REAL-TIME THREE DIMENSIONAL ECHOCARDIOGRAPHY: EVOLUTION AND CURRENT APPLICATIONS

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INTRODUCTION

While two-dimensional (2-D) echocardiography has had a tremendous impact on the diagnosis and management of patients with cardiac disease, three-dimensional (3-D) echocardiography provides visualization of structures in their spatial orientation that is not feasible with 2-0 imaging. This article reviews clinical applications of past and current 3-0 technologies, and highlights several issues - including method of data acquisition, off-line review/data rendering, and potential clinical applications - needed to integrate 3-D echocardiography into day-to-day clinical practice.[1-12]

3-D HISTORICAL PERSPECTIVE

The first 3-D echocardiographic images in 1974 were acquired sequentially and stacked to produce a 3-D data set without gating for heart rate or respiration - a method appropriate for static imaging bur not for dynamic structures such as the heart. During the early 1990s, respiratory and ECG gating were used co reduce the amount of artifact in the data set by establishing thresholds to limit image acquisition for specific respiratory and ECG parameters throughout the cardiac cycle.

Now, with new acquisition techniques and more comprehensive review formats, 3-D technology is poised co become an integral echocardiographic cool: real-time 3-D echocardiography is available with live 3-D rendering, offers more information in less time and provides anatomical, aesthetically pleasing images that are more intuitive than 2-D echocardiography (Figure 1).1 However, a gated form of 3-D echocardiography is still currencly used due to the high-quality data set resolution and the need to image che ocl1 heart, even though some artifacts may be inherent due to the nature of the acquisition. The semi-gated format acquires four chick slices of che heart over sequential heartbeats and "stitches" them together to represent one cardiac cycle (Figure 2). While both techniques provide a 3-D data set chat allows quantitative assessment and rendering, both have their advantages and disadvantages. Gated imaging offers excellent image resolution, a tendency for motion artifacts and total volume rendering of che heart. Real-time 3-D imaging is instantaneous without morion artifacts and is independent of gating, bur limited slice width interrogation does not allow total heart visualization.

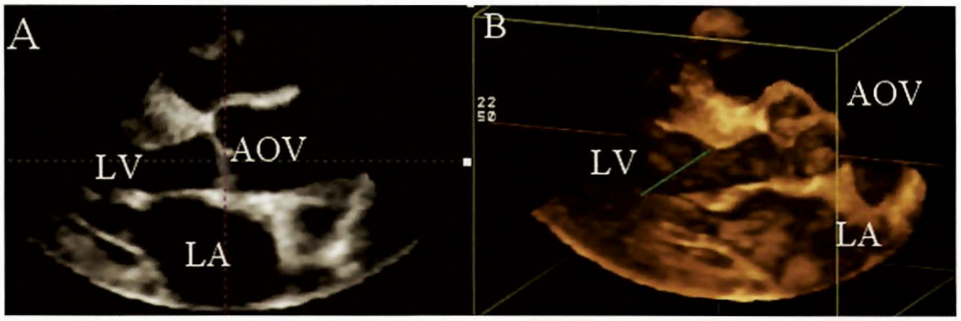

Figure 1.
Parasternal view of the heart in 2-D (left) and 3-D (right) showing the left ventricle (LV), left atrium (LA) and aortic valve (AoV). Note the depth of view provided by 3-D compared to 2-D echocardiography.

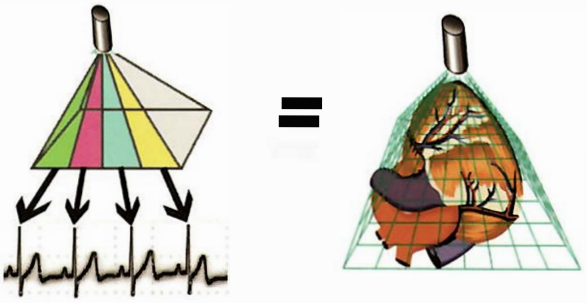

Figure 2.
Schematic representing the semi-gated acquisition technique of four real-time 3-D acquisitions acquired over four cardiac cycles in order to represent one large full volume of the heart.

3-DIMENSIONAL DATA REVIEW

All 3-D data sets are acquired and reviewed digitally, with data stored in a DICOM format that can be interpolated by multiple software reviewing systems. Three-dimensional studies can increase diagnostic confidence by allowing interpreting physicians to view different perspectives of the same anatomy - for example, they can view any 2-D slice within the 3-D volume or create multiple, any plane anacomical rendering views. This ability to manipulate the entire heart with unlimited planar views will furcher advance the field of digital echocardiography and improve its accuracy in evaluating cardiac structure and function.

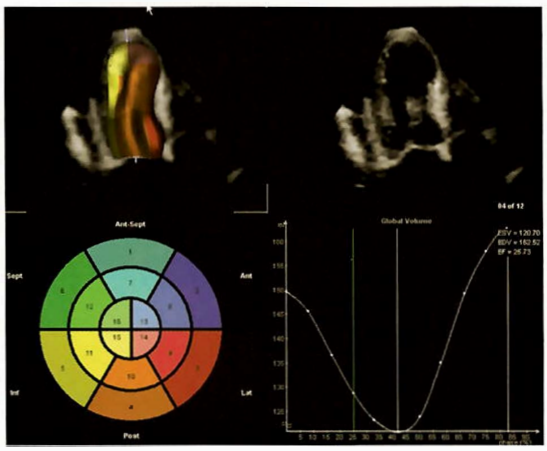

Figure 3.
3-0 analysis and display of left ventricular volumes and regional function (left upper panel} with a corresponding 2-0 display from the apical view (right upper panel). Regional segments of the ventricle are coded (left lower) and a time-volume curve is generated (right lower) during the cardiac cycle.

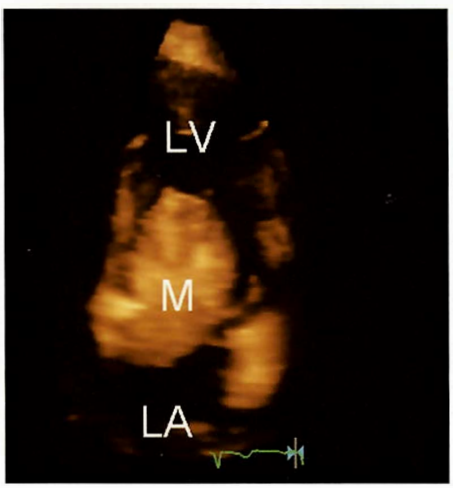

Figure 4.
A large left atrial myxoma (M) is seen on 3-0 imaging, crossing the mitral valve annulus into the left ventricle (LV) in diastole; color flow shows the flow around the mass and the significant resulting obstruction to left ventricular inflow.

CURRENT AND POTENTIAL CLINICAL APPLICATIONS

Prior to real-time imaging, 3-D echocardiography was primarily limited to morphologic and quantitative research analysis due to the time constraints and limitations inherent with gated sequential imaging. However, easy acquisition and real-time 3-D have created new clinical applications chat complement and improve the clinical use of 2-D echocardiography (Table 1). These applications are detailed below.

Quantitation of Ventricular Volumes, Fwiction, Mass

With 2-D echocardiography, quantitating volumes of the cardiac chambers, ejection fraction and left ventricular mass relies on geometric assumptions and is therefore subject to inaccuracies, particularly when there is asymmetric distortion of ventricular geometry such as following myocardial infarction. Three-dimensional echocardiography improves the accuracy in quantitating volumes, ejection fraction and left ventricular mass since it does not rely on geometric assumptions of the cardiac chambers (Figure 3). Several studies also have shown 3-D echocardiography to improve reproducibility and render measurements chat are comparable to chose with magnetic resonance imaging (MRI).2,7 Lastly, 3-D echocardiography may also enhance regional wall motion assessment and quantitation, since we can now perform sequential tomographic cuts to evaluate wall motion. It may even be feasible to evaluate regional contraction synchrony, which would provide an important application of evaluating and optimizing resynchronization therapy for heart failure with bi-ventricular pacing.

Morphologic Analysis

A rendered 3-D data set allows visualization of complex cardiac structures similar to a surgeon's view, enabling greater spatial perception. In fact, anatomical 3-D rendering has been reported to help diagnose congenital heart disease and its management (e.g. measuring atrial septa! defect size), valvular heart disease and cardiac masses (Figures 4 and 5).3-6

Stress Echocardiography

Stress echocardiography is an established diagnostic tool for detecting coronary artery disease and

Table 1.

CLINICAL APPLICATIONS OF 3-0 ECHOCARDIOGRAPHY

- Quantitation-volumes, regional and global function, and cardiac mass
- Morphologic analysis-congenital heart disease, anatomical structures in 3-0
- Stress echocardiography
- Echo-guided invasive procedures
- Surgical planning and guidance-preoperative, intraoperative and postoperative
- Valvular heart disease
- Color flow quantification of flow and valvular regurgitation

evaluating prognosis. For treadmill exercise, this time-dependent test requires echocardiographic image acquisition within 60 to 90 seconds of peak exercise. Current technology allows for simultaneous biplane imaging, which shortens the acquisition time and improves echocardiogram sensitivity and specificity. However, the future advent of real-time, full-volume imaging will enable us to acquire all standard and non-standard views from one acquisition. Instant imaging of the entire heart will not only allow for multi-planar analysis of myocardial segments, but may also improve diagnostic confidence and accuracy of interpretation.

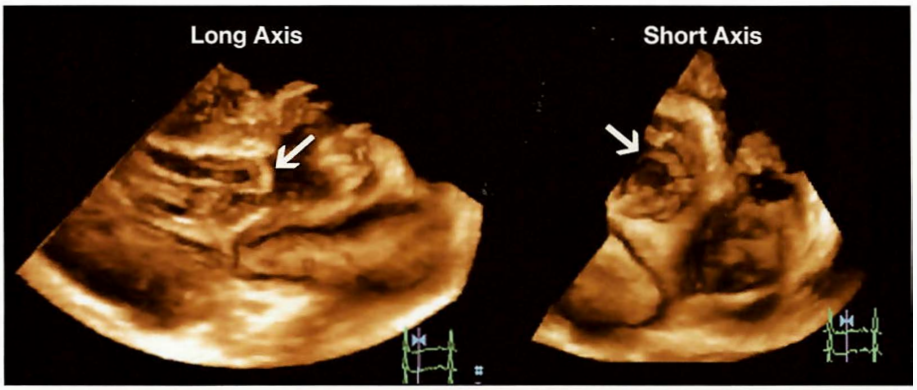

Figure 5.
A 3-0 visualization of a congenital subaortic membrane (arrow), seen from the parasternal and short axis views.

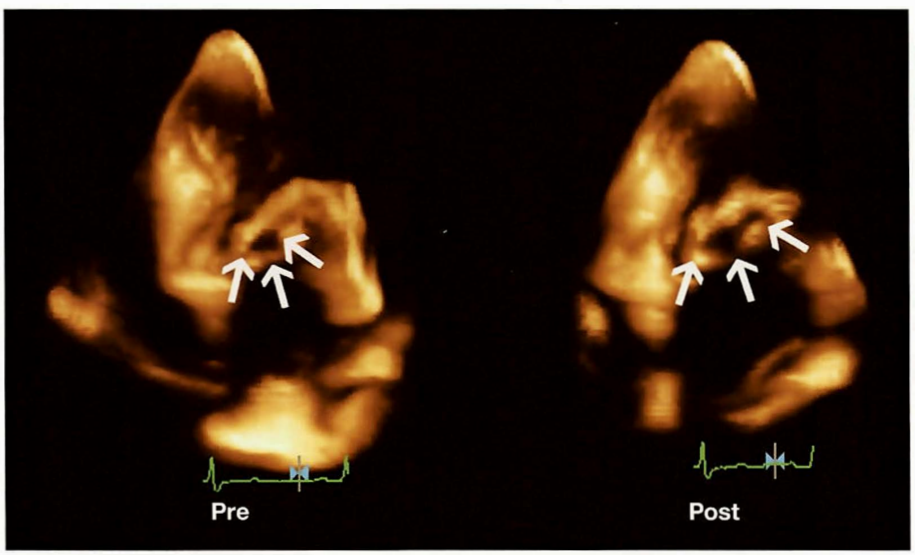

Figure 6.
3-0 echocardiography of a mitral valve stenosis imaged pre- and post-balloon valvuloplasty. Note the significant increase in leaflet separation and valve area after valvuloplasty.

3-D Echo-Guided Invasive Procedures

The role of echocardiography during invasive procedures is growing. Some of the clinical applications for 3-0 echo-guided invasive procedures include pericardiocentesis, valvuloplasty and selected cases of cardiac biopsy, pacemaker and electrophysiologic studies. In comparing real-time volumetric 3-0 imaging with biplane fluoroscopy, real-rime 3-0 imaging provides exact anatomic location of catheter placement. It may also offer advantages over 2-D intracardiac ultrasound by giving a 3-0 orientation to catheter positions in relation to cardiac anatomy. Real-time 3-D imaging offers multiple customized views displayed from a single imaging position, thereby indicating accurate placement of the bioptome for biopsy of cardiac masses or right ventricular endomyocardial biopsy in transplant patients. During pericardiocentesis, the wide imaging area obtained with real-rime 3-D may be more effective than the thin slice acquired with 2-0. Additional 3-0 echo-guided applications include the complementary role it provides during valvuloplasry (Figure 6). Anatomic visualization of valve structure and area in 3-0 aids in evaluating the results of valvuloplasty and can complement the hemodynamic assessment provided by Doppler techniques since the pressure half-time method for calculating valve area has limited accuracy immediately after valvuloplasry.[9,10]

Surgical Planning - Preoperative, intraoperative and postoperative

Three-dimensional echocardiography has a significant potential in planning surgical interventions that would complement current techniques. Real-time 3-0 echocardiography allows portable and rapid, noninvasive interrogation of cardiac masses, congenital heart defects and valvular lesions, and 3-0 assessment of both tumors and thrombi has been shown to provide additional information regarding size, origin and extent of cardiac involvement. In addition, 3-D echo evaluation of atrial and ventricular septa! defects offers more precise measurements to plan strategy and appropriateness

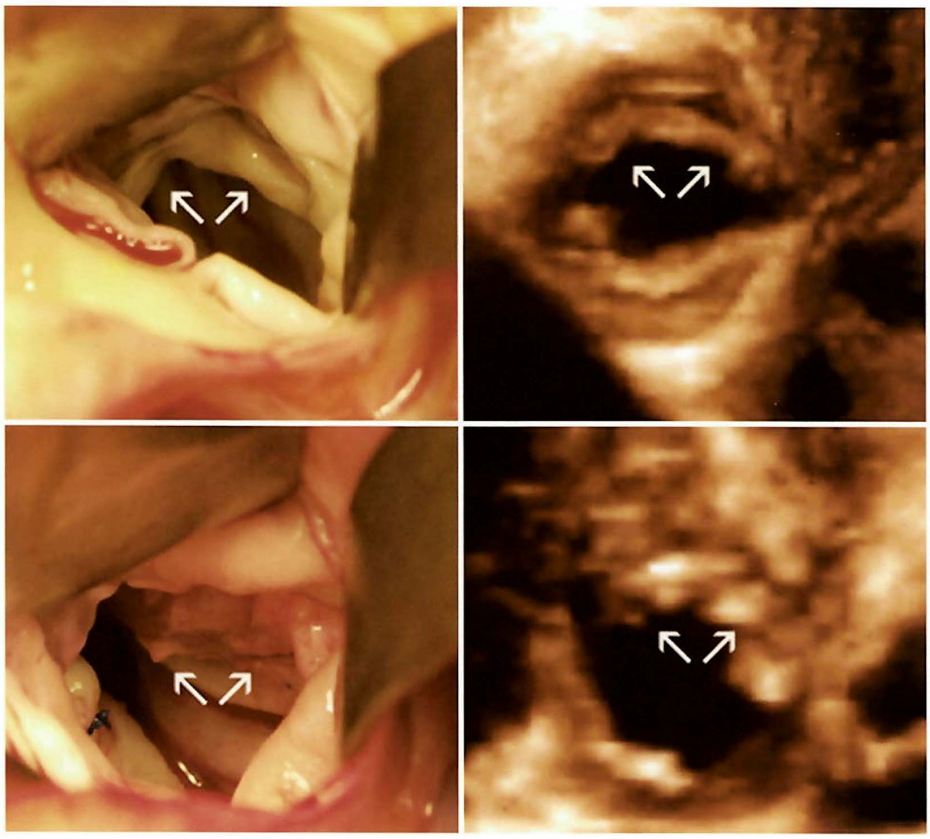

Figure 7.
Echo-anatomic correlation at surgery of a patient with subaortic membrane. Prior to surgery (left panels), the extent of the membrane in the left ventricular outflow is shown. After resection of the membrane, 3-0 image shows resection results.

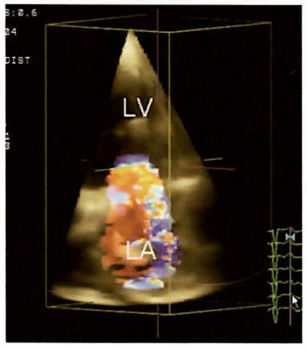

Figure 8.
3-0 color flow echocardiography in a patient with significant mitral regurgitation shows the extent and eccentric direction of the regurgitant jet into the left atrium.

of closure devices.

Three-dimensional echocardiography provides a unique perspective on valvular structure and motion. When performed from the transthoracic approach in real time, it helps identify the mechanism of valvular pathology in planning for surgical correction. Three-dimensional reconstruction of sequential gated planes also can be performed with transesophageal echocardiography, although this approach is not yet available in real time. Real-time 3-D in the operative setting can be performed with the epicardial approach using a sterile sheath. Initial experience has shown excellent image quality, providing real-time 3-D images of rhe valvular apparatus pre- and post-surgical correction in the operating room - possibly giving the surgeon immediate feedback on the outcome of the procedure or valvular repair (Figure 7).

Color Flow Quantification

Currencly, che standard screening technique for valvular regurgitation is 2-D echocardiography with Doppler. Guidelines for assessing the severity of regurgitation were recently put forth by the American Sociery of Echocardiography and endorsed by the American College of Cardiology and other major organizations.12 While 2-D color flow can quancitate the severity of regurgitation, the regurgitanc jet components are not fully visualized in the 3-D domain, a limitation particularly evident in eccentric regurgitant jets.[12] Furthermore, the proximal flow convergence jet characteristics used in 2-D color Doppler for quanticarion assume a hemispheric shape that has inherent limitations. Initial reports on 3-D color flow have provided information on the complex geometry of regurgitant jets (Figure 8). Currently, research at the Methodist DeBakey Heart Center and Baylor College of Medicine is evaluating the impact of improved visualization of regurgitant jets with 3-D echocardiography on the accuracy of quancitation of regurgitanc lesions. These results are very promising since geometric assumptions will no longer be needed.

CONCLUSION

Recent developments in echocardiography have produced a completely non-invasive modality chat can image the heart in real time and in 3-D. While this modaliry may be considered in its infancy, several potential clinical applications have already surfaced - from improved quamiracion of global and regional

function to better evaluation of cardiac masses, valvular structure and valvular regurgitation. Since 3-D technology can be used in conjunction with established Doppler and 2-D techniques, it will undoubtedly enhance the evaluation of cardiac structure and function, and lead to further refinement, development and research, with the ultimate goal of improved and more cost-effective patient care.

Future 3-D developments include the addition of contrast agents to evaluate real-time myocardial perfusion, higher frequency transducers for pediatric patients, 3-D tissue Doppler mapping for enhanced diastolic function assessment and 3-D transesophageal echocardiography. As we watch these technologies and applications unfold, it is always amazing to reflect on the power of innovation: while the principle of cardiac imaging with reflected ultrasound has remained the same, the field has drastically evolved over the past 50 years into 3-D real-time imaging that provides a unique non-invasive window into the heart.

REFERENCES

1. *Nanda NC, Kisslo j, Lang R, Pandian N, Marwick T, Shirali G, Kel y G. Examination prutocol for three-dimensional echocardiography. Echocardiography 2004 Nov; 21(8):763-768.*
2. *Mor-Avi V, S$_{ugeng}$ L, Weinert L, .MacEneaney P. Caiani EG, Koch R, Sa/go IS, Lang R/1.1. Fast measurement of left ventricular mass with real-time three-dimensional echocardiography: comparison with magnetic resonance imaging. Circulation 2004 Sep 28; 110(13):1814-1818.*
3. *Lokhandwala]. Liu Z, Jundi M. Loyd A, Strong M, Vannan M. Three-Dimensional Echocardiography of Intracardiac Masses. Echocardiography 2004; 21:2.*
4. *Macnab A, Jenkins NP, Ewington I, Bridgewater BJM, Hooper TL, Greengalgh DL, Patrick MR, Ray SG. A methodfor the morphulogical analysis of the regurgitant mitral z,alve using three-dimensional echocardiography. Hearl 2004; 90:771-776.*
5. *Chamoun A], MCCulloch M,)(ie T, Shah S, Ahmad M. Real-Time Three-Dimensional Echocardiography i•ersus Two-Dimensional Echocardiography in the Diagnosis of Left Ventricular Apical Thrombi: Preliminary Findings. Journal of Clinical Ultrasound October 2003; 31:8.*
6. *McCulloch M, Tran T, Quinones M, Zoghbi WA. Real-Time three-dimensional echocardiography in the differential diagnosis of/.eft i•entricular apical thrombi without and with contfast enhancement: comparison with two-dimensional echocardiography. j Am Soc Echocardiogr 2004; l."7(5):519.*
7. *Kuhl HP, Schreckenb$_{erg}$ J\f, Ru/ands D, Katoh A.I, Schafer W, Schummers G, Bucker A, Hanrath P, Franke A. High-resolution transthoracic real-time three-dimensional echocardiography: Quantitation of cardiac volumes and fimction using semi-automatic border detection and comparison with cardiac magnetic resonance imaging. J Am Coll Cardiol 2004; 43:11.*
8. *Varandas]. Baptista P, Santos J, Rarlins R, Dias J VOLUS---a visualization system of 3D ultrasound data. Ultrasonics 2004; 42:689-694.*
9. *Simon RDB, Rinaldi C, Baszko A, Gill JS. Electroanatomic mapping of the right atrium with a right atrial basket catheter and three-dimensional intracardiac echocardiography. PACE 2004 March; 27:318-326.*
10. *Zamorano J, Cordeiro P, Sugeng L, de Isla LP, Weinert L, Macaya C, Rodri$_{g\,u}$ez E, Lang RAJ. Real-time, three-dimensional echocardiography for rheumatic mitral l'alve stenosis evaluation: An accurate and nox•el approach. j Am Coll Cardiol 2004; 43:JJ.*
11. *£ch-Broder £, Ushakov FB, Jmbar T, Yagel S. Application offree-hand three-dimensional echocardiography in the evaluation of fetal cardiac ejection fraction: a preliminary study. Ultrasound Obstet Gynecol 2004; 23:546-551.*
12. *Zoghbi WA, Enriquez-Sarano M, Foster E, Grayburn PA, Kraft CD, Levine RA, Nih$_{oy}$annop oulos P, Otto CM, Quinones MA, Rakowski H, Stewarl Wj. Wagvnner A, Weissman NJ Recommendations for evaluation of the severity of native valvular regurgitation with two-dimensional and Doppler echocardiography. A report from the American Society of Echocardiograph/s Nomenclature and Standards Commitlee and Task Force on Valz'ttlar Regurgitation. J Am Soc of Echocardiogr 2003; 16:777-802.*