REVIEW

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Role of modern 3D echocardiography in valvular heart disease

Takahiro Shiota

Department of Medicine, Heart Institute, Cedars-Sinai Medical Center and University of California, Los Angeles, Los Angeles, CA, USA

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Correspondence to
Takahiro Shiota, M.D.
Department of Medicine, Heart Institute, Cedars-Sinai Medical Center, 8700 Beverly Blvd, Los Angeles, CA 90048, USA
Tel: +1-310-423-6889
Fax: +1-310-423-8571
E-mail: takahiro.shiota@cshs.org

Three-dimensional (3D) echocardiography has been conceived as one of the most promising methods for the diagnosis of valvular heart disease, and recently has become an integral clinical tool thanks to the development of high quality real-time transesophageal echocardiography (TEE). In particular, for mitral valve diseases, this new approach has proven to be the most unique, powerful, and convincing method for understanding the complicated anatomy of the mitral valve and its dynamism. The method has been useful for surgical management, including robotic mitral valve repair. Moreover, this method has become indispensable for nonsurgical mitral procedures such as edge to edge mitral repair and transcatheter closure of paravaluvular leaks. In addition, color Doppler 3D echo has been valuable to identify the location of the regurgitant orifice and the severity of the mitral regurgitation. For aortic and tricuspid valve diseases, this method may not be quite as valuable as for the mitral valve. However, the necessity of 3D echo is recognized for certain situations even for these valves, such as for evaluating the aortic annulus for transcatheter aortic valve implantation. It is now clear that this method, especially with the continued development of real-time 3D TEE technology, will enhance the diagnosis and management of patients with these valvular heart diseases.

Keywords: Echocardigraphy; Mitral valve; Aortic valve; Three-dimensional

INTRODUCTION

Echocardiography has been used to evaluate and diagnose patients with valvular heart disease for many years. New echocardiography methods with improved diagnostic accuracy have been proposed for over 40 years. In particular, 3-dimensional (D) echocardiography is now used clinically due to the development of the high-quality real-time transesophageal echocardiography (TEE). In general, 3D echocardiography allows visualization of cardiac structures such as the mitral valve (MV) from any spatial point of view. However, there are limitations to the currently available 3D ultrasound methods, especially the transthoracic version, due to its relatively low image quality and low time resolution. However, this method is widely used to evaluate valvular heart disease.

Herein, the author will discuss the clinical applications of 3D echocardiography for the mitral, aortic, and tricuspid valves (TVs) individually.

THE MITRAL VALVE

Among the four heart valves, 3D echocardiography, especially real-time 3D TEE, is most useful for the diagnosis and management of MV conditions.

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MITRAL REGURGITATION

Mitral regurgitation (MR) is fundamentally classified as either organic or functional in etiology. Organic MR is usually caused by degenerative abnormalities, including valve prolapse and/or flail. Locating the prolapse and/or flail of the mitral leaflet (medial, central, and lateral) and its geometry is essential for selecting a surgical and/or transcatheter correction technique. However, conventional 2D echocardiography requires multiple views of the MV and mental reconstruction of the 3D image of the diseased structure. Many investigators have reported the usefulness of 3D echocardiography for visualizing, localizing, and quantifying MV abnormalities in patients with MR [1-12]. The superiority of transthoracic real-time 3D echocardiography over conventional 2D echo methods in analyzing the anatomy of MV in patients with MR has been reported multiple times since the introduction of transthoracic real-time 3D echocardiography [6,8-10,12,13].

The use of TEE has also been repeatedly reported to evaluate MV anatomy in patients with MR [1,2,5,11]. However, 3D TEE was not clinically accepted until user-friendly real-time 3D TEE was introduced circa 2007. In 2008, Sugeng et al. [11] reported clinical use of real-time 3D TEE in 211 patients. Excellent visualization of the MV (85% to 91% for all scallops of both MV leaflets, the interatrial septum 84%, left atrial appendage 86%, and left ventricle 77%) was observed. This real-time 3D TEE yields high-quality images of the MV (Fig. 1). Since these initial publications, many reports have described the use of real-time 3D TEE for imaging MV pathology [14-39]. For example, in 2013, we published a study on the superiority of real-time 3D TEE

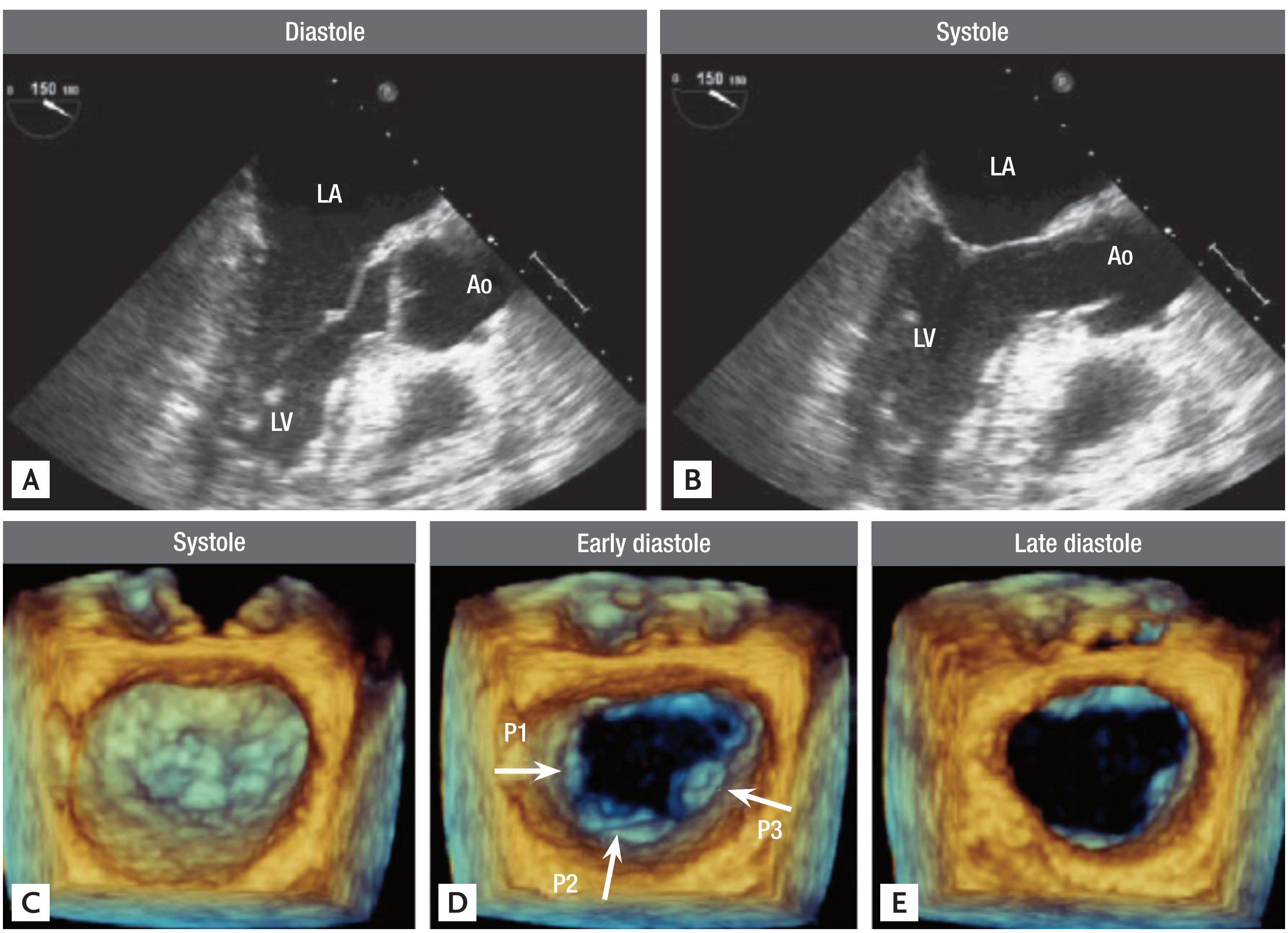

Figure 1. Normal mitral valve imaged by 2-dimensional (D) echo (A, a long axis view in diastole; B, in systole) and real-time 3D transesophageal echocardiography (C, a view from the left atrium in systole; D, in eerily diastole; E, in late diastole). Arrows indicate each leaflet: lateral P1, middle P2, and medial P3. Ao, aorta; LA, left atrium; LV, left ventricle.

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over 2D TEE for measuring the gap and width of a MV prolapse and flail [22]. As seen in this paper and many others, real-time 3D TEE provides a better overall perspective of the MV than 2D TEE, including the shape of the prolapse and the exact size and location of the MV, with the use of the so-called surgical view (Fig. 2). This specific view facilitates communication between echocardiologists and surgeons and interventionists.

In patients with MR, color Doppler capability, which was initially introduced in reconstruction 3D systems, then later in real-time 3D transthoracic and real-time 3D TEE, can provide 3D images of regurgitant flow jets (Fig. 3) and flow convergence [40-48]. The location and size of the flow convergence zone or proximal isovelocity surface area (PISA) can determine the location of the regurgitant orifice and severity of MR [48]. Such information, especially on the location of the regurgitant orifice, is critical for selection of an appropriate treatment protocol; i.e., either surgery or the edge-to-edge clip procedure [49]. For instance, for the edge-to-edge clip procedure, A2/P2 MR is preferred for the commissural origin of MR in the ongoing clinical mitral clip trial, Clinical Outcomes Assessment of Percutaneous Treatment, in the United States.

Also, color Doppler 3D echocardiography has demonstrated that in many conditions the flow convergence zone is not hemispherical, such as for irregular or asymmetrical orifices, and in patients with functional or ischemic MR [47,50-53]. Multiple investigators have proposed more realistic geometric shapes for flow convergence zones, such as a hemiellipse or hemiellipsoid, to obtain more accurate regurgitant volumes [46,53,54].

The vena contracta (VC) area determined by color Doppler 3D echocardiography has been repeatedly found useful for quantitatively defining the MR severity [55-59]. These studies also noted a variety of VC shapes, including a curved VC, in functional MR patients (Fig. 4) [57]. Another recent study using 3D TEE demonstrated multiple VC shapes in a patient and added them together to determine MR severity [58]. The idea of 3D VC seems attractive because it is independent of geometric assumptions. However, the location

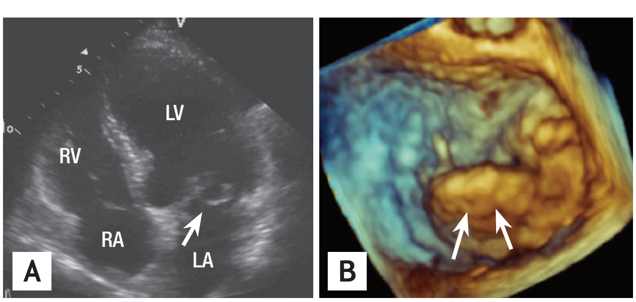

Figure 2. Mitral valve prolapse imaged by (A) 2-dimensional (D) transthoracic echocardiography (arrow) and (B) real-time 3D transesophageal echocardiography (arrows). LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

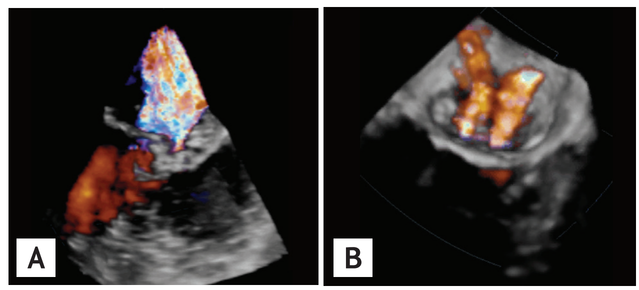

Figure 3. Two types (A, one continuous jet; B, two separate jets) of functional mitral regurgitation jet clearly distinguished by color Doppler 3-dimensional transesophageal echocardiography.

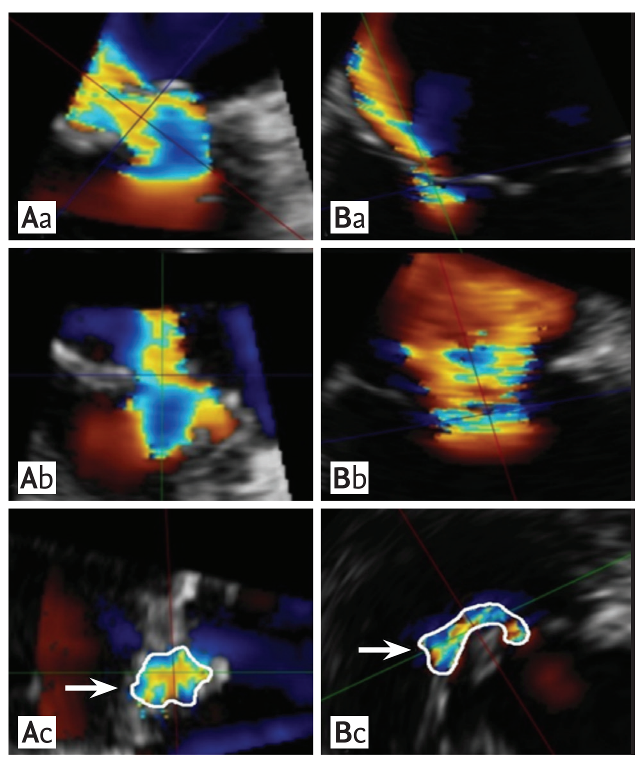

Figure 4. Difference in the shape of vena contracta from degenerative mitral valve disease (Ac) and functional mitral valve disease (Bc) delineated by color Doppler 3-dimensional transesophageal echocardiography.

and size of VC from the PISA to the distal jet may vary depending on the operator and cutting the VC in the exact plane in 3D space is difficult, especially when the jet is quite eccentric. In addition, the cutoff value of the VC area for severe MR has not been firmly established. Practically, therefore, one may prefer the size of the PISA when it is appropriately imaged with proper Nyquist limits to the 3D VC for determining MR severity. Both methods can be used together with classic regurgitant jet imaging to increase accuracy.

As mentioned above, edge-to-edge clip repair was approved for high-risk surgical patients with severe degenerative MR in the United States in October 2013. In the catheterization laboratory, 3D TEE can assist the positioning of the clip on the MV orifice, grasping of both MV leaflets, and evaluating the result, including visualization of the residual MR (Fig. 5) [60-63]. At the author's institution, 3D TEE is indispensable for the success of this procedure. We reported previously the value of real-time 3D TEE for determining the unique shape, size and location of the atrial septal defect created by septal puncture with the large catheter and its sheath (24 F) used for the clip procedure [64].

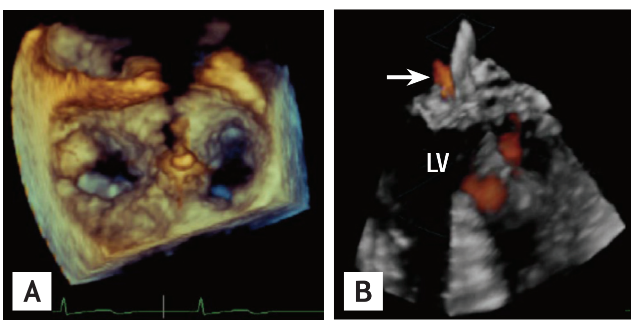

Figure 5. Mitral valve and residual small regurgitant jet (an arrow) imaged by 3-dimensional transesophageal echocardiography (A) without and (B) with color Doppler after clip procedure. LV, left ventricle.

Regarding postoperative evaluation of MV repair or replacement, 3D TEE has been shown to facilitate visualization of the entire structure of the new artificial valve [65]. In addition, color Doppler 3D TEE can delineate the location of the paravalvular MR, especially useful for transcatheter closure of the leak [65-68]. In our study, color Doppler 3D TEE showed the exact location of the circumferential orifice of paravalvular regurgitation around the artificial MV, thus assisting the transcatheter device closure procedure [66]. Fig. 6 shows a case of postoperative residual paravalvular MR. Color Doppler 3D TEE showed the exact location of the residual MR, which allowed immediate successful surgical correction (Fig. 6).

MITRAL STENOSIS

Mitral stenosis (MS) is usually caused by rheumatic MV

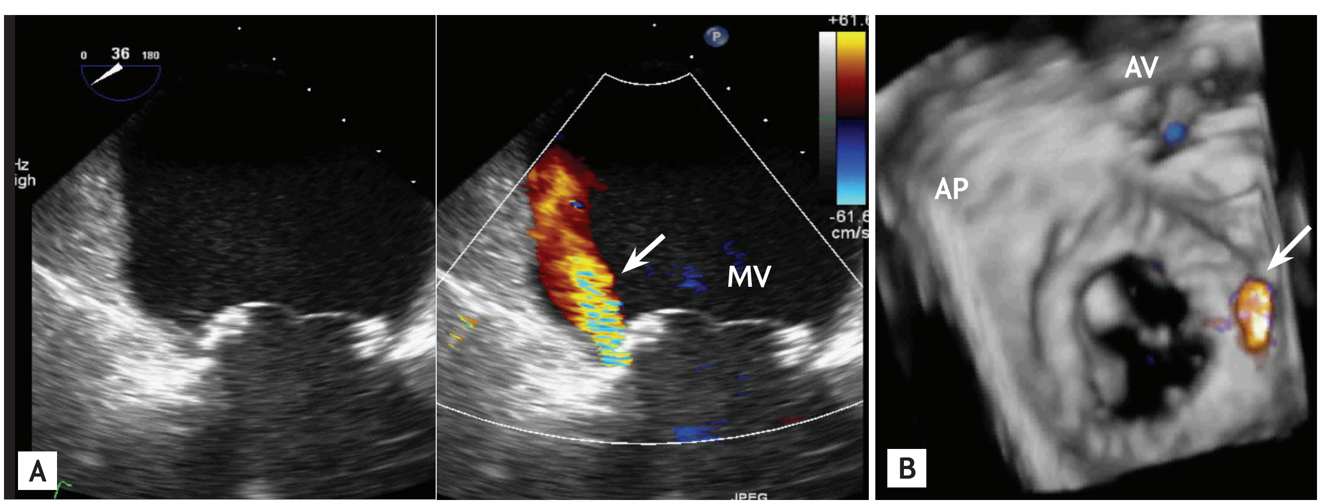

Figure 6. A residual mitral regurgitation immediately after surgical mitral valve replacement (a tissue valve). (A) The upper panel shows 2-dimensional (D) transesophageal echocardiography (TEE) image. (B) Color Doppler 3D TEE image could demonstrate the exact location of the residual mitral regurgitation (MR) (arrow) which could assist in second pump correction of the MR. AP, appendage; AV, aortic valve; MV, mitral valve.

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disease. Fusion of the commissure is the major cause of the stenosis. Conventional 2D echocardiography has been widely used to determine the smallest valve area. However, 2D echocardiography can only minimally visualize the entire MV and the subvalvular apparatus, resulting in erroneous measurement of the smallest valve area. Three-dimensional echocardiography has been reported to be superior to conventional 2D echocardiography for determining the smallest area and visualizing morphological abnormalities [6,29,32,69-78]. In an early study, 3D echocardiography provided accurate and highly reproducible measurements of the mitral valve area (MVA) and was easily performed via an apical approach [70]. In another study, a real-time 3D echocardiographic system was used for MV planimetry [72]. This was reportedly more accurate than the Gorlin method for measurement of the valve area. The authors concluded that 3D echo planimetry may be a better reference method than the Gorlin method in terms of assessing the severity of rheumatic MS [72]. The recently introduced real-time 3D TEE yields striking images of MS in patients (Fig. 7) [79]. Not only the stenosis but also the shape, location, and anatomical abnormalities of the MV leaflets, such as heavy calcification, are visualized intuitively. In a clinical study of 43 patients with rheumatic MV stenosis, 3D TEE allowed excellent assessment of commissural fusion and MVA planimetry (Fig. 7) [75]. Also, a recent Korean study showed a tendency of overestimation of MVA by 2D planimetry and concluded that 3D TEE should be considered for accurate MVA assessment, especially in patients with a large left atrium and large angle between the lines of the true MV tip and the echo beam-to-the tip [38].

Additionally, in 63 consecutive patients with rheumatic MS, valve area assessment using the flow convergence (or PISA) method with a newly developed single-beat real-time 3D color Doppler echocardiography was reportedly feasible in a clinical setting and more accurate than the conventional 2D PISA method [79]. This new type of real-time 3D TEE seems clinically feasible and useful with and without color Doppler.

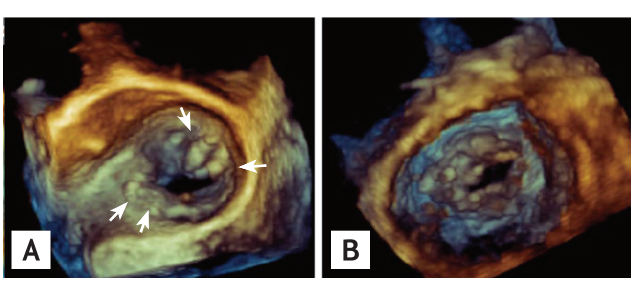

Figure 7. Three-dimensional transesophageal echocardiography images of a stenotic mitral valve (A) from the left atrium and (B) from the left ventricle. Arrows indicate severe calcifications.

APPLICATION OF 3D ECHOCARDIOGRAPHY FOR BALLOON MITRAL VALVULOPLASTY

Application of 3D echocardiography for mitral valvuloplasty has also been reported [80-83]. In one of these studies, an old type of reconstruction 3D TEE enabled visualization of the MV, allowing visualization of commissural splitting and leaflet tears not seen on 2D echocardiography [80].

Thanks to the recent development of relatively high quality transthoracic real-time 3D echocardiography, improvement of valve area and changes in valve geometry after balloon valvuloplasty were reported in a clinical study [81]. In this study, transthoracic real-time 3D echo, instead of multiplane TEE 3D reconstruction, was employed to measure the valve area in 29 patients with rheumatic MS who underwent balloon valvuloplasty [81]. The authors concluded that transthoracic real-time 3D echocardiography is a feasible and accurate technique for measuring the MVA in patients with rheumatic MV stenosis [81]. In another study, real-time 3D echocardiography improved visualization of valvular anatomy and provided a unique assessment of the extent of commissural splitting [84].

Anwar et al. [85] proposed a new score system based on real-time transthoracic 3D echocardiography that was feasible and highly reproducible for the assessment of MV morphology in patients with MS. According to this study, the score system can provide incremental prognostic information in addition to the Wilkins score [85].

More recently, real-time 3D TEE showed its superiority for evaluating the efficacy of mitral valvuloplasty due to its higher-resolution MV images compared to the old-type reconstruction 3D TEE and transthoracic real-time 3D echocardiography [86].

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THE MITRAL ANNULUS

Real-time 3D echocardiographic methods have been used to evaluate non-planarity and area changes in the mitral annulus in animals and humans [87-98]. Extracted 3D images obtained with multiplane TEE can also be used to evaluate non-planarity and area changes of the mitral annulus in patients with an annuloplasty ring [99,100]. The saddle-shaped geometry of the mitral annulus has been repeatedly reported and confirmed by 3D echocardiography, and its assessment of mitral annular size and function in control subjects and patients with cardiomyopathy was reportedly accurate and well correlated with magnetic resonance imaging (MRI) findings [101]. Three-dimensional echocardiography allowed quantitative analysis of not only the annulus geometry but also the valve tethering or tenting in ischemic cardiomyopathy and idiopathic cardiomyopathy [91,94,102,103]. In one recent study of real-time 3D TEE, the mitral annulus in functional MR was significantly larger, rounder, and flatter, and dilated further and became more flattened at late systole, compared to controls [95]. Considering the clinical importance of annuloplasty for managing such patients with MR, detailed geometric evaluation should be performed to improve surgical results. Real-time 3D TEE showed that in 35 patients undergoing elective surgical aortic valve replacement, the mitral annulus underwent significant geometric changes immediately postoperatively. A 16.3% reduction in the mitral annular area was observed. The anterior annulus underwent a greater reduction in length compared to the posterior annulus, which suggested mechanical compression by the prosthetic valve [98].

THE AORTIC VALVE

Considering its 3D structure, the aortic valve may prove to be one of the most important applications of 3D echocardiography [104-107].

AORTIC VALVE REGURGITATION

Aortic regurgitation (AR) is caused by valvular abnormalities such as a bicuspid aortic valve, senile degenerative (calcification) valvular disease, and rheumatic valve disease and also by aortic annular dilations such as Marfan syndrome and annular ectasia. In addition, another new type of AR has recently drawn the attention of cardiologists, interventionists, and surgeons due to the development of transaortic valve replacement (TAVR). AR post-TAVR is paravalvular in nature, and its severity is often difficult to determine. Three-dimensional echocardiography, especially real-time 3D TEE, is particularly important for the prevention and diagnosis of this type of AR [108,109]. In general, the role of 3D echocardiography in AR evaluation, including this post-TAVR AR, is probably twofold: providing detailed anatomical assessment of the valve and leakage location and size, and quantitative evaluation of the severity of AR [110].

Three-dimensional echocardiography, especially re-

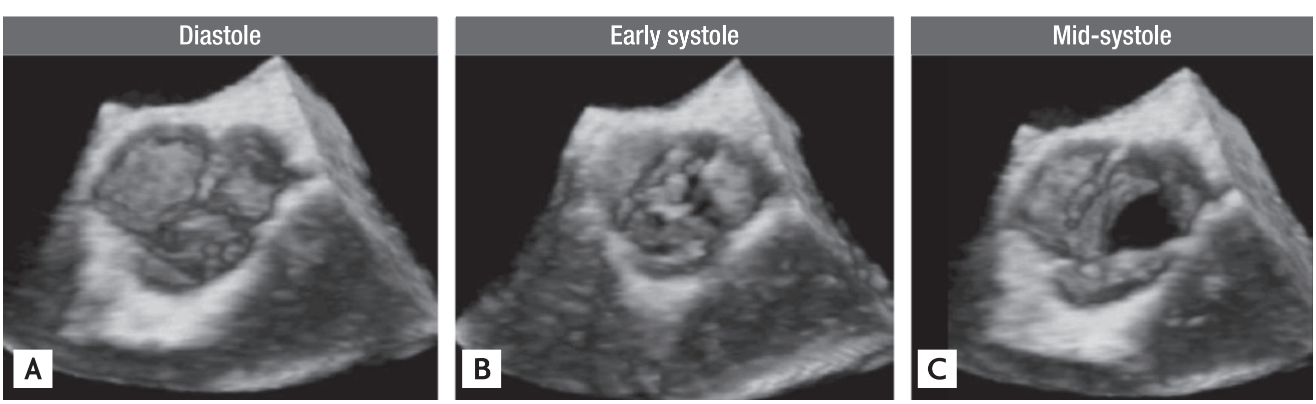

Figure 8. Three-dimensional transesophageal echocardiography images of normal aortic valve in a cardiac cycle (A, diastole; B, early systole; C, mid-systole).

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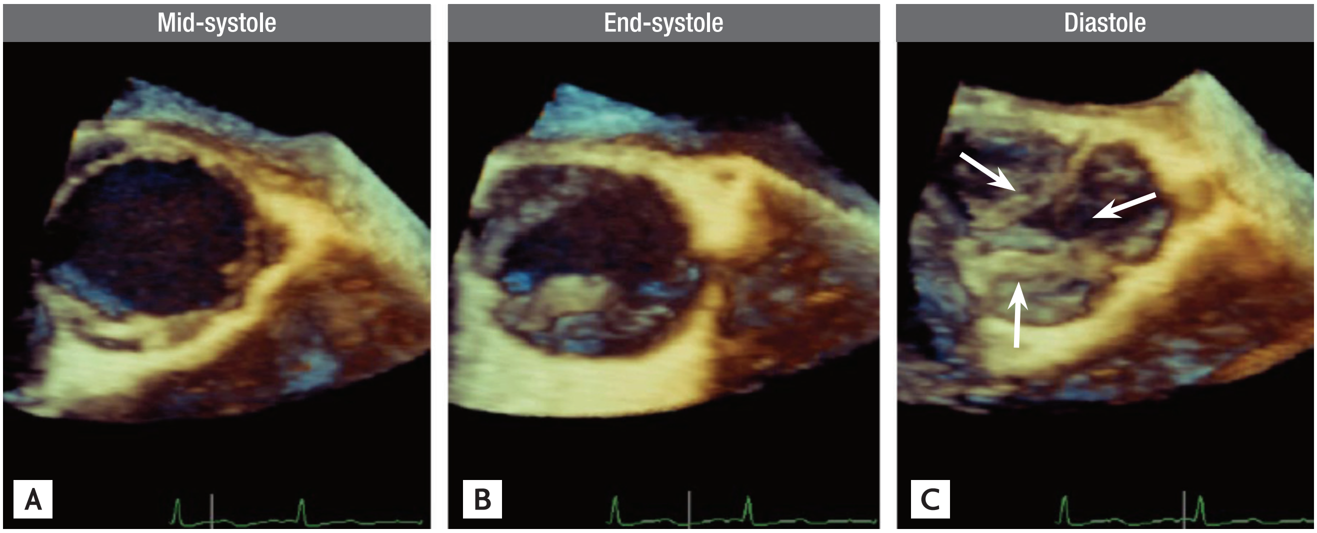

Figure 9. Three-dimensional transesophageal echocardiography images of an aortic valve with severe aortic valve regurgitation. (A) Panel shows the valve in mid systle, (B) panel in end systole, and (C) panel in diastole. Arrows indicate a large regurgitant orifice viewed from the ascending aorta.

al-time 3D TEE, has an advantage over 2D echo methods for visualizing the aortic valve anatomy in depth (Figs. 8 and 9) [111]. We reported that real-time 3D TEE could reveal characteristic anatomical differences between type I (annular dilation) and type II (prolapsed) AR [111].

As for AR severity, quantitative assessment of AR with 2D echocardiography remains challenging. A recent clinical study in 32 patients with AR reported the accuracy of 2D and 3D transthoracic echocardiography (TTE) for AR quantification, using 3D three-directional velocity-encoded (VE)-MRI as the reference method. With color Doppler TTE, the 2D area was calculated using PISA. From the 3D TTE multiplanar reformation data, the 3D area was calculated using planimetry of the VC. Regurgitant volumes were obtained by multiplying the 2D and 3D area by the velocity-time integral of the AR jet, then compared with those obtained using VE-MRI. For the entire population, the 3D TTE-derived regurgitant volume was highly correlated to the VE-MRI-derived regurgitant volume (r = 0.94 and –13.6 to 15.6 mL per beat, respectively). In contrast, the 2D TTE-derived regurgitant volume showed a modest correlation and large limits of agreement with the VE-MRI (r = 0.70 and –22.2 to 32.8 mL per beat, respectively). The investigators concluded that AR regurgitant volume quantification using 3D TTE is accurate, and is particularly advantageous over 2D TTE in patients with eccentric jets [112]. However, AR volume quantification is not often required in a clinical setting. Thus, 3D echo quantification as reported above may be impractical in many cases.

AORTIC VALVE STENOSIS

Aortic stenosis (AS) is either congenital (usually bicuspid) or acquired (degenerative calcific valve). The normal aortic valve area is ~3 to 4 cm^2. In this current aging population, degenerative calcific aortic valve stenosis is the most commonly detected by conventional 2D echocardiography. In one clinical study on AS, 3D echocardiographic methods for planimetry of the aortic valve area showed good agreement with the standard TEE technique in patients with AS [106]. Also, 3D planimetry methods were at least as good as standard TEE and had better reproducibility [106]. The authors concluded that 3D aortic valve planimetry is a novel non-invasive technique that provides an accurate and reliable quantitative assessment of AS [106]. However, the image quality of the aortic valve with TTE is often suboptimal, which may hinder measurement of the smallest valve area. TEE is certainly superior to TTE in this regard. Multiple publications have reported the usefulness of 3D TEE, especially real-time 3D TEE for this purpose [113,114]. We reported better agreement between the

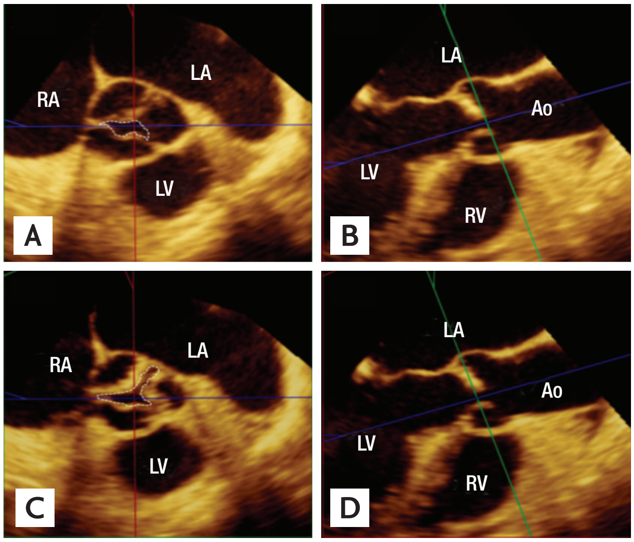

Figure 10. The measurement of aortic valve area by three-dimensional transesophageal echocardiography. (A, B) The tip of the aortic valve was obtained as the smallest possible area. (C, D) The shape and area of the aortic valve changed in a trivial different plane from the tip. The dotted lines indicate aortic valve area at each level. Ao, aorta; LA, left atrium; LV, left ventricle; RA, right atrium.

continuity aortic valve area and planimetry area with the use of real-time 3D TEE than with conventional 2D echocardiography [114]. The advantage of 3D over 2D echocardiography is evidenced by the ability of the 2D plane to search for the smallest valve area in the 3D space (Fig. 10) [114].

THE AORTIC ANNULUS

The geometry and size of the left ventricular outflow tract (LVOT) or the aortic annulus has become the focus of 3D computed tomography (CT) and echo research because of the development of TAVR and its residual AR. Greater than mild paravalvular AR after TAVR is reportedly a poor prognostic indicator. Thus, proper sizing of the aortic annulus is necessary for the success of TAVR. CT and 3D echocardiography, especially real-time 3D TEE, have contributed to the analysis of the shape and size of the aortic annulus or LVOT where the new aortic valve will be placed. Three-dimensional imaging techniques, including 3D echocardiography, can demonstrate that the shape of the annulus is not circular, but oval. Thus, 3D methods, including CT and 3D TEE, should be used to evaluate the aortic annulus area because 2D imaging techniques provide only a sagittal view, which may underestimate it [109,114-117]. In conjunction with this, assessment of LVOT stroke volume with 3D echocardiography is more accurate than that by the conventional 2D continuity method [107,114]. Thus, 3D echocardiography is highly recommended over 2D echo for determining the LVOT area [114].

Regarding the subaortic membrane, multiplane analysis of 3D datasets is reportedly a sensitive and accurate method for delineation of morphological details of discrete sub-AS, adding to information gained from 2D echocardiography [118]. Recently, we reported the value of real-time 3D TEE for evaluating dynamic changes in the LVOT in both the subaortic membrane and in obstructive hypertrophic cardiomyopathy (Fig. 11) [119].

THE TRICUSPID VALVE

Assessment of TV size and function plays an important role in a number of disease states. However, all three TV leaflets (septal, anterior, and posterior) cannot be visualized in one cross-sectional view using either transthoracic or transesophageal 2D echocardiography. In contrast, 3D echocardiography allows visualization of the entire TV from any perspective (Fig. 12). This capability significantly improves our understanding of the pathophysiological mechanism underlying various TV diseases.

TRICUSPID VALVE REGURGITATION

Causes of tricuspid regurgitation (TR) may be classified into two major categories, primary and secondary, as in MR. The former is caused by an anatomical abnormality of the TV itself while the latter is caused not by the valve itself, but by abnormalities of the surrounding or supporting structures, such as tricuspid annular dilation and/or RV dilation and dysfunction and pulmonary hypertension. Two-dimensional echocardiography is widely used to evaluate the cause and severity of TR. However, its clinical utility is far from perfect.

Three-dimensional echocardiography has been reported to be advantageous over 2D echocardiography

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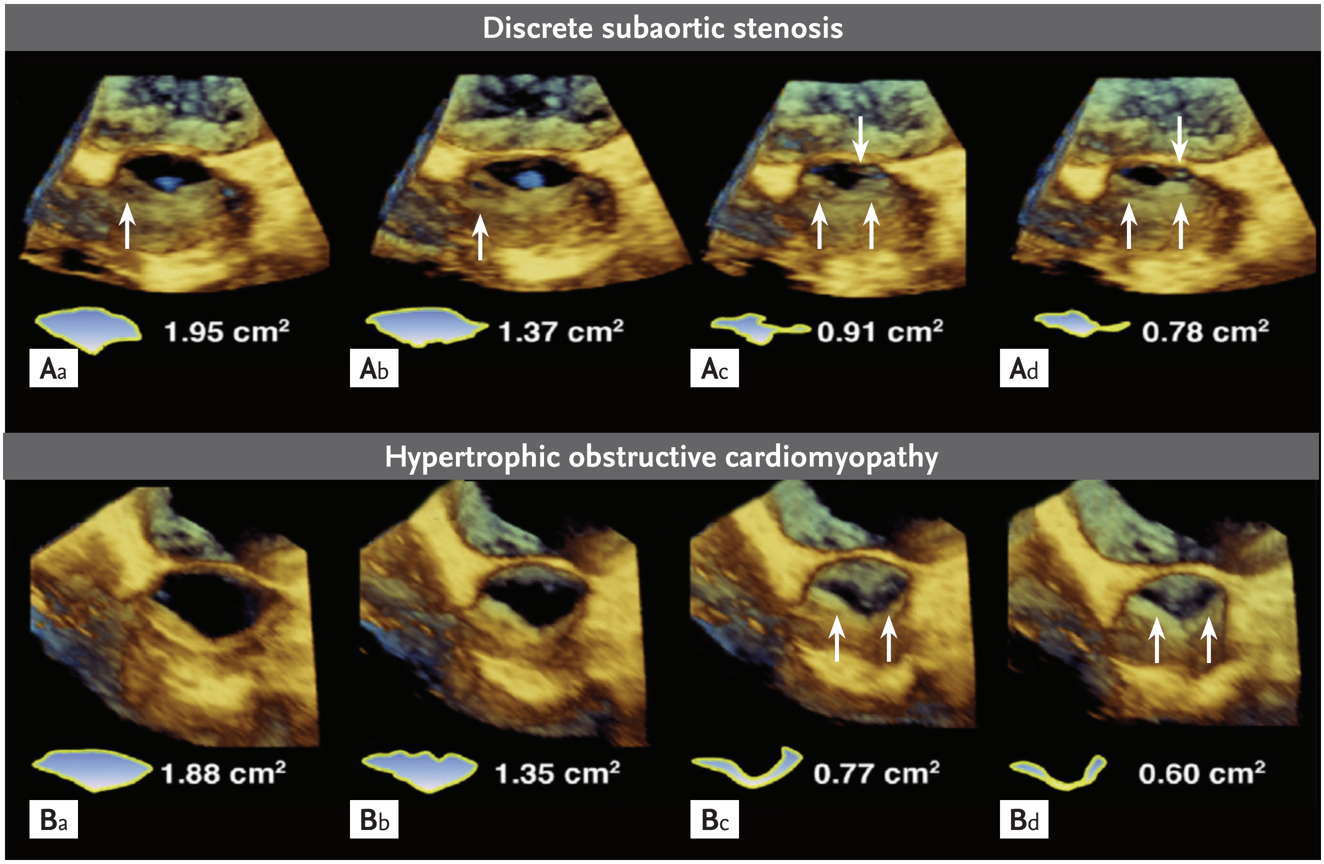

Figure 11. Real-time three-dimensional transesophageal images, showing the difference in the shape of left ventricular outflow tract (LVOT) between discrete subaortic stenosis (DSS) and hypertrophic obstructive cardiomyopathy. (A) The DSS images show the almost oval or flat shape of the LVOT (Ad) and subaortic membrane with small fenestration at left upper site of membrane (Aa and Ab, arrow). The thin membranous structure changes its angle to decrease the LVOT area along the blood stream (Ac and Ad, arrows). (B) In hypertrophic obstructive cardiomyopathy, the shape of the LVOT is a V formation or two separate open spaces due to systolic anterior motion of mitral anterior leaflet (Bc and Bd, arrows).

for evaluation of the anatomical abnormalities of the TV and the location of the TR orifice. Primary TR is caused by a variety of anatomical abnormalities that can be better visualized using 3D than 2D echocardiography, including an apically located leaflet in Epstein disease, or a thickened and restricted leaflet in carcinoid syndrome [120-126]. One important finding with 3D echocardiography is lead-derived TR related to a pacer/device. Multiple publications have reported the usefulness of 3D echocardiography for detecting the location of the lead and its relationship to significant TR [127-129]. In one of these studies, 45 of 100 patients showed device-lead TV leaflet interference. The septal leaflet was the most commonly affected (n = 23). On multivariate analysis, the preimplantation VC width and the presence of an interfering lead were independently associated with postdevice TR. Additionally,

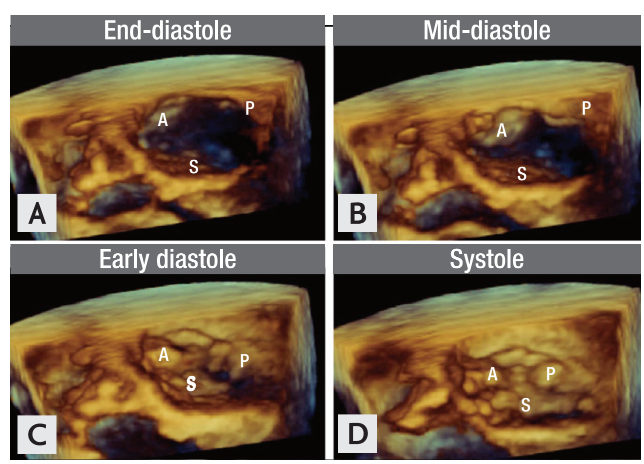

Figure 12. Three-dimensional transesophageal close up views of the normal tricuspid valve in a cardiac cycle. (A) Panel shows the tricuspid valve in end-diastole, (B) in mid-diastole, (C) in early diastole, and (D) in systole. A, anterior cusp; P, posterior cusp; S, septal cusp.

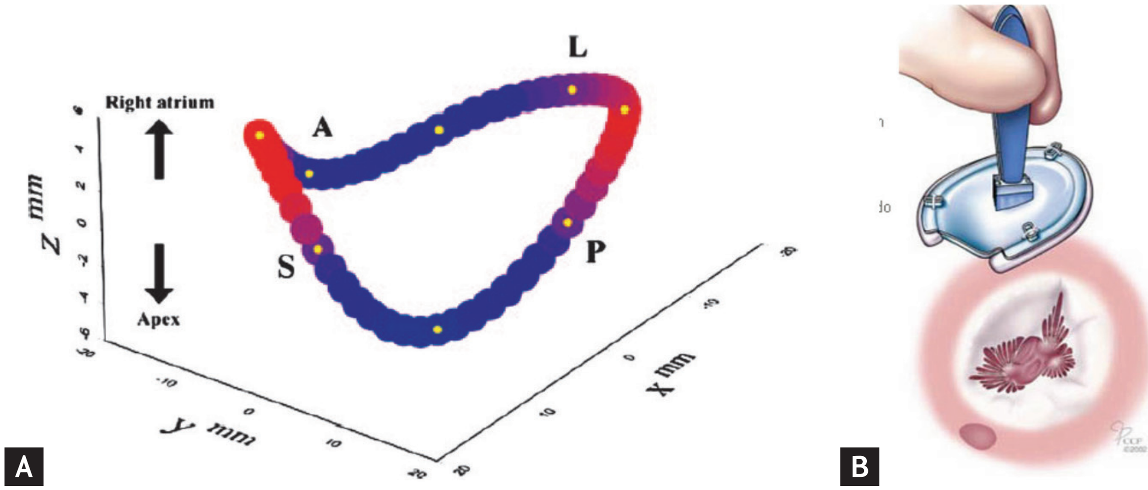

Figure 13. Reconstructed normal tricuspid annulus with the use of (A) 3-dimensional (D) echocardiography and (B) its application to the development of a new 3D ring for surgical annuloplasty. A, anterior; L, lateral; P, posterior; S, septal.

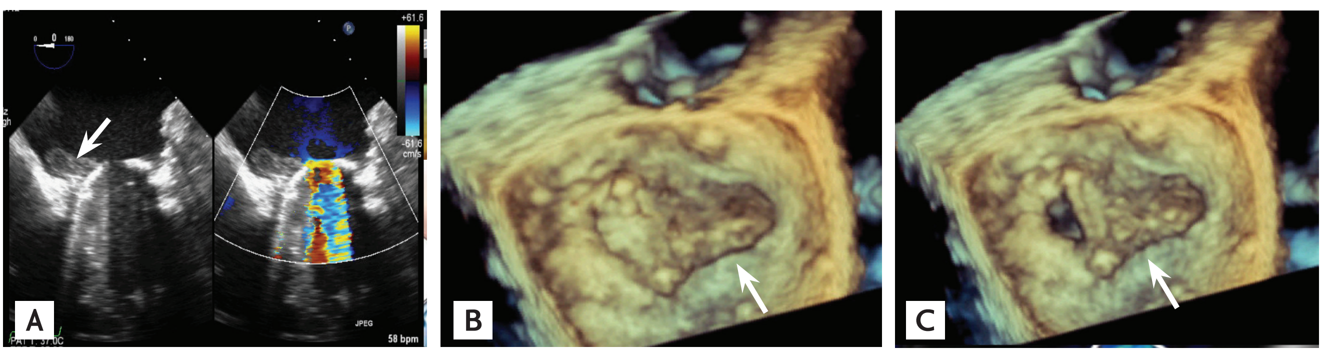

Figure 14. (A) Upper panel shows 2-dimensional (D) transesophageal (TEE) images without (left) and with (right) color Doppler in a patient with thrombus formation on the mechanical mitral valve (arrow). The lateral leaflet does not open. Lower panels show real-time 3D TEE images from the same patient, (B) left in systole and (C) right in diastole. A large thrombus is well visualized with 3D TEE (arrows).

the presence of an interfering lead was the only factor associated with TR worsening, increasing the likelihood of developing moderate or severe TR. The authors concluded that lead-leaflet interference as seen on 3D echocardiography is associated with TR after device lead placement, suggesting that 3D echocardiography should be used to assess lead interference in patients with significant TR [127].

One of the causes of secondary or functional TR is reportedly dilation of the tricuspid annulus, which can be determined using 3D echocardiography [130]. In another clinical 3D echocardiographic study of 54 patients with various degrees of functional TR, its severity was determined based mainly on septal leaflet tethering, septal-lateral annular dilatation, and the severity of pulmonary hypertension [131].

THE TRICUSPID ANNULUS

The geometry and size of the tricuspid annulus have been investigated using 3D echocardiography [101,102,130-133]. We found that a normal tricuspid annulus has a unique 3D geometry (Fig. 13) [130]. With the 3D geometric concept, a new annuloplasty ring for a tricuspid annulus was developed and used in patients with severe TR (Fig. 12) [134]. Short term results with this new annuloplasty ring appear to be satisfactory [135]. Three-dimensional

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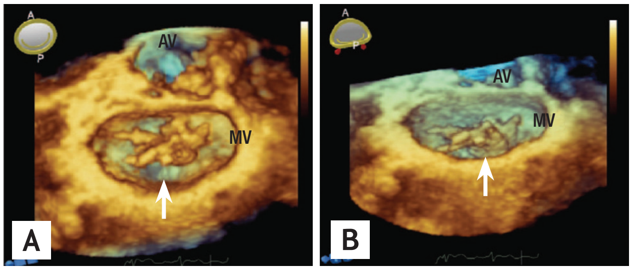

Figure 15. (A) En-face view of mitral valve with a vegetation attached to both anterior and posterior leaflets. Arrow indicates vegetation. (B) The same vegetation in (A) after rotation of the image and showing its complete morphology and spatial orientation, which could only be assessed with 3-dimensional echocardiography. AV, aortic valve; MV, mitral valve.

echocardiography has been valuable not only for understanding complicated cardiac structures but also for developing new strategies, such as this new annuloplasty ring, for treatment of patients.

INFECTIVE ENDOCARDITIS

The current diagnostic protocol for endocarditis does not include 3D echocardiography, mainly because 2D echocardiography, especially 2D TEE, is fully capable in this regard. The author admits that 3D TEE is less sensitive than 2D TEE for detecting small vegetations due to its lower image quality. However, the shape, location, and extension of the endocarditis findings, including vegetations, perforations, and abscesses, are evaluated with greater accuracy and in more detail than with conventional 2D echocardiography (Figs. 14 and 15) [20,65,136-138]. It is almost impossible to image the entirety of a complicated mobile vegetation with 2D echocardiography. In contrast, 3D echocardiography, especially real-time 3D TEE, facilitates visualization of the full extension and motion of the complicated vegetation in one view from any desired angle (Fig. 15). As a result, the maximum size of the vegetation was underestimated by 2D TEE as compared to 3D TEE (a mean difference of 3.2 mm) in our recent study [138].

In summary, 3D echocardiography has been shown to be useful for clarifying complicated valvular anatomy. In particular, real-time 3D TEE has reduced the technical and quality problems of previous 3D echocardiography and has resulted in widespread use of 3D echocardiography in patients with valvular heart disease.

Conflict of interest

No potential conflict of interest relevant to this article was reported.

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REFERENCES

1. Hozumi T, Yoshikawa J, Yoshida K, Akasaka T, Takagi T, Yamamuro A. Assessment of flail mitral leaflets by dynamic three-dimensional echocardiographic imaging. Am J Cardiol 1997;79:223-225.
2. Chauvel C, Bogino E, Clerc P, et al. Usefulness of three-dimensional echocardiography for the evaluation of mitral valve prolapse: an intraoperative study. J Heart Valve Dis 2000;9:341-349.
3. Macnab A, Jenkins NP, Bridgewater BJ, et al. Three-dimensional echocardiography is superior to multiplane transoesophageal echo in the assessment of regurgitant mitral valve morphology. Eur J Echocardiogr 2004;5:212-222.
4. Macnab A, Jenkins NP, Ewington I, et al. A method for the morphological analysis of the regurgitant mitral valve using three dimensional echocardiography. Heart 2004;90:771-776.
5. Delabays A, Jeanrenaud X, Chassot PG, Von Segesser LK, Kappenberger L. Localization and quantification of mitral valve prolapse using three-dimensional echocardiography. Eur J Echocardiogr 2004;5:422-429.
6. Sugeng L, Coon P, Weinert L, et al. Use of real-time 3-dimensional transthoracic echocardiography in the evaluation of mitral valve disease. J Am Soc Echocardiogr 2006;19:413-421.
7. Ryan LP, Salgo IS, Gorman RC, Gorman JH 3rd. The emerging role of three-dimensional echocardiography in mitral valve repair. Semin Thorac Cardiovasc Surg 2006;18:126-134.
8. Pepi M, Tamborini G, Maltagliati A, et al. Head-to-head comparison of two- and three-dimensional transthoracic and transesophageal echocardiography in the localization of mitral valve prolapse. J Am Coll Cardiol 2006;48:2524-2530.
9. Agricola E, Oppizzi M, Pisani M, Maisano F, Margonato A. Accuracy of real-time 3D echocardiography in the

evaluation of functional anatomy of mitral regurgitation. Int J Cardiol 2008;127:342-349.

10. Hirata K, Pulerwitz T, Sciacca R, et al. Clinical utility of new real time three-dimensional transthoracic echocardiography in assessment of mitral valve prolapse. Echocardiography 2008;25:482-488.
11. Sugeng L, Shernan SK, Salgo IS, et al. Live 3-dimensional transesophageal echocardiography initial experience using the fully-sampled matrix array probe. J Am Coll Cardiol 2008;52:446-449.
12. Gutierrez-Chico JL, Zamorano Gomez JL, Rodrigo-Lopez JL, et al. Accuracy of real-time 3-dimensional echocardiography in the assessment of mitral prolapse: is transesophageal echocardiography still mandatory? Am Heart J 2008;155:694-698.
13. Zakkar M, Patni R, Punjabi PP. Mitral valve regurgitation and 3D echocardiography. Future Cardiol 2010;6:231-242.
14. Wei J, Hsiung MC, Tsai SK, et al. The routine use of live three-dimensional transesophageal echocardiography in mitral valve surgery: clinical experience. Eur J Echocardiogr 2010;11:14-18.
15. Tauras JM, Zhang Z, Taub CC. Incremental benefit of 3D transesophageal echocardiography: a case of a mass overlying a prosthetic mitral valve. Echocardiography 2011;28:E106-E107.
16. Siddiqi N, Seto A, Patel PM. Transcatheter closure of a mechanical perivalvular leak using real-time three-dimensional transesophageal echocardiography guidance. Catheter Cardiovasc Interv 2011;78:333-335.
17. La Canna G, Arendar I, Maisano F, et al. Real-time three-dimensional transesophageal echocardiography for assessment of mitral valve functional anatomy in patients with prolapse-related regurgitation. Am J Cardiol 2011;107:1365-1374.
18. Fattouch K, Murana G, Castrovinci S, et al. Mitral valve annuloplasty and papillary muscle relocation oriented by 3-dimensional transesophageal echocardiography for severe functional mitral regurgitation. J Thorac Cardiovasc Surg 2012;143(4 Suppl):S38-S42.
19. Faletra FF, Pedrazzini G, Pasotti E, Moccetti T. Side-by-side comparison of fluoroscopy, 2D and 3D TEE during percutaneous edge-to-edge mitral valve repair. JACC Cardiovasc Imaging 2012;5:656-661.
20. Thompson KA, Shiota T, Tolstrup K, Gurudevan SV, Siegel RJ. Utility of three-dimensional transesophageal echocardiography in the diagnosis of valvular perforations. Am J Cardiol 2011;107:100-102.
21. Martin A, White J, Pemberton J. Severe mitral regurgitation secondary to dehiscence of a mitral annuloplasty ring shown on 3D transoesophageal echocardiography. Heart Lung Circ 2012;21:194-195.
22. Izumo M, Shiota M, Kar S, et al. Comparison of real-time three-dimensional transesophageal echocardiography to two-dimensional transesophageal echocardiography for quantification of mitral valve prolapse in patients with severe mitral regurgitation. Am J Cardiol 2013;111:588-594.
23. Hoffmann R, Kaestner W, Altiok E. Closure of a paravalvular leak with real-time three-dimensional transesophageal echocardiography for accurate sizing and guiding. J Invasive Cardiol 2013;25:E210-E211.
24. Hien MD, Rauch H, Lichtenberg A, et al. Real-time three-dimensional transesophageal echocardiography: improvements in intraoperative mitral valve imaging. Anesth Analg 2013;116:287-295.
25. Havins J, Lick S, Boor P, Arora H, Ahmad M. Real time three-dimensional transesophageal echocardiography in partial posteromedial papillary muscle rupture. Echocardiography 2013;30:E179-E181.
26. Shroff H, Benenstein R, Freedberg R, Mehl S, Saric M. Mitral valve Libman-Sacks endocarditis visualized by real time three-dimensional transesophageal echocardiography. Echocardiography 2012;29:E100-E101.
27. Lee AP, Fang F, Jin CN, et al. Quantification of mitral valve morphology with three-dimensional echocardiography: can measurement lead to better management? Circ J 2014;78:1029-1037.
28. Maslow A, Mahmood F, Poppas A, Singh A. Three-dimensional echocardiographic assessment of the repaired mitral valve. J Cardiothorac Vasc Anesth 2014;28:11-17.
29. Kutty S, Colen TM, Smallhorn JF. Three-dimensional echocardiography in the assessment of congenital mitral valve disease. J Am Soc Echocardiogr 2014;27:142-154.
30. Kocabas A, Ekici F, Cetin I, Aktas D. Three-dimensional echocardiographic evaluation of a patient with double-orifice mitral valve, bicuspid aortic valve, and coarctation of aorta. Echocardiography 2014;31:E33-E34.
31. Jung HJ, Yu GY, Seok JH, et al. Usefulness of intraoperative real-time three-dimensional transesophageal echocardiography for pre-procedural evaluation of

 http://dx.doi.org/10.3904/kjim.2014.29.6.685

mitral valve cleft: a case report. Korean J Anesthesiol 2014;66:75-79.
32. Jain S, Malouf JF. Incremental value of 3-D transesophageal echocardiographic imaging of the mitral valve. Curr Cardiol Rep 2014;16:439.
33. Faletra FF, Pedrazzini G, Pasotti E, et al. 3D TEE during catheter-based interventions. JACC Cardiovasc Imaging 2014;7:292-308.
34. Cobey FC, Swaminathan M, Phillips-Bute B, et al. Quantitative assessment of mitral valve coaptation using three-dimensional transesophageal echocardiography. Ann Thorac Surg 2014;97:1998-2004.
35. Berkowitz E, Kronzon I. Isolated accessory mitral valve: identification and anatomic description using 3D transesophageal echocardiography. Eur Heart J Cardiovasc Imaging 2014;15:596.
36. Sordi M, Brochet E, Messika-Zeitoun D. Mitral paravalvular leak detected by three-dimensional transoesophageal echocardiography. Arch Cardiovasc Dis 2013;106:627-628.
37. Ozkan M, Gursoy OM, Astarcioglu MA, et al. Real-time three-dimensional transesophageal echocardiography in the assessment of mechanical prosthetic mitral valve ring thrombosis. Am J Cardiol 2013;112:977-983.
38. Min SY, Song JM, Kim YJ, et al. Discrepancy between mitral valve areas measured by two-dimensional planimetry and three-dimensional transoesophageal echocardiography in patients with mitral stenosis. Heart 2013;99:253-258.
39. Looi JL, Lee AP, Wan S, et al. Diagnosis of cleft mitral valve using real-time 3-dimensional transesophageal echocardiography. Int J Cardiol 2013;168:1629-1630.
40. Shiota T, Sinclair B, Ishii M, et al. Three-dimensional reconstruction of color Doppler flow convergence regions and regurgitant jets: an in vitro quantitative study. J Am Coll Cardiol 1996;27:1511-1518.
41. De Simone R, Glombitza G, Vahl CF, Albers J, Meinzer HP, Hagl S. Three-dimensional color Doppler: a clinical study in patients with mitral regurgitation. J Am Coll Cardiol 1999;33:1646-1654.
42. Li X, Shiota T, Delabays A, et al. Flow convergence flow rates from 3-dimensional reconstruction of color Doppler flow maps for computing transvalvular regurgitant flows without geometric assumptions: an in vitro quantitative flow study. J Am Soc Echocardiogr 1999;12:1035-1044.
43. Sitges M, Jones M, Shiota T, et al. Real-time three-dimensional color doppler evaluation of the flow convergence zone for quantification of mitral regurgitation: validation experimental animal study and initial clinical experience. J Am Soc Echocardiogr 2003;16:38-45.
44. Sugeng L, Spencer KT, Mor-Avi V, et al. Dynamic three-dimensional color flow Doppler: an improved technique for the assessment of mitral regurgitation. Echocardiography 2003;20:265-273.
45. Sugeng L, Lang RM. Current status of three-dimensional color flow Doppler. Cardiol Clin 2007;25:297-303.
46. Yosefy C, Levine RA, Solis J, Vaturi M, Handschumacher MD, Hung J. Proximal flow convergence region as assessed by real-time 3-dimensional echocardiography: challenging the hemispheric assumption. J Am Soc Echocardiogr 2007;20:389-396.
47. Matsumura Y, Fukuda S, Tran H, et al. Geometry of the proximal isovelocity surface area in mitral regurgitation by 3-dimensional color Doppler echocardiography: difference between functional mitral regurgitation and prolapse regurgitation. Am Heart J 2008;155:231-238.
48. Altiok E, Hamada S, van Hall S, et al. Comparison of direct planimetry of mitral valve regurgitation orifice area by three-dimensional transesophageal echocardiography to effective regurgitant orifice area obtained by proximal flow convergence method and vena contracta area determined by color Doppler echocardiography. Am J Cardiol 2011;107:452-458.
49. Chikwe J, Adams DH, Su KN, et al. Can three-dimensional echocardiography accurately predict complexity of mitral valve repair? Eur J Cardiothorac Surg 2012;41:518-524.
50. Shiota T, Jones M, Yamada I, et al. Effective regurgitant orifice area by the color Doppler flow convergence method for evaluating the severity of chronic aortic regurgitation: an animal study. Circulation 1996;93:594-602.
51. Li XK, Irvine T, Wanitkun S, et al. Direct computation of multiple 3D flow convergence isovelocity surfaces from digital 3D reconstruction of colour Doppler data of the flow convergence region: an in vitro study with differently shaped orifices. Eur J Echocardiogr 2000;1:244-251.
52. Little SH, Igo SR, Pirat B, et al. In vitro validation of real-time three-dimensional color Doppler echocardiography for direct measurement of proximal isoveloc-

ity surface area in mitral regurgitation. Am J Cardiol 2007;99:1440-1447.

53. Matsumura Y, Saracino G, Sugioka K, et al. Determination of regurgitant orifice area with the use of a new three-dimensional flow convergence geometric assumption in functional mitral regurgitation. J Am Soc Echocardiogr 2008;21:1251-1256.
54. Hopmeyer J, He S, Thorvig KM, et al. Estimation of mitral regurgitation with a hemielliptic curve-fitting algorithm: in vitro experiments with native mitral valves. J Am Soc Echocardiogr 1998;11:322-331.
55. Kahlert P, Plicht B, Schenk IM, Janosi RA, Erbel R, Buck T. Direct assessment of size and shape of noncircular vena contracta area in functional versus organic mitral regurgitation using real-time three-dimensional echocardiography. J Am Soc Echocardiogr 2008;21:912-921.
56. Yosefy C, Hung J, Chua S, et al. Direct measurement of vena contracta area by real-time 3-dimensional echocardiography for assessing severity of mitral regurgitation. Am J Cardiol 2009;104:978-983.
57. Zeng X, Levine RA, Hua L, et al. Diagnostic value of vena contracta area in the quantification of mitral regurgitation severity by color Doppler 3D echocardiography. Circ Cardiovasc Imaging 2011;4:506-513.
58. Hyodo E, Iwata S, Tugcu A, et al. Direct measurement of multiple vena contracta areas for assessing the severity of mitral regurgitation using 3D TEE. JACC Cardiovasc Imaging 2012;5:669-676.
59. Maragiannis D, Little SH. Quantification of mitral valve regurgitation: new solutions provided by 3D echocardiography. Curr Cardiol Rep 2013;15:384.
60. Swaans MJ, Van den Branden BJ, Van der Heyden JA, et al. Three-dimensional transoesophageal echocardiography in a patient undergoing percutaneous mitral valve repair using the edge-to-edge clip technique. Eur J Echocardiogr 2009;10:982-983.
61. Altiok E, Paetsch I, Jahnke C, et al. Percutaneous edge-to-edge mitral valve repair: assessment of immediate post-procedural treatment effect using color 3-dimensional transesophageal echocardiography and cardiac magnetic resonance imaging. J Am Coll Cardiol 2011;58:e21.
62. Wunderlich NC, Siegel RJ. Peri-interventional echo assessment for the MitraClip procedure. Eur Heart J Cardiovasc Imaging 2013;14:935-949.
63. Schueler R, Momcilovic D, Weber M, et al. Acute changes of mitral valve geometry during interventional edge-to-edge repair with the MitraClip system are associated with midterm outcomes in patients with functional valve disease: preliminary results from a prospective single-center study. Circ Cardiovasc Interv 2014;7:390-399.
64. Saitoh T, Izumo M, Furugen A, et al. Echocardiographic evaluation of iatrogenic atrial septal defect after catheter-based mitral valve clip insertion. Am J Cardiol 2012;109:1787-1791.
65. Anwar AM, Nosir YF, Alasnag M, Chamsi-Pasha H. Real time three-dimensional transesophageal echocardiography: a novel approach for the assessment of prosthetic heart valves. Echocardiography 2014;31:188-196.
66. Biner S, Kar S, Siegel RJ, Rafique A, Shiota T. Value of color Doppler three-dimensional transesophageal echocardiography in the percutaneous closure of mitral prosthesis paravalvular leak. Am J Cardiol 2010;105:984-989.
67. Johri AM, Yared K, Durst R, et al. Three-dimensional echocardiography-guided repair of severe paravalvular regurgitation in a bioprosthetic and mechanical mitral valve. Eur J Echocardiogr 2009;10:572-575.
68. Hamilton-Craig C, Boga T, Platts D, Walters DL, Burstow DJ, Scalia G. The role of 3D transesophageal echocardiography during percutaneous closure of paravalvular mitral regurgitation. JACC Cardiovasc Imaging 2009;2:771-773.
69. Chen Q, Nosir YF, Vletter WB, Kint PP, Salustri A, Roelandt JR. Accurate assessment of mitral valve area in patients with mitral stenosis by three-dimensional echocardiography. J Am Soc Echocardiogr 1997;10:133-140.
70. Binder TM, Rosenhek R, Porenta G, Maurer G, Baumgartner H. Improved assessment of mitral valve stenosis by volumetric real-time three-dimensional echocardiography. J Am Coll Cardiol 2000;36:1355-1361.
71. Perez de Isla L, Benitez DR, Serra V, Cordeiro P, Zamorano JL. Usefulness of real time 3D echocardiography in assessment of rheumatic mitral stenosis. Arch Cardiol Mex 2005;75:210-221.
72. Perez de Isla L, Casanova C, Almeria C, et al. Which method should be the reference method to evaluate the severity of rheumatic mitral stenosis? Gorlin's method versus 3D-echo. Eur J Echocardiogr 2007;8:470-473.
73. Valocik G, Kamp O, Mannaerts HF, Visser CA. New

 http://dx.doi.org/10.3904/kjim.2014.29.6.685

quantitative three-dimensional echocardiographic indices of mitral valve stenosis: new 3D indices of mitral stenosis. Int J Cardiovasc Imaging 2007;23:707-716.
74. Chu JW, Levine RA, Chua S, et al. Assessing mitral valve area and orifice geometry in calcific mitral stenosis: a new solution by real-time three-dimensional echocardiography. J Am Soc Echocardiogr 2008;21:1006-1009.
75. Schlosshan D, Aggarwal G, Mathur G, Allan R, Cranney G. Real-time 3D transesophageal echocardiography for the evaluation of rheumatic mitral stenosis. JACC Cardiovasc Imaging 2011;4:580-588.
76. Weyman AE. Assessment of mitral stenosis: role of real-time 3D TEE. JACC Cardiovasc Imaging 2011;4:589-591.
77. Dreyfus J, Brochet E, Lepage L, et al. Real-time 3D transoesophageal measurement of the mitral valve area in patients with mitral stenosis. Eur J Echocardiogr 2011;12:750-755.
78. Soliman OI, Anwar AM, Metawei AK, McGhie JS, Geleijnse ML, Ten Cate FJ. New scores for the assessment of mitral stenosis using real-time three-dimensional echocardiography. Curr Cardiovasc Imaging Rep 2011;4:370-377.
79. de Agustin JA, Mejia H, Viliani D, et al. Proximal flow convergence method by three-dimensional color Doppler echocardiography for mitral valve area assessment in rheumatic mitral stenosis. J Am Soc Echocardiogr 2014;27:838-845.
80. Applebaum RM, Kasliwal RR, Kanojia A, et al. Utility of three-dimensional echocardiography during balloon mitral valvuloplasty. J Am Coll Cardiol 1998;32:1405-1409.
81. Zamorano J, Perez de Isla L, Sugeng L, et al. Non-invasive assessment of mitral valve area during percutaneous balloon mitral valvuloplasty: role of real-time 3D echocardiography. Eur Heart J 2004;25:2086-2091.
82. Messika-Zeitoun D, Brochet E, Holmin C, et al. Three-dimensional evaluation of the mitral valve area and commissural opening before and after percutaneous mitral commissurotomy in patients with mitral stenosis. Eur Heart J 2007;28:72-79.
83. de Agustin JA, Nanda NC, Gill EA, de Isla LP, Zamorano JL. The use of three-dimensional echocardiography for the evaluation of and treatment of mitral stenosis. Cardiol Clin 2007;25:311-318.
84. Shashanka C, Rajasekhar D, Vanajakshamma V, Kumar ML. Three-dimensional echocardiographic assessment before and after percutaneous transvenous mitral commissurotomy in patients with rheumatic mitral stenosis. J Heart Valve Dis 2013;22:543-549.
85. Anwar AM, Attia WM, Nosir YF, et al. Validation of a new score for the assessment of mitral stenosis using real-time three-dimensional echocardiography. J Am Soc Echocardiogr 2010;23:13-22.
86. Eng MH, Salcedo EE, Quaife RA, Carroll JD. Implementation of real time three-dimensional transesophageal echocardiography in percutaneous mitral balloon valvuloplasty and structural heart disease interventions. Echocardiography 2009;26:958-966.
87. Gillinov AM, Cosgrove DM 3rd, Shiota T, et al. Cosgrove-Edwards Annuloplasty System: midterm results. Ann Thorac Surg 2000;69:717-721.
88. Kwan J, Shiota T, Agler DA, et al. Geometric differences of the mitral apparatus between ischemic and dilated cardiomyopathy with significant mitral regurgitation: real-time three-dimensional echocardiography study. Circulation 2003;107:1135-1140.
89. Ahmad RM, Gillinov AM, McCarthy PM, et al. Annular geometry and motion in human ischemic mitral regurgitation: novel assessment with three-dimensional echocardiography and computer reconstruction. Ann Thorac Surg 2004;78:2063-2068.
90. Daimon M, Shiota T, Gillinov AM, et al. Percutaneous mitral valve repair for chronic ischemic mitral regurgitation: a real-time three-dimensional echocardiographic study in an ovine model. Circulation 2005;111:2183-2189.
91. Watanabe N, Ogasawara Y, Yamaura Y, et al. Quantitation of mitral valve tenting in ischemic mitral regurgitation by transthoracic real-time three-dimensional echocardiography. J Am Coll Cardiol 2005;45:763-769.
92. Watanabe N, Ogasawara Y, Yamaura Y, Kawamoto T, Akasaka T, Yoshida K. Geometric deformity of the mitral annulus in patients with ischemic mitral regurgitation: a real-time three-dimensional echocardiographic study. J Heart Valve Dis 2005;14:447-452.
93. Anwar AM, Soliman O, van den Bosch AE, et al. Assessment of pulmonary valve and right ventricular outflow tract with real-time three-dimensional echocardiography. Int J Cardiovasc Imaging 2007;23:167-175.
94. Daimon M, Saracino G, Gillinov AM, et al. Local dysfunction and asymmetrical deformation of mitral

annular geometry in ischemic mitral regurgitation: a novel computerized 3D echocardiographic analysis. Echocardiography 2008;25:414-423.
95. Lin QS, Fang F, Yu CM, et al. Dynamic assessment of the changing geometry of the mitral apparatus in 3D could stratify abnormalities in functional mitral regurgitation and potentially guide therapy. Int J Cardiol 2014 Aug 8 [Epub]. http://dx.doi.org/10.1016/j.ijcard.2014.08.001.
96. Kwan J, Jeon MJ, Kim DH, Park KS, Lee WH. Does the mitral annulus shrink or enlarge during systole? A real-time 3D echocardiography study. J Korean Med Sci 2009;24:203-208.
97. Moustafa SE, Mookadam F, Alharthi M, Kansal M, Bansal RC, Chandrasekaran K. Mitral annular geometry in normal and myxomatous mitral valves: three-dimensional transesophageal echocardiographic quantification. J Heart Valve Dis 2012;21:299-310.
98. Mahmood F, Warraich HJ, Gorman JH 3rd, et al. Changes in mitral annular geometry after aortic valve replacement: a three-dimensional transesophageal echocardiographic study. J Heart Valve Dis 2012;21:696-701.
99. Yamaura Y, Yoshikawa J, Yoshida K, Hozumi T, Akasaka T, Okada Y. Three-dimensional analysis of configuration and dynamics in patients with an annuloplasty ring by multiplane transesophageal echocardiography: comparison between flexible and rigid annuloplasty rings. J Heart Valve Dis 1995;4:618-622.
100. Yamaura Y, Yoshida K, Hozumi T, Akasaka T, Okada Y, Yoshikawa J. Three-dimensional echocardiographic evaluation of configuration and dynamics of the mitral annulus in patients fitted with an annuloplasty ring. J Heart Valve Dis 1997;6:43-47.
101. Anwar AM, Soliman OI, Nemes A, van Geuns RJ, Geleijnse ML, Ten Cate FJ. Value of assessment of tricuspid annulus: real-time three-dimensional echocardiography and magnetic resonance imaging. Int J Cardiovasc Imaging 2007;23:701-705.
102. Kwan J, Kim GC, Jeon MJ, et al. 3D geometry of a normal tricuspid annulus during systole: a comparison study with the mitral annulus using real-time 3D echocardiography. Eur J Echocardiogr 2007;8:375-383.
103. Kwan J, Gillinov MA, Thomas JD, Shiota T. Geometric predictor of significant mitral regurgitation in patients with severe ischemic cardiomyopathy, undergoing Dor procedure: a real-time 3D echocardiographic study. Eur J Echocardiogr 2007;8:195-203.
104. Vengala S, Nanda NC, Dod HS, et al. Images in geriatric cardiology: usefulness of live three-dimensional transthoracic echocardiography in aortic valve stenosis evaluation. Am J Geriatr Cardiol 2004;13:279-284.
105. Fang L, Hsiung MC, Miller AP, et al. Assessment of aortic regurgitation by live three-dimensional transthoracic echocardiographic measurements of vena contracta area: usefulness and validation. Echocardiography 2005;22:775-781.
106. Goland S, Trento A, Iida K, et al. Assessment of aortic stenosis by three-dimensional echocardiography: an accurate and novel approach. Heart 2007;93:801-807.
107. Poh KK, Levine RA, Solis J, et al. Assessing aortic valve area in aortic stenosis by continuity equation: a novel approach using real-time three-dimensional echocardiography. Eur Heart J 2008;29:2526-2535.
108. Gripari P, Ewe SH, Fusini L, et al. Intraoperative 2D and 3D transoesophageal echocardiographic predictors of aortic regurgitation after transcatheter aortic valve implantation. Heart 2012;98:1229-1236.
109. Jilaihawi H, Doctor N, Kashif M, et al. Aortic annular sizing for transcatheter aortic valve replacement using cross-sectional 3-dimensional transesophageal echocardiography. J Am Coll Cardiol 2013;61:908-916.
110. Perez de Isla L, Zamorano J, Fernandez-Golfin C, et al. 3D color-Doppler echocardiography and chronic aortic regurgitation: a novel approach for severity assessment. Int J Cardiol 2013;166:640-645.
111. Shibayama K, Watanabe H, Sasaki S, et al. Impact of regurgitant orifice height for mechanism of aortic regurgitation. JACC Cardiovasc Imaging 2013;6:1347-1349.
112. Ewe SH, Delgado V, van der Geest R, et al. Accuracy of three-dimensional versus two-dimensional echocardiography for quantification of aortic regurgitation and validation by three-dimensional three-directional velocity-encoded magnetic resonance imaging. Am J Cardiol 2013;112:560-566.
113. Furukawa A, Abe Y, Tanaka C, et al. Comparison of two-dimensional and real-time three-dimensional transesophageal echocardiography in the assessment of aortic valve area. J Cardiol 2012;59:337-343.
114. Saitoh T, Shiota M, Izumo M, et al. Comparison of left ventricular outflow geometry and aortic valve area in patients with aortic stenosis by 2-dimensional ver-

sus 3-dimensional echocardiography. Am J Cardiol 2012;109:1626-1631.

115. Altiok E, Koos R, Schroder J, et al. Comparison of two-dimensional and three-dimensional imaging techniques for measurement of aortic annulus diameters before transcatheter aortic valve implantation. Heart 2011;97:1578-1584.

116. Wu VC, Kaku K, Takeuchi M, et al. Aortic root geometry in patients with aortic stenosis assessed by real-time three-dimensional transesophageal echocardiography. J Am Soc Echocardiogr 2014;27:32-41.

117. Garcia E, Almeria C, Unzue L, Jimenez P, Cuadrado A, Macaya C. Transfemoral implantation of Edwards Sapien XT aortic valve without previous valvuloplasty: role of 2D/3D transeophageal echocardiography. Catheter Cardiovasc Interv 2014 Jan 31 [Epub]. http://dx.doi.org/10.1002/ccd.25417.

118. Bharucha T, Ho SY, Vettukattil JJ. Multiplanar review analysis of three-dimensional echocardiographic datasets gives new insights into the morphology of subaortic stenosis. Eur J Echocardiogr 2008;9:614-620.

119. Mihara H, Shibayama K, Harada K, Berdejo J, Itabashi Y, Shiota T. LV outflow tract area in discrete subaortic stenosis and hypertrophic obstructive cardiomyopathy: a real-time 3-dimensional transesophageal echocardiography study. JACC Cardiovasc Imaging 2014;7:425-428.

120. Patel V, Nanda NC, Rajdev S, et al. Live/real time three-dimensional transthoracic echocardiographic assessment of Ebstein's anomaly. Echocardiography 2005;22:847-854.

121. van Noord PT, Scohy TV, McGhie J, Bogers AJ. Three-dimensional transesophageal echocardiography in Ebstein's anomaly. Interact Cardiovasc Thorac Surg 2010;10:836-837.

122. Negoi RI, Ispas AT, Ghiorghiu I, et al. Complex Ebstein's malformation: defining preoperative cardiac anatomy and function. J Card Surg 2013;28:70-81.

123. Bhattacharyya S, Burke M, Caplin ME, Davar J. Utility of 3D transoesophageal echocardiography for the assessment of tricuspid and pulmonary valves in carcinoid heart disease. Eur J Echocardiogr 2011;12:E4.

124. Bhattacharyya S, Toumpanakis C, Burke M, Taylor AM, Caplin ME, Davar J. Features of carcinoid heart disease identified by 2- and 3-dimensional echocardiography and cardiac MRI. Circ Cardiovasc Imaging 2010;3:103-111.

125. Dumaswala B, Bicer EI, Dumaswala K, et al. Live/real time three-dimensional transthoracic echocardiographic assessment of the involvement of cardiac valves and chambers in carcinoid disease. Echocardiography 2012;29:E72-E77.

126. Fazlinezhad A, Moravvej Z, Azari A, Bigdelu L. Carcinoid heart disease and the utility of 3D trans-thoracic and trans-esophageal echocardiography: two clinical cases. J Saudi Heart Assoc 2014;26:51-55.

127. Addetia K, Maffessanti F, Mediratta A, et al. Impact of implantable transvenous device lead location on severity of tricuspid regurgitation. J Am Soc Echocardiogr 2014 Aug 14 [Epub]. http://dx.doi.org/10.1016/j.echo.2014.07.004.

128. Klein AL, Jellis CL. 3D imaging of device leads: "taking the lead with 3D". JACC Cardiovasc Imaging 2014;7:348-350.

129. Mediratta A, Addetia K, Yamat M, et al. 3D echocardiographic location of implantable device leads and mechanism of associated tricuspid regurgitation. JACC Cardiovasc Imaging 2014;7:337-347.

130. Fukuda S, Saracino G, Matsumura Y, et al. Three-dimensional geometry of the tricuspid annulus in healthy subjects and in patients with functional tricuspid regurgitation: a real-time, 3-dimensional echocardiographic study. Circulation 2006;114(1 Suppl):I492-I498.

131. Park YH, Song JM, Lee EY, Kim YJ, Kang DH, Song JK. Geometric and hemodynamic determinants of functional tricuspid regurgitation: a real-time three-dimensional echocardiography study. Int J Cardiol 2008;124:160-165.

132. Anwar AM, Geleijnse ML, Ten Cate FJ, Meijboom FJ. Assessment of tricuspid valve annulus size, shape and function using real-time three-dimensional echocardiography. Interact Cardiovasc Thorac Surg 2006;5:683-687.

133. Mahmood F, Kim H, Chaudary B, et al. Tricuspid annular geometry: a three-dimensional transesophageal echocardiographic study. J Cardiothorac Vasc Anesth 2013;27:639-646.

134. Daimon M, Gillinov AM, Liddicoat JR, et al. Dynamic change in mitral annular area and motion during percutaneous mitral annuloplasty for ischemic mitral regurgitation: preliminary animal study with real-time 3-dimensional echocardiography. J Am Soc Echocardiogr 2007;20:381-388.

135. Fukuda S, Gillinov AM, McCarthy PM, Matsumura Y, Thomas JD, Shiota T. Echocardiographic follow-up of

tricuspid annuloplasty with a new three-dimensional ring in patients with functional tricuspid regurgitation. J Am Soc Echocardiogr 2007;20:1236-1242.
136. Naqvi TZ, Rafie R, Ghalichi M. Real-time 3D TEE for the diagnosis of right-sided endocarditis in patients with prosthetic devices. JACC Cardiovasc Imaging 2010;3:325-327.
137. Tanis W, Teske AJ, van Herwerden LA, et al. The additional value of three-dimensional transesophageal echocardiography in complex aortic prosthetic heart valve endocarditis. Echocardiography 2014 Apr 12 [Epub]. http://dx.doi.org/10.1111/echo.12602.
138. Berdejo J, Shibayama K, Harada K, et al. Evaluation of vegetation size and its relationship with embolism in infective endocarditis: a real-time 3-dimensional transesophageal echocardiography study. Circ Cardiovasc Imaging 2014;7:149-154.

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