Review Article

Clinical Application of 3-Dimensional Echocardiography

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3D cardiac ultrasound is a promising imaging technology currently still in development, which can provide intuitive recognition of cardiac structures from any spatial point of view and may provide complete information about absolute heart chamber volumes and functions. Although there are still severe limitations to the currently available 3D ultrasound methods due to its system complexity and relatively low image quality, this method would be one of the ultimate goals of cardiac imaging.

Although a number of techniques have been introduced for 3D ultrasound, there exist two fundamentally different methods for 3D ultrasound imaging. One is employing a series of 2D images with ECG and respiratory gating for synchronized reconstruction. The other is real-time 3D ultrasound, which uses massive parallel processing and sparse array technology to obtain 3D volume data in real-time or high speed scanning of 2D planes with rapid motion of the 2D scanner to cover a volumetric space. In either method, there are two major, definite advantages of 3D imaging over conventional 2D echocardiography as follows:

1) Quantification of absolute cardiac chamber volumes, including left ventricle (LV), right ventricle (RV) and left atrial (LA) volumes and their functions, and
2) Visualization of the 3D structure and dynamic motion images of the heart, especially valve structures.

1) Quantification of absolute cardiac chamber volume and function.

a) LV volumes and LV ejection fractions

Absolute LV volumes and their dynamic changes during cardiac cycles are indispensable and are fundamental indices for assessing LV function in any cardiac disease. 3D imaging methods provide an essential and unique capability for determining absolute LV volumes, stroke volumes, and ejection fractions (EF) [1-6]

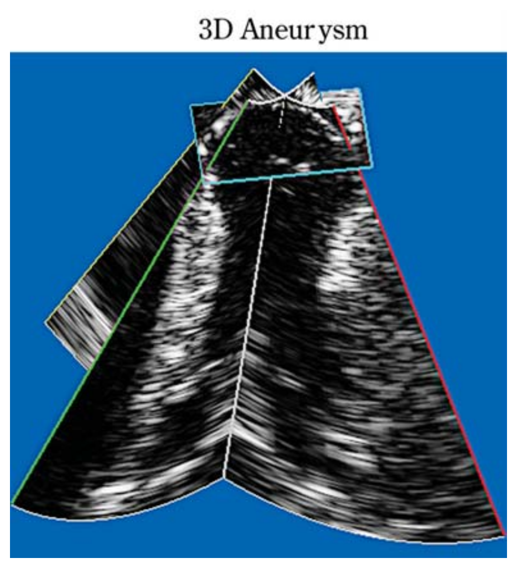

Fig. 1. The left ventricular (LV) aneurysm in a patient with ischemic cardiomyopathy visualized by real-time 3D echocardiography. One can see different 2D images in 3D space by moving color-coded 2D planes.

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[1-14]. For example, in a patient with an LV aneurysm (Figure 1), it is impossible to determine absolute LV volumes using conventional 2D methods, which assume a certain symmetric geometry of the LV cavity for determining LV volumes. For a patient with LV aneurysm, 2D methods could not be used for determining absolute LV volumes and EF because of its complex geometry. In one view, which does not include the aneurysm, EF may be estimated as 45% while another 2D view may result in only 15%. In such a patient, only 3D methods can definitely determine absolute LV end-diastolic/end-systolic volumes (LVEDV/ESV) with the resultant EF of, for instance, 24%.

Most previously reported non-real-time 3D methods required complicated systems and carefully recorded ECG/respiratory gating thus having prolonged imaging times [1-6]. Because of these technical complexities, their clinical application was limited [1-6]. The more recently introduced real-time 3D imaging system provides a simpler approach with a hand-held transducer although the image is of relatively poor quality. This real-time 3D technique is potentially essential for critically ill patients who cannot tolerate prolonged examinations such as magnetic resonance imaging (MRI) [7-9]. In a study performed at the Cleveland Clinic, in patients with/without LV aneurysm, we found an excellent agreement between MRI and real-time 3D for absolute LV volumes and EF. In this study along with others, conventional 2D echocardiography underestimated LV volumes determined by MRI [9]. Further studies demonstrated that absolute LV volumes were important prognostic indices for infarct excision surgery for patients with severe heart failure due to ischemic cardiomyopathy with LV aneurysms [10].

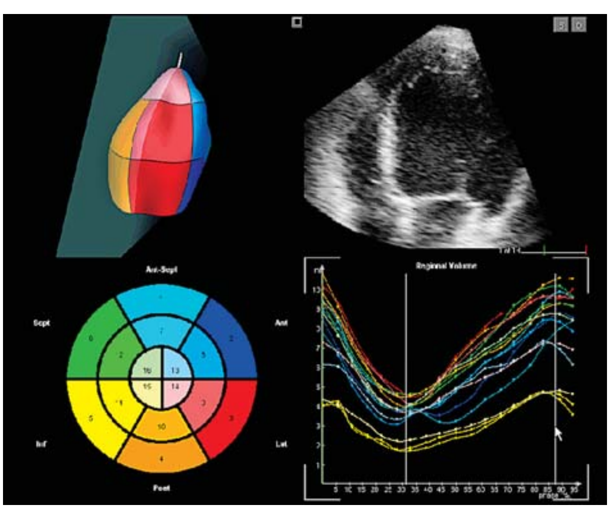

Fig. 2. A representative example of an automated LV analysis using an image of real-time three-dimensional echocardiography. Left upper panel is showing the reconstructed segmental color-coded image, while right lower panel is presenting the time-volume curves of each segment.

More recent development of computer software for real-time 3D echocardiography enabled us to obtain not only total LV volumes mentioned above but also regional LV volumes and ejection fractions as seen in Figure 2.

Stress Echocardiography

In conjunction with the development of 3D computer software for determining regional LV volume and function, I would like to mention the potential use of real-time 3D echo for stress echocardiographic analysis. Stress echocardiography is now widely accepted in the USA for evaluating patients with coronary artery disease (CAD). However, conventional 2D stress echocardiography requires acquisition of at least four different 2D image planes, including the parasternal long-axis and short-axis and the apical 4 and 2 chamber views to analyze all the LV segmental walls. Even with experienced sonographers, it usually takes about 20 to 30 seconds to obtain all four 2D images. This may lead to some images being acquired at submaximal heart rates at presumed "peak" heart rates. This limitation has been shown to reduce the specificity and sensitivity of stress echocardiography. Real-time 3D echocardiography may be able to overcome this limitation by its fast scanning of all the LV walls [15-18]. Ahmad et al. reported that the mean scanning time was 27 seconds by real-time 3D and 62 seconds by 2D echocardiography. In addition, in 90 patients who had coronary angiography, 3D demonstrated higher sensitivity of 87% in the detection of CAD compared with 79% by 2D echo [17]. Regional LV wall motion by 3D echocardiography may provide quantitative analysis of CAD, replacing the visual or subjective judgment of segmental LV wall motion analysis.

Evaluation of LV mass

In addition to LV cavity volumes, LV mass can also be determined by 3D echocardiography. Cardiovascular mortality and morbidity have been shown to increase with left ventricular hypertrophy independent of other cardiovascular risk factors [19-20]. Increased LV mass also reflects the cumulative effects of cardiovascular risk factors. Therefore, LV mass is an important and independent index of cardiac functional status for patient prognosis. 3D echocardiography has been introduced to evaluate LV mass and has been reported to be reliable in both types [21-26]. Infarction size is also of great interest, and 3D echocardiography is reportedly accurate to evaluate infarcted LV mass [27]. However, LV mass or infarct size determination by 3D echocardiography may not be necessary or indicated in most patients routinely.

b) RV volumes and functions

From a clinical point of view, there may be relatively less concern about RV volumes and RV functions than LV volumes and LV functions. However, in certain conditions such as those in patients with congenital heart diseases and those with cor pulmonale, RV functions can be more important than LV functions. For determining absolute RV chamber volumes and stroke volumes, 3D methods are even more important than for determining LV volumes because the RV chamber has complex geometry [28-31] (Figure 3). Employing the real-time volumetric images of the RV digitally stored in an animal model of RV volume overload, RV stroke volumes were determined by use of parallel slices of the 3D volume in one of our previous studies [29]. Good correlation and agreement were found between RV stroke volumes obtained by electromagnetic flow probes and meters and those obtained by the real-time 3D method (r=0.80) [29]. In another clinical study, the real-time 3D system was proven to be feasible to estimate RV volumes, suggesting important applications of this new 3D method in patients [30]. In vitro models were also used to validate 3D echocardiography for determining RV volumes [32].

c) LA volumes and functions

The size of the LA is also an important index for assessing severity of mitral valve stenosis, mitral valve regurgitation, and LV stiffness. LA size has been determined by M-mode or 2D echocardiography at the present time [2] and appears to be sufficient for clinical evaluation. However, considering its complicated anatomical geometry, LA volume is potentially more accurately assessed by 3D methods, which provide the entire image of the complicated LA cavity, including LA appendages [33-34]. In our recent study, which employed real-time 3D echocardiography, LA functions were found to be closely related to LV functions [35]. This study also demonstrated a dramatic depression of LA function during proximal left circumflex coronary artery occlusion [35]. Considering the importance of LA compensation in patients with LV systolic dysfunction, precise and accurate analysis of LA function is essential for clinical management. LA volume measurement by 3D echocardiography is potentially vital for such an analysis.

2) 3D visualization of cardiac structures

The other important advantage of 3D over conventional 2D is virtual visualization of the anatomy of car-

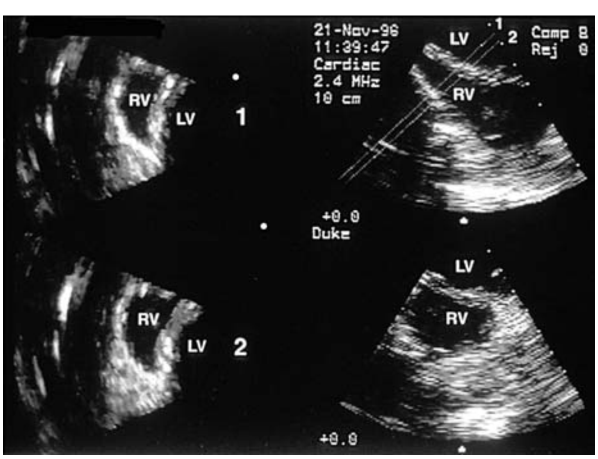

Fig. 3. A 3D echocardiographic image of the right ventricle (RV). Note the crescent shape of the 2D sliced imaging of the right ventricle on the left panels. LV = left ventricle.

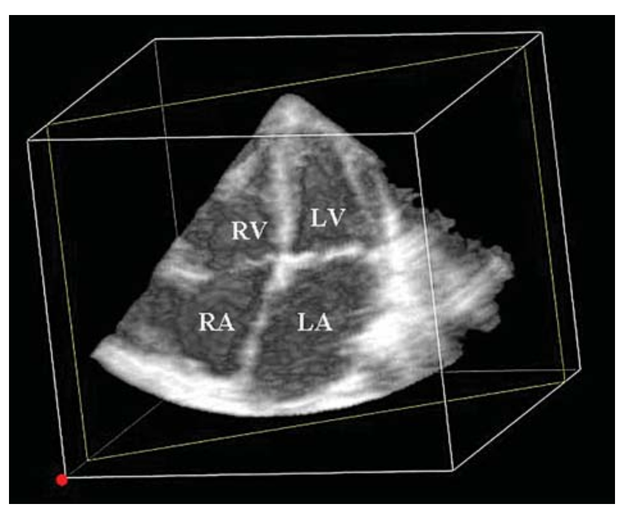

Fig. 4. A real-time 3D imaging of an entire heart. Note the depth of all 4 chambers (left ventricle, LV, left atrium, LA, right ventricle, RV, and right atrium, RA) visualized by 3D echocardiography.

diac structures such as heart chambers (Figure 4) and valves (Figures 5-8). Rotated and bird's eye views would provide unique and critical views of morphological disorders.

a) Valvular Heart Diseases

Heart valve structures are complicated, and thus current 2D echo requires multiple views to assess them thoroughly (Figures 5-8). For example, in patients with mitral valve prolapse/flail and mitral regurgitation, location of the flail or prolapsed leaflet (medial, central and lateral) and its geometry are essential information for determining etiology of mitral regurgitation and its surgical corrections. However, conventional 2D echocardiography requires multiple views of the mitral valve and mental reconstruction of the 3D image of the diseased structure. In recent studies, mitral valve anatomy was determined by the reconstruction 3D method (Figure 5) [35-36]. Enface 3-dimensional views of the mitral valve from the left atrium were possible in 21 of the 27 patients, concluding that 3D echocardiography provided new insight into the anatomic determinants of MR [36]. As opposed to the reconstruction methods, a real-time 3D system could show mitral valve morphologies after a short acquisition time although the current real-time 3D images are not yet optimal in most patients.

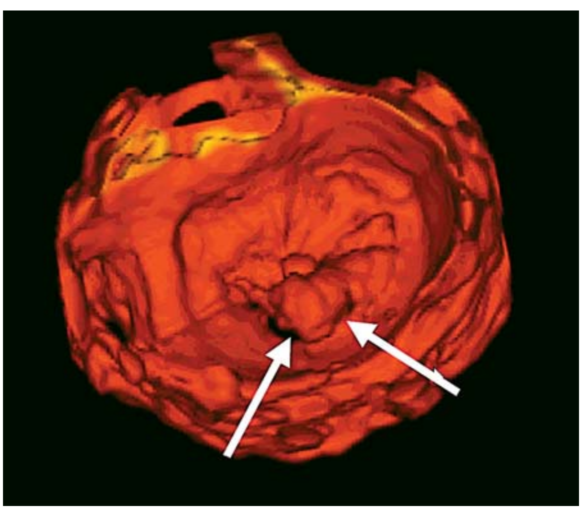

Fig. 5. Enface 3D views of a mitral valve from the left atrium in a patient with severe prolapse of the mid portion of the posterior leaflet (white arrows).

It has been reported that extracted 3D images obtained by multiplane transesophageal echocardiography could be used in the evaluation of non-planarity and area change of the mitral annulus in patients with an annuloplasty ring [38-39]. Real-time 3D methods were also feasible in the evaluation of non-planarity and area change of the mitral annulus in animals and in patients [40-45]. Saddle-shaped geometry of the mitral annulus is clearly visualized by 3D echocardiography. Not only the annulus geometry, but also valve tethering or tenting in ischemic cardiomyopathy and idiopathic cardiomyopathy were quantitatively analyzed by these studies. Considering the clinical importance of the annuloplasty for ischemic mitral regurgita-

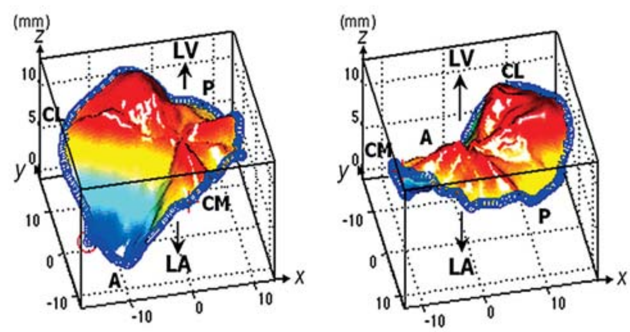

Fig. 6. 3D reconstruction of a mitral annulus and valve morphology extracted from multiple annular points and curved leaflets lines (see text in detail).

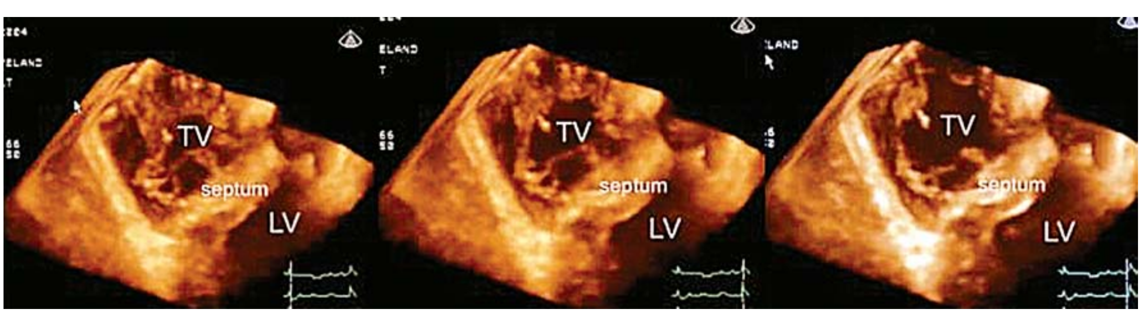

Fig. 7. Enface 3D views of a tricuspid valve in three different timings in a cardiac cycle.

tion, such detailed geometric evaluation should be performed in order to improve surgical results in patients with ischemic mitral regurgitation. Figure 6 shows mitral annulus and valve morphology extracted from multiple annular points and curved leaflets' lines [44-45]. A non-surgical approach to manage ischemic mitral regurgitation was introduced recently, and real-time 3D echo was used to evaluate geometric changes of the mitral annulus before and after percutaneous mitral valve repair [43].

Color Doppler 3D Echocardiography

In patients with valvular regurgitation, color Doppler capability, which has been recently introduced in both reconstruction and real-time 3D systems, could provide 3D images of regurgitant flow jet velocity and flow convergence [46-55]. As seen in Figure 9, the location of flow convergence and its size can determine the location of the regurgitant orifice and the severity of valvular regurgitation. Thus, real-time 3D tissue imaging with color Doppler capability could give quantitative information required for the assessment of severity of MR as well as LV and LA absolute volumes [53]. For example, in a patient with a regurgitant volume of 42 ml/beat determined by the flow convergence method and LVEDV and LVESV of 178 ml and 94 ml by the real-time 3D tissue method, one can estimate the net stroke volume as (178 ml−94 ml)−42 ml, which is equal to 42 ml/beat. On the other hand, color Doppler 3D echocardiography can show the velocity profile of the cross-section of the left ventricular outflow tract as seen in Figure 10. Time integration of this spacial velocity profile over the entire systole results in the net forward stroke volume [50,54,55]. Then one can cross-check the net stroke volumes by these 2 different 3D methods, one by subtraction and the other by direct integration. If they are close to each other, the value could be reliable. In the above case, for instance, if the color Doppler 3D echocardiography estimates 41 ml/beat as the net stroke volume, we can somehow trust these results (if not coincident) and may consider that regurgitant fraction to be about 50%. Complete assessment of LV volumes, LV systolic function, stroke volumes, regurgitant volumes, and fractions by 3D echocardiography with color Doppler capability is potentially possible in patients with mitral regurgitation [53]. This concept was successfully applied in aortic regurgitation in our clinical study [56]. Pulmonary regurgitation was also successfully quantitated by 3D Doppler echocardiography in an animal study [52]. 3D echocardiographic methods can also provide aortic valve morphology as well as such quantification in patients with aortic regurgitation. In

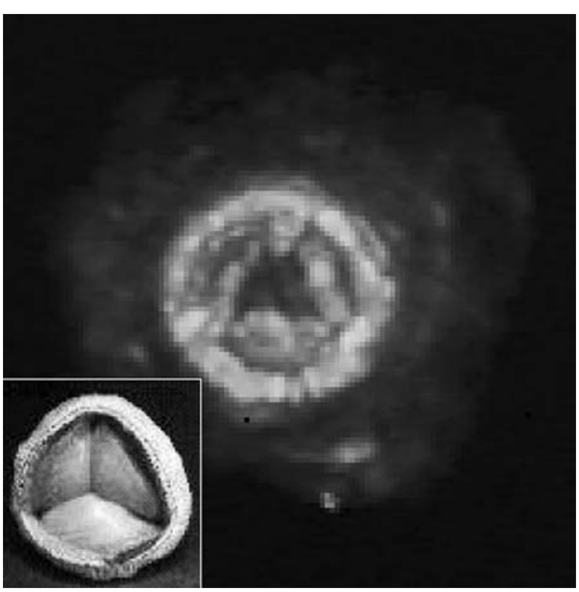

Fig. 8. Enface 3D (center panel) and actual (left lower panel) views of an artificial physiologic valve.

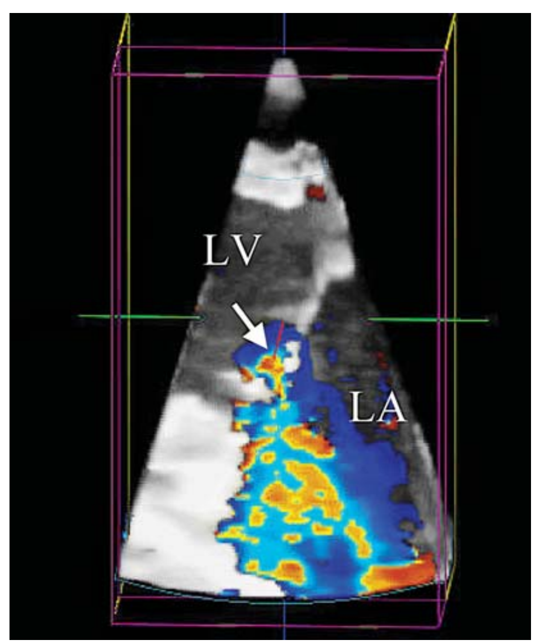

Fig. 9. A color Doppler 3D echocardiographic image of mitral regurgitation. The location of flow convergence (white arrow) and its size can be used to estimate the site of the regurgitant orifice and the severity of regurgitation. LA = left atrium, LV = left ventricle.

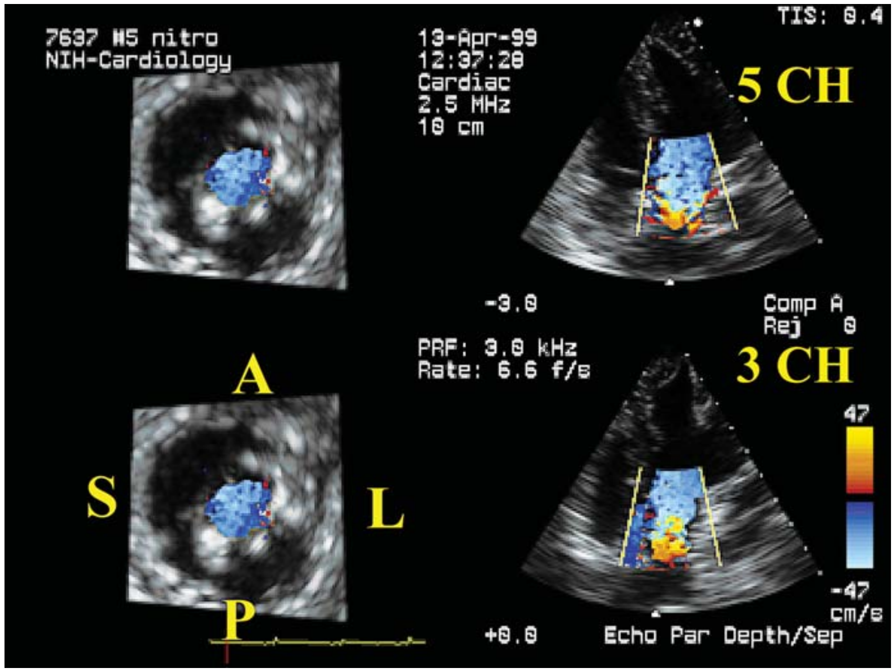

Fig. 10A. An example of color Doppler 3D echocardiography, showing cross-sectional color Doppler velocity coding at left panels and 3 and 5 chamber views of the left ventricular outflow tract (LVOT) in the right panels. A = anterior, L = lateral, P = posterior, S = septal.

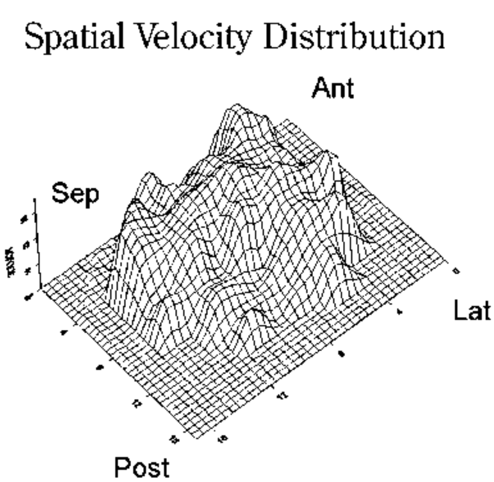

Fig. 10B. An example of a spacial velocity distribution over a cross-sectional LVOT area.

patients with aortic stenosis or those with mitral stenosis, 3D echocardiographic methods could provide visualization of the valve pathology and direct measurement of the stenotic area with reasonable accuracy [57-61].

b) Hypertrophic Cardiomyopathy

In patients with hypertrophic obstructive cardiomyopathy (HOCM), regional wall motion and wall thickness can be assessed by 3D methods. In a study with reconstruction 3D methods, significant impairment in fractional thickening was observed in the septum compared with the lateral free wall in patients with hypertrophic cardiomyopathy [62]. In this study, regional systolic function was inversely related to end-diastolic wall thickness [62]. In addition, the location of the systolic anterior motion of the mitral valve was observed by 3D visualization. In TEE reconstruction 3D and our more recent real-time 3D studies, the leftventricular outflow tract (LVOT) areas could be quantified by 3D echocardiography [63-66], and we also found more medially located systolic anterior motion of the mitral valve (SAM) with successful surgical management of hypertrophic obstructive cardiomyopathy (HOCM) as seen in Figure 11. 3D echocardiography may play an indispensable role in the operating room for determining the precise location of myectomy in the future [66].

C) Congenital Heart Disease

Considering the critical importance of the anatomical analysis of the heart chamber and the great vessels, it is needless to emphasize the value of 3D echocardiography in congenital heart disease. Conventional 2D

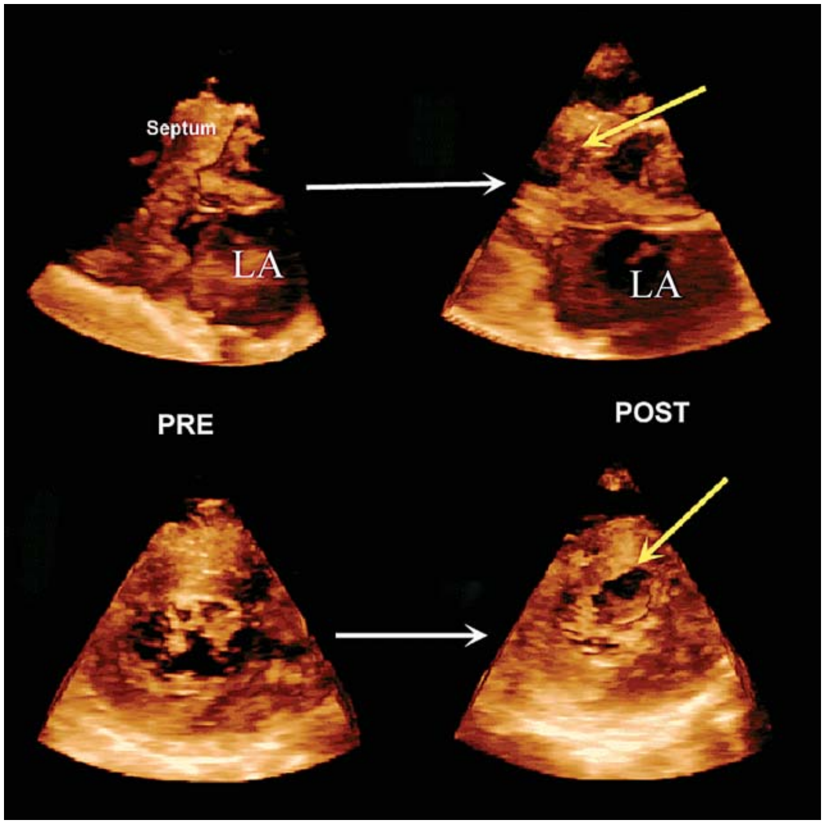

Fig. 11. 3D echocardiographic imaging of hypertrophic obstructive cardiomyopathy pre (left panels) and post (right panels) myectomy. Yellow arrows demonstrate the site of myectomy. Upper panels show long-axis views while lower panels, short-axis views. LA = left atrium.

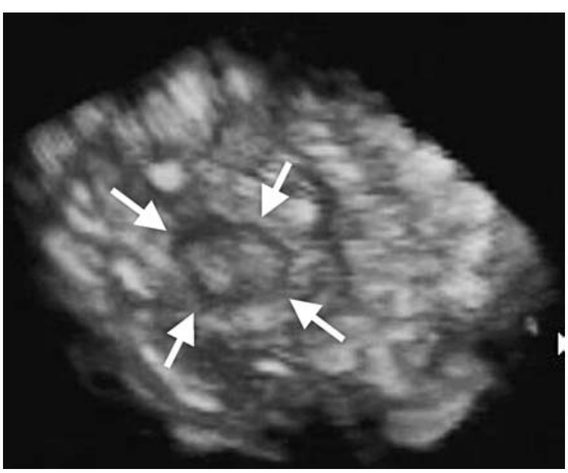

Fig. 12. An enface view of an atrial septal defect (ASD) seen from the right atrium in a 7-year-old girl.

echocardiography cannot demonstrate even the shape and size of atrial septal defect (ASD) and ventricular septal defect (VSD). In a recent study, which used reconstruction 3D echocardiography, better qualitative and quantitative information on the dynamic geometry, location, and extension of ASD was reported as compared with standard 2D echocardiography [67]. Also, by using reconstruction 3D echocardiography, the location, the relation to the aortic and tricuspid valve, and the size of the ventricular septal defect (VSD) was assessed and compared with 2D echocardiography and intraoperative findings [68-69]. The authors concluded that reconstruction 3D echocardiography accurately assesses the anatomy of VSD, provides additional information, and can be considered a valuable preoperative diagnostic tool [68]. In addition to reconstruction 3D methods, real-time 3D echocardiography was introduced successfully for visualizing ASD and VAD as seen in Figures 12 and 13. It was also used in 75 patients with suspected congenital heart defects in a clinical study [70]. Real-time 3D echocardiography identified all structural abnormalities except for a small ASD in 2 patients and coronary artery anatomy in D-transposition of the great arteries. Less than 5 minutes were needed to acquire real-time 3D images in all cases, and sedation was never required. In a more

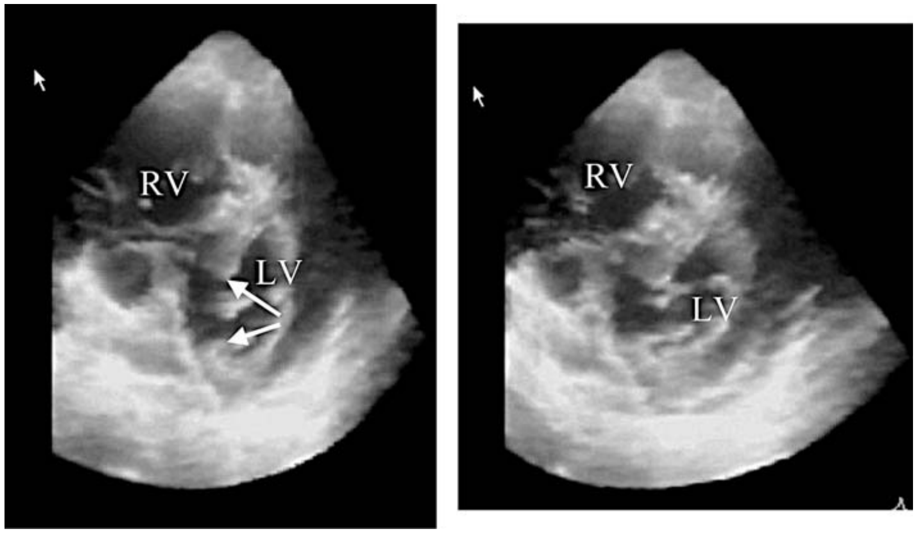

Fig. 13. Rotated 3D views of a ventricular septal defect (VSD). LV = left ventricle, RV = right ventricle.

recent study in 20 fetuses, 110 children and 20 adults with various congenital heart lesions, real-time 3D imaging gave accurate description of ASD and congenital valvular lesions [71]. Profound merits of real-time 3D echocardiography in congenital heart disease were projected by such clinical studies.

In summary

3D echocardiography has shown unique capabilities for clarifying complicated cardiac anatomies and hemodynamics despite the present technical problems, such as limited image quality and complicated systems. In the future, continued development of computer technology, ultrasound transducer and scanner engineering, and introduction of real-time TEE 3D echocardiography may overcome such ongoing problems, resulting in widespread use of 3D echocardiography in routine clinical settings.

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