prosthesis showing the location of 3 separate paravalvular leaks (arrow). Quantitative assessment of leakage size using three-dimensional analysis software and multiplanar reconstruction (MPR) mode. MR- mitral regurgitation

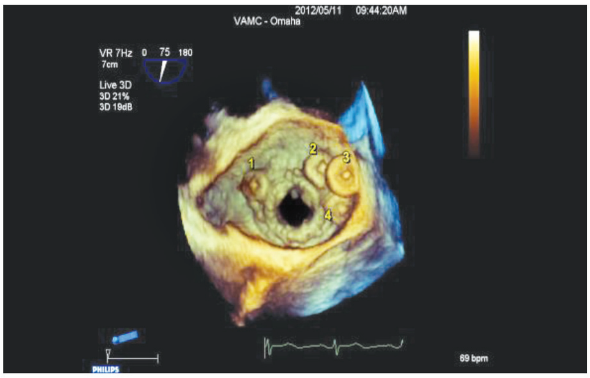

Figure 8. Live/three-dimensional transesophageal echocardiography en face view of the mitral valve. #1, #2, #3 and #4 represent four Amplatzer occluder devices implanted around the bioprosthetic mitral valve ring for severe paravalvular leaks.

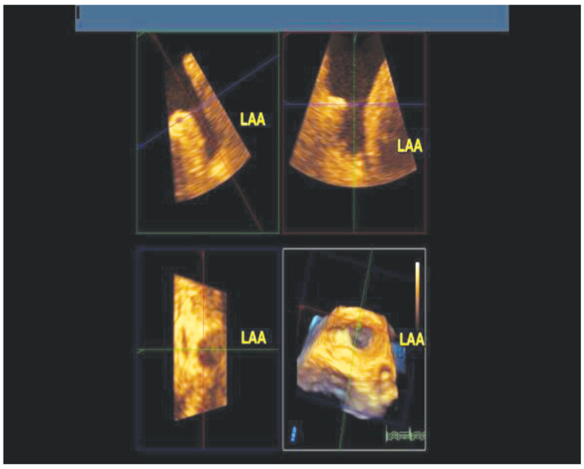

Figure 9. Three-dimensional transesophageal zoom image of left atrial appendage viewed in multiplanar reconstruction (MPR) mode for accurate measurement of orifice size and depth prior to Watchman procedure (arrow). LAA=left atrial appendage.

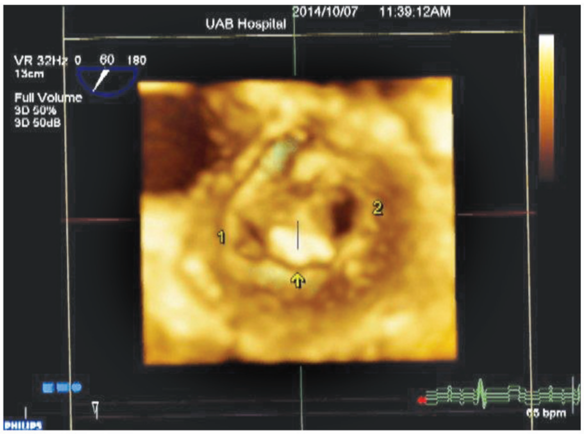

Figure 10. Live/real time three-dimensional transesophageal echocardiography. Arrow points to MitraClip. #1 and #2 represent the two mitral orifices resulting from MitraClip device placement.

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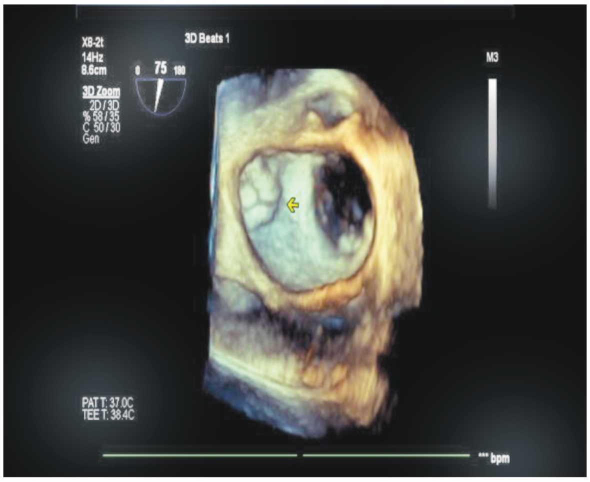

Figure 11A. Live/real time three-dimensional transesophageal image shows a well-seated Watchman device (arrow) within the left atrial appendage.

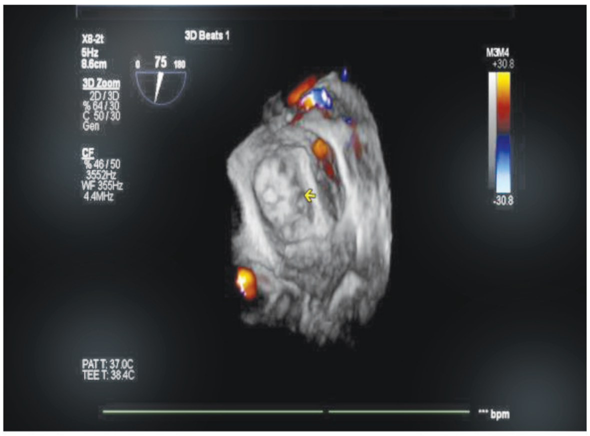

Figure 11B. Three-dimensional color Doppler image shows appropriate device placement (arrow) with no peri-device leak.

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