Incremental Value of 3-D Transesophageal Echocardiographic Imaging of the Mitral Valve

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Abstract Transesophageal echocardiography provides excellent visualization of the posteriorly located mitral valve. Over the last decade, 3-dimensional transesophageal echocardiography (3D TEE) has emerged as an exciting imaging modality, particularly of the mitral valve. The current generation matrix array technology allows the operator to perform 2D and 3D imaging with a single transducer. 3D TEE affords the unique ability to view the mitral valve and its surrounding structures "en face" in real time (RT), and provide contextual anatomical guidance during surgical and transcatheter interventions. Additionally, offline quantification has made significant contributions to our mechanistic understanding of the normal and diseased mitral valve, and alterations induced by therapeutic intervention such as surgical repair. This review will address recent advances in the incremental role of 3D TEE in mitral valve imaging.

Keywords Echocardiography · Three-dimensional transesophageal echocardiography · Real-time 3D TEE · Interventional echocardiography · Mitral valve · Mitral valve disease · Mitral regurgitation · Mitral stenosis · Mitral valve repair · Valvular heart disease · Valvuloplasty

Abbreviations

2D	2-dimensional
3D	3-dimensional
DMVD	Degenerative mitral valve disease
Echo	Echocardiography
FMR	Functional mitral regurgitation
IMR	Ischemic mitral regurgitation
MR	Mitral regurgitation
MS	Mitral stenosis
MV	Mitral valve
MVP	Mitral valve prolapse
MAIVF	Mitral-aortic inter valvular fibrosa
PVR	Paravalvular regurgitation
TEE	Transesophageal echocardiography
RT3D TEE	Real time 3-dimensional transesophageal

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Introduction

Echocardiography (Echo) is the primary imaging modality for the diagnosis, therapeutic guidance, and follow-up of mitral valvular disease. Due to the proximity of the imaging probe to the left atrium, transesophageal echocardiography (TEE) is ideally suited to image the mitral valve (MV). Recently, 3-dimensional transesophageal echocardiography (3D TEE) has emerged as an indispensable tool for imaging of the MV, and current matrix array technology confers both 2-dimensional (2D) and 3-dimensional (3D) functionality within a single transducer. A distinct advantage of 3D TEE over conventional 2D TEE is the ability to visualize the entire MV and support apparatus from a single transducer position and in real time. 3D echocardiography (3DE) allows an unprecedented "enface view" of the MV superiorly from the left atrium (LA), which corresponds to the surgeon's view, or alternatively, inferiorly from the left ventricle (LV), which corresponds to the fluoroscopic view in the cardiac catheterization laboratory. The current review will explore the incremental role of 3D TEE in the assessment of mitral regurgitation and stenosis, and mitral percutaneous and surgical interventions, with emphasis on recent advances and research.

Normal Mitral Valve

The MV is a complex structure consisting of the mitral annulus, anterior and posterior leaflets, chordae tendinea, and the papillary muscles. A comprehensive understanding of normal mitral anatomy and its alteration in diseased states is fundamental to the appreciation of 3DE.

The mitral annulus is the D-shaped circumferential junction of the LA, LV, and mitral leaflets attachment, with a straight anterior and curved posterior portion. The anterior annulus is interposed between the right and left fibrous trigones and is in direct fibrous continuity with the aortic valve, referred to as the aortomitral curtain or more commonly, the mitral-aortic inter valvular fibrosa (MAIVF). This results in coupling of the mitral and aortic valve dynamics. The mitral annulus has a unique saddle shape, with anterior and posterior peaks and medial and lateral commissural valleys. This shape is best suited to minimize leaflet stress, and maintain optimal leaflet coaptation in systole. The entire annulus has a characteristic dynamic motion during the cardiac cycle, which is distinctly abnormal in various mitral pathologies [1].

The thicker anterior leaflet attaches to the anterior one-third or the straight portion of the D whereas the long and thin posterior leaflet attaches to the remaining two thirds of the annular circumference or the posterior curved portion of the D. When viewed from the left atrium, minor commissures that are cleft like indentations not associated with underlying papillary muscles, divide the posterior leaflet into 3 distinct scallops (segments). They are classified by Carpentier as P1 (anterolateral), P2 (middle), and P3 (posteromedial). Rarely, there are accessory scallops. The anterior leaflet is correspondingly divided into 3 segments A1, A2, and A3.

The chordae insert the inferior surface of the leaflets to the anterolateral and posteromedial papillary muscles and LV wall.

This intricate architecture of the MV apparatus results in optimal function by reducing leaflet stress and maintaining coaptation in systole, and leaflet excursion in diastole. It is difficult to visualize these anatomical details and dynamics with 2DE. With 3DE, not only can the entire apparatus be visualized in real time, but various aspects such as annular circumference, motion and nonplanar geometry, leaflet surface area, integrity of segments, and length of chordae, in normal and diseased mitral valves can be studied.

3D Acquisition, Display, and Orientation

3D TEE is in real-time (RT3D TEE) when the image in the form of a volume data set is acquired in a single heartbeat. A major limitation of RT3D TEE is the low frame rate or more accurately the volume rate when there is need for a large volume data set particularly if imaging includes 3D color flow Doppler. This limitation may be overcome by multi-beat acquisition, but the

volume data set generated is postprocessed, hence, not in real time, and is subject to "stitch" artifacts. Conventionally, when viewed from the left atrium, the MV is displayed with the aorta on top (12 o'clock), the medial commissure to the right (3 o'clock) and the lateral commissure and left atrial appendage, an anterolateral structure, to the left (9 o'clock). The leaflet scallops are named from the left to the right as A1/P1, A2/P2, A3/P3. EAE/ASE recommendations for 3D echo image acquisition and display [2••], and ASE framework for 3D imaging of the MV [3] have been published.

Mitral Regurgitation

3DE has played a central role in understanding the functional anatomy and dynamics of the MV complex in the normal state and various etiologies of mitral regurgitation (MR) including degenerative and functional. Degenerative mitral valve disease (DMVD), commonly known as MV prolapse is due to an intrinsic abnormality of the MV leaflets and subvalvular apparatus. It results in excess leaflet tissue, chordal thinning, elongation or rupture and single or multi-segmental prolapse or flail. DMVD is the most common cause of MR requiring surgical intervention. The ability to view the entire surface of the leaflets allows easy identification and classification of prolapsing or flail segments. Several authors have demonstrated that 3D and 2D TEE are comparable (98 % vs 90 %) in accurately identifying degenerative and functional etiologies of severe MR in patients undergoing surgical MV repair [4–6]. But, 3D TEE has superior diagnostic accuracy in identifying scallop specific pathology [5–7], and in more complex disease with anterior leaflet, bileaflet, or commissural involvement. A recent study showed that physicians across a gamut of echocardiographic experience were better able to localize prolapsed and flail segments with 3D TEE. Both experienced and inexperienced echocardiographers (residents and fellows) achieved higher diagnostic scores with 3D TEE compared with 2D TEE [8•].

Mitral Annular Dynamics and Morphologic Changes in Degenerative Mitral Valve Disease

Early studies using 3DE elegantly demonstrated that the mitral annulus is not planar but saddle shaped with a unique dynamic motion throughout the cardiac cycle [9]. This nonplanar geometry and motion cannot be appreciated by 2D imaging. The saddle shape minimizes leaflet stress and maintains competency during systole. Due to various architectural changes, this motion is distinctly abnormal in DMVD. Compared with normals, the myxomatous mitral annulus is larger in surface area, wider in diameter, and flatter in early systole, and therefore less capable of maintaining leaflet coaptation. One study

[10] demonstrated significant differences in mitral annular dynamics between normal controls, degenerative MR, and ischemic MR using 3D TEE. The normal mitral annulus remains dynamic throughout the cardiac cycle with a systolic decrease in the anteroposterior (AP) diameter and annular area, no change in inter commissural diameter (IC), and early-systolic accentuation of the saddle shape. In DMVD, the annulus demonstrates a systolic increase in all dimensions— AP and IC diameters, circumference and area— and a less prominent systolic accentuation of the saddle shape. In ischemic MR, the annulus is adynamic, with an increased AP diameter but unchanged IC diameter. Following standard MV repair with a flexible annuloplasty ring, the degenerative mitral annulus did not regain systolic accentuation of its saddle shape underscoring the fact that current surgical techniques do not completely restore normal mitral annular dynamics in DMVD.

DMVD covers a wide pathomorphologic spectrum with fibroelastic deficiency (FED) at one end, and Barlow's Disease (BD) at the other. The hallmark features of FED are thin, translucent leaflets with abnormal single segmental thickening, and chordal elongation with prolapse or flail, typically involving the P2 scallop of the posterior leaflet. In BD, there is excessive annular dilatation, billowing of several thickened segments, with thickened and elongated chords (Fig. 1, Video 1). Chandra et al [11••] used RT3D TEE to demonstrate differences between FED
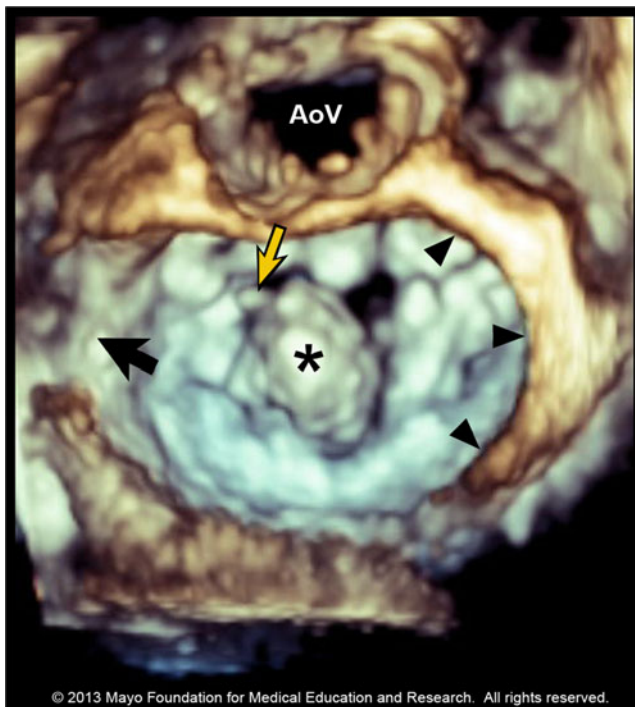
Fig. 1 Three-dimensional transesophageal echocardiography 'surgeons view' from the left atrial perspective showing a mitral valve with P2 prolapse (*asterisk*) and a ruptured chord (*yellow arrow*). Demonstrates the aortic valve (AoV) at the 12 o'clock position, interatrial septum (*black arrowheads*), and ostium of the left atrial appendage (*black arrow*). © Mayo Foundation

and BD and identify predictors of surgical complexity. In both FED and BD, there was an increase in AP and IC diameters, leaflet surface area, leaflet billowing height and billowing volume. Not surprisingly, these changes were more exaggerated in BD. In FED, the P2 scallop was most frequently abnormal, followed by P1 and P3. Interestingly, the mitral annulus retained its normal contour in FED, but became circular in BD. They identified a billowing height of > 1.0 mm as the strongest predictor of differentiating normal from DMVD, and a billowing volume of > 1.15 ml as the strongest differentiator of FED from BD. Immediately postoperatively, the differences in dimensions between the 2 subgroups remained, but were significantly reduced. Maffessanti et al found similar results in a subset of patients with FED and BD undergoing mitral repair [12].

In a more recent study, Lee and colleagues were the first to prospectively study mitral annular shape in DMVD with and without MR using RT3D TEE [13••, 14]. They identified flattening of the mitral annulus - quantified as the annular height to commissural width ratio - as an important prognostic parameter. As the annulus flattened, leaflet billowing volume, chordal rupture and MR severity increased. It suggests that flattening of the annulus maybe a marker for better risk stratifying patients with DMVD.

Prominent posterior leaflet inter scallop commissures referred to as "deep clefts" have been observed in MVP and are associated with immediate postoperative residual MR following mitral valve repair [15]. Accurate characterization of clefts with 2D echo is not possible. In a 3D TEE study, Ring and colleagues [16••] reported that deep clefts are significantly more prevalent in MVP at 84 %, compared with 16 % in functional MR, and 12 % in controls. Interestingly, they were only present around or within prolapsing or flail segments, and their numbers increased with the number of prolapsing segments. Regurgitation through the cleft was better detected by 3D rather than 2D TEE. They proposed that deep clefts represent a structural abnormality that could contribute to the burden of prolapse, mechanism of regurgitation, and results of surgical repair.

Such nuanced differentiation of morphology or dynamicity has previously not been possible with 2D TEE or direct surgical inspection of a flaccid heart during cardiopulmonary bypass.

Aortic Mitral Valve Coupling in Normal and Degenerative Mitral Valve

There is coupling of the aortic and mitral valvular dynamics because of their attachment through the MAIVF. Veronesi et al were the first to study aortic and MV coupling using 3D TEE [17•]. They demonstrated that the common fibrous anchoring renders a reciprocal dynamicity between the 2 valves. In early diastole, when the MV is open, the mitral annulus area (MAA) is maximal, and the aortic annular area

(AoA) is minimal. Conversely, when the aortic valve opens in systole, the AoA is maximal and the MAA is minimal. The angle between the 2 valves decreases during ventricular ejection. In a separate study, the same authors noted changes in coupled dynamics before and after surgical repair for DMVD [18]. Prior to surgery, despite changes in mitral annular dimensions and geometry, the dynamic reciprocal coupled motion of the mitral and aortic valves is maintained. Following surgical repair and insertion of annuloplasty ring, there is a decrease in mitral annular dimensions, and an associated tightening of the mitral aortic complex. This results in a decreased intervalvular angle and attenuated reciprocal motion of the 2 valves. These findings support the concept of the aortic and MV as a single dynamic valvular unit rather than 2 truly independent structures.

Functional MR

In functional mitral regurgitation (FMR), the mitral leaflets are normal. FMR can occur in the setting of dilated cardiomyopathy or coronary artery disease. When the latter is the underlying etiology, FMR is referred to as ischemic mitral regurgitation (IMR). IMR is most commonly associated with prior inferior or inferolateral myocardial infarction, but may occur following an anterior myocardial infarction. The key pathophysiologic events leading to IMR are LV remodeling of the infarcted myocardial segment(s) underlying a papillar muscle with secondary lateral and apical papillary muscle displacement, which in turn results in asymmetric or symmetric tethering and mal coaptation of the mitral leaflets. Annular dilatation and left ventricular systolic dysfunction also contribute to mitral regurgitation. Similar mechanisms are in play in patients with nonischemic dilated cardiomyopathy. Papillary muscle displacement is not unique to FMR, however. Otani and colleagues [19••] demonstrated, that even in degenerative MR, mild to moderate LV dilatation and remodeling results in papillary muscle displacement and tenting of the nonprolapsed segments, which in turn, exacerbates the degree of mitral regurgitation.

Both 3D transthoracic [20, 21] and 3D TEE [10] studies have shown that in IMR the annulus dilates, flattens and becomes adynamic, with an increased tenting volume. 3D TEE has the advantage of quantifying indices of FMR severity such as increase in tenting length, tenting volume, papillary muscle displacement and LV volumes [22, 23].

Quantification of Mitral Regurgitation

The quantification of MR has important implications for severity classification and therapy. The complementary role of 3DE in this setting is being increasingly recognized [24•].

Two-D estimation of MR severity is frequently done by the proximal isovelocity surface area (PISA) method that assumes a circular mitral orifice. However, it has been shown that, the effective regurgitant orifice (ERO) or vena contracta (VC) is frequently asymmetrical or ellipsoid, particularly in functional and/or eccentric MR, leading to a consistent underestimation of ERO area (EROA) and regurgitant volume (RVol) by the 2D PISA method [25–27]. With 3D, the EROA and VC can be directly visualized and planimetered [28]. Shanks and colleagues compared MR quantification by 2D TEE, 3D TEE, and magnetic resonance imaging (MRI) [29]. EROA was obtained by direct planimetry in the en face view, and regurgitant volume (RVol) was calculated as the product of EROA and mitral velocity time integral (VTI). RVol-3D was comparable with that derived by MRI. There was a significant underestimation of both EROA-2D and RVol-2D when compared with 3D and MRI, particularly in eccentric jets. Hence, a significant proportion of patients were reclassified to a greater severity of MR by 3D TEE.

Current guidelines and expert opinion mention a potential role for 3D quantification of MR but do not make specific recommendations regarding the indications or normal reference values [2••, 30–32]. Studies addressing outcomes of patients undergoing 3D quantification of MR are lacking.

Intraoperative 3D TEE in Mitral Valve Repair

Accurate measurement of prognostic parameters such as leaflet and prolapse length, billowing height and volume, and inter-trigonal length can help plan surgical technique, and anticipate complications such as systolic anterior motion leading to postoperative MR [11••, 33]. Recent data suggest that the dynamicity of the mitral annulus is better preserved with surgical repair without leaflet resection compared with traditional leaflet resection techniques [34].

Up to 30 % of patients who undergo surgical band annuloplasty repair for ischemic MR develop recurrent MR. Traditional surgical repair with an undersized ring annuloplasty addresses the dilated annulus, but not the sub valvar abnormalities. Langer et al [35] identified a leaflet tenting height ≥10 mm as an echocardiographic marker of significant leaflet tethering and repair failure. When these patients underwent a modified technique of annuloplasty ring and relocation of the posterior papillary muscle (RING + STRING technique), a significant freedom from recurrent MR at 2 years was achieved.

Similarly, semi rigid band annuloplasty for functional MR has been shown to reestablish coaptation, and support regional LV remodeling [36].

In 1study, experienced operators could acquire a single focused RT-3D TEE MV image from the left atrial perspective in 60±18 seconds, providing all the necessary information required for presurgical planning in patients undergoing

surgical repair for MR [5]. Hence, intraoperative 3D TEE can be performed expeditiously and has a promising role in recognizing important variables to aid customized modifications in surgical technique, which would improve hemodynamic results and long-term durability of repair [11••, 22, 37].

Mitral Stenosis

In rheumatic mitral stenosis, there is extensive post inflammatory fibrosis, asymmetric scarring, and calcification of the MV leaflets and subvalvar apparatus. The anatomy is significantly distorted rendering 2D transthoracic imaging challenging. The orifice area should be planimetered at the leaflet tips, during their maximal separation in early to mid-diastole. Planimetry measurements below the leaflet tips will overestimate the area. 2D planimetry is prone to erroneous overestimation of valve area due to the technical difficulty in accurately establishing the plane of the leaflet tips in the parasternal short axis view. 3D echo overcomes this limitation by the ability to identify the plane of the leaflet tips. Studies with head to head comparison of transthoracic 2D and 3D have shown that 3D planimetry correlates more closely with invasively derived area, both before and after commissurotomy [38–40]. Schlosshan and colleagues [41] compared the mitral valve area (MVA) by 3D TEE with traditional 2D TTE methods. They concluded that 3D TEE is feasible and provides reproducible, superior imaging of the rheumatic MV and commissural fusion in nearly all patients. MVA-3D planimetry was significantly lower than MVA-2D planimetry and pressure half time, but agreed closely with the continuity method. Min and colleagues [42] confirmed that 2D planimetry significantly overestimated MVA by >0.2 cm^2 in nearly half the patients. Two factors predicted area overestimation - left atrial diameter > 49 mm and an angle of deviation of the ultrasound plane from the leaflet tips ≥ 9.5°. 3D TEE may offer incremental value in patients with discrepant clinical and 2D echocardiographic severity of mitral stenosis.

However, the primary role for 3D TEE in mitral stenosis is in percutaneous mitral balloon valvuloplasty (PMBV). This is described in a subsequent section below.

Valvular Vegetations and Perforation

Complications of endocarditis include vegetations and perforations of both native and prosthetic mitral valves. Definitive therapy relies on echocardiographic diagnosis. Mitral valvular perforations are commonly caused by bacterial endocarditis. 2D TEE is established as the diagnostic modality of choice with a sensitivity of 94 % and specificity of 100 %. However, 2D imaging is unable to visualize the entire valve surface in a single view. A retrospective study comparing 2D- and 3D-TEE reported that 3D TEE was superior in diagnosing and anatomically localizing perforations, particularly of the MV [43]. 3D TEE also provides incremental information such as quantification of vegetation volumes, area of valve destruction, site and extension of abscesses, and identification of chordal rupture, as confirmed by surgical inspection [44].

Prosthetic Mitral Valves

Krim et al were the first to report that 3D TEE diastolic orifice area correlated closely with the manufacture defined geometric area of St Jude mechanical mitral prostheses, but the standard Doppler derived effective orifice area was consistently smaller than both [45••]. Sugeng and colleagues [46] demonstrated good correlation between RT3D TEE of bioprosthetic and mechanical mitral prosthetic leaflets, struts and sewing rings, and subvalvar apparatus, and surgical findings. Mechanical MV images were superior from the LA perspective, whereas bioprosthetic valves were equally well visualized from the LA or LV. Due to the high spatial resolution, accurate anatomic delineation of prosthetic dehiscence, perivalvular regurgitation, and masses can be easily achieved. This is a huge advantage over 2D imaging. In a study of 2D vs 3D TEE assessment of postoperative MR secondary to mitral ring or prosthetic valve dehiscence, Kronzon et al [47] concluded that 3D TEE provided additional anatomical details of the dehisced segment and regurgitant jet that would help better plan intervention, either surgical or percutaneous.

3D TEE in Transcatheter Mitral Interventions

Conceivably the most clinically applicable, and incremental role for 3D TEE is in the patient selection, planning and procedural guidance of percutaneous or transcatheter mitral interventions [48, 49, 50•, 51]. A recent EAE/ASE guideline document concisely outlines the role of 2D and 3D echocardiography in various transcatheter valvular interventions [52]. The main mitral procedures are:

(1) Closure of mitral paravalvular regurgitation.
(2) Edge-to-edge repair of mitral regurgitation.
(3) Valve in valve implantation.
(4) Balloon valvuloplasty in mitral stenosis.

Transcatheter Closure of Paravalvular Regurgitation

Paravalvular regurgitation (PVR) or paravalvular leak is a regurgitant jet occurring through a defect between a prosthetic valve and surrounding tissue. Clinically significant PVR occurs in 3 %–6 % of all patients, most commonly in mitral

prostheses [53]. Redo surgery is recommended in symptomatic patients. Over the last decade, percutaneous closure of PVR has emerged as a feasible alternative for poor surgical candidates [54–56]. Approximately 80 % of transcatheter closures are done for paramitral defects [55]. Technical success and safety depend on careful patient selection. Active endocarditis and presence of significant transvalvular regurgitation preclude PVR closure. Currently available closure plugs are predominantly circular in shape and therefore suboptimally suited to most defects that are irregular or crescent shaped. In addition, large defects that involve greater than 20 % of the sewing ring limit successful closure [56]. Prior to offering transcatheter closure as a therapeutic option, anatomical details of location, number, size and shape of the defects have to be meticulously characterized.

Due to the length and complexity of the procedure, transcatheter closure of mitral PVR is done under general anesthesia with TEE as the preferred imaging modality. 3D TEE offers distinct incremental value over 2D imaging for patient selection, intraprocedural guidance, and post-procedure assessment. Due to the high spatial resolution, 3D TEE can separate paravalvular from transvalvular regurgitation, identify single vs multiple defects, describe their respective shapes and sizes, and elucidate spatial relationships to the prosthetic valve and surrounding structures. Only 3D echo permits an en face view of the defect(s), and simultaneous visualization of the catheter, guide wire, and closure device. Following deployment, technical success and potential complications such as device impingement on prosthetic leaflets, device migration or embolization, residual regurgitation, and iatrogenic atrial septal defect from the transeptal puncture can be rapidly assessed. As experience with transcatheter closure increases, several high volume centers have adopted 3D TEE for patient selection and procedural navigation [53–55].

Catheter Based Edge-to-Edge Repair of Mitral Regurgitation

Percutaneous mitral valve repair (PMVR) using the edge-to-edge technique has emerged as a feasible option for eligible patients with significant chronic mitral regurgitation and high surgical risk. Eligibility is determined by clinical variables and extensive echocardiographic criteria based on mitral anatomy, MR severity and LV function [57]. In the Phase I [58] and phase II [59] EVEREST (Endovascular Valve Edge-to-Edge REpair STudy) trials, all patients underwent TEE prior to selection, during and postprocedure. PMVR emulates the double orifice surgical technique or Alfieri stitch. A clip is used to approximate the free edges of A2/P2 leaflet scallops, resulting in a double orifice that diminishes the degree of MR.

The procedure is performed under general anesthesia, with fluoroscopic and TEE imaging. The MitraClip system consists of a steerable catheter delivery system with the clip attached distally. The clip has 2 arms that can be opened to grip mitral leaflet tissue, then closed shut and deployed. After transeptal puncture, the delivery system is navigated into the left atrium. Precise positioning of the clip is crucial to success of the procedure, and relies largely on TEE guidance. The clip has to be positioned perpendicular to the long axis of the leaflets, and in the center of the mitral orifice and regurgitant jet. This critical step can be optimally visualized using RT3D TEE. The clip is then carefully advanced into the LV and then pulled back to grip the leaflets in the mid portion. After TEE confirms a double orifice and maximal reduction of MR, the clip is deployed. Additional clips maybe used as indicated. Postprocedure, TEE evaluates clip stability, residual MR and mitral orifice area calculated by pressure half time and planimetry (sum of the 2 orifices at the level of the clip). Potential complications include pericardial effusion and tamponade, clip detachment or embolization, leaflet tear, injury to sub valvar apparatus and iatrogenic mitral stenosis.

RT3D TEE has been shown to be superior to 2D TEE in guiding most steps of PMVR. Altiok et al found that compared with 2D TEE, RT3D TEE offered incremental procedural guidance in 9 out of 11 steps [60]. Potentially prognostic data can also be obtained. A recent study [61] used 3D TEE to demonstrate a significant postprocedural reduction in RV, VC, mitral annular circumference, and diastolic MV area. Furthermore, at 6-month follow-up, the patients who had a >50 % reduction in VC post PMVR had smaller left atrial and left ventricular end diastolic volumes. Faletra et al have authored a side by side comparison of fluoroscopy, 2D and 3D TEE [62], as well as a detailed review of the role of RT3D TEE in percutaneous edge-to-edge mitral repair [63•]. A recent novel case report describes intraprocedural RT3D TEE with stereovision or depth vision capability provided by the use of red-blue/cyan glasses by the operator [64•]. The review by Delgado et al outlines the role of 3DE in the multimodality imaging of PMVR [65].

Valve in Valve Procedures

First reported in 2009 by Cheung and colleagues, the transcatheter mitral valve-in-valve implantation is an off-label option for high-risk patients with degenerated bioprosthetic surgical valves [66]. The procedure can be performed via an antegrade transfemoral approach, a retrograde transapical approach or by using both routes to create a rail. An appropriate valve is chosen based on at least 10 % oversizing of the inner diameter of the existing mitral bioprosthesis. The procedure is done under general anesthesia with fluoroscopic and TEE guidance. RT3D TEE may be superior in accurate sizing, and guiding precise positioning of the valve [67, 68]. Postdeployment, 2D TEE is used for assessing the gradient,

degree of MR and other complications. RT3D TEE is complementary in ensuring appropriate seating and stability of the new valve, assessing for clots and differentiating new perivalvular from transvalvular MR by 3D color Doppler.

Percutaneous Mitral Balloon Valvuloplasty

PMBV is a long established treatment option for selected patients with symptomatic mitral stenosis in the absence of significant mitral regurgitation. Patient selection is based on clinical profile and favorable valve anatomy [31, 69]. An echocardiographic assessment of the extent of commissural calcification, fusion, and involvement of subvalvar apparatus is required. 3D TEE provides a superior description of commissural calcification [70] and fusion [41] from the LA and LV perspectives, and may identify the safest site for transeptal puncture with respect to surrounding structures. Special care is taken to avoid the aorta while allowing adequate room to maneuver the catheter and balloon tip coaxially towards the mitral orifice, thereby helping in appropriate sizing as well. The balloon is then positioned for inflation without damaging the sub valvar structures. 3D TEE is superior in post valvuloplasty detection of commissural splitting and leaflet tears [71].

Advantages

The well recognized advantages of traditional 2D TEE apply to 3D TEE as well – widely applicable, close proximity to the MV allowing excellent visualization, low complication rate, absence of radiation, and contrast exposure. Additionally, in contrast to the need for frequent transducer manipulation with 2D TEE to appreciate the full extent of the MV pathology, a panoramic view of the MV and surrounding anatomy including the left atrial appendage, pulmonary veins, atrial septum, and aortic valve is readily obtained by 3D TEE in real time from a single transducer position and with minimal or no probe manipulation. Dual capability transducers permit swapping between 2D and 3D via a touchscreen function. The "en face" views from the left atrial or left ventricular perspectives are unique to 3D echo. They facilitate a visually intuitive depiction of the MV in anatomical context to neighboring structures, catheters, and intracardiac devices that can be easily appreciated by surgeons, interventionalists, and imagers. 3D TEE can, therefore, enhance patient selection, procedural planning and safety. "Off line" quantitative analyses promote mechanistic understanding of the normal and diseased MV, and aid refinement of procedural and surgical techniques.

Limitations

Current 3DE limitations include low frame rates with color flow imaging and real time single beat acquisitions, and drop out artifacts. Multi-beat acquisition is frequently associated with stitch artifacts from respiratory motion and arrhythmias. Volumetric assessments require offline processing and analysis, which can be time consuming and laborious.

Conclusions

3DE is an imaging modality in evolution. Technological advances will, undoubtedly, address current limitations. Current literature supports that it has a sizable incremental advantage over 2DE in the assessment of MV disease. While 2D echo remains essential, 3D TEE is well on its way to becoming widely integrated into clinical practice as part of multimodality imaging of the MV. Echocardiographers, interventionalists, and cardiac surgeons stand to gain from familiarity with the technique.

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