Three dimensional echocardiography: approaches and clinical utility

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Three dimensional echocardiography: approaches and clinical utility

Amer M Johri, Jonathan J Passeri, Michael H Picard

Effective performance and interpretation of two dimensional (2D) echocardiography requires one to mentally integrate the collected images into a three dimensional (3D) reconstruction of the heart. For example, prolapse of the mitral leaflets may involve the entire leaflet, or only a leaflet portion, requiring the echocardiographer to examine each individual leaflet portion from a series of 2D images and then to mentally ‘map’ the valve to define the location and nature of the abnormality. To do this accurately, one must understand the relationship of each 2D image to one another. Quantification of cardiac structure and function by 2D echocardiography typically requires assumptions about the geometry of the structure being measured so that specific formulae can be accurately used. The shapes of these structures may become altered in various diseases and thus the geometric assumptions about shape become less accurate as do the values calculated from the formulae.

3D echocardiography eliminates the need for cognitive reconstruction of image planes and use of geometric assumptions about shape of structures for cardiac quantitation. This particularly applies to complex shapes such as the right ventricle, an aneurysmal left ventricle (LV), an asymmetrically stenotic or regurgitant valve orifice, eccentric regurgitant jets assessed by colour Doppler, valve annulae, and the complex structural relationships observed in congenital heart lesions. 3D echocardiography can be performed from the transthoracic or transoesophageal approach. The 3D echocardiographic technique has the potential to decrease the time required for complete image acquisition of the heart. Also, the 3D echocardiogram can be viewed from various projections by rotation of the images resulting in an improved appreciation of the relationships between various cardiac structures.

Up until recently, 3D echocardiography was primarily a research tool because off-line image reconstruction from a series of component 2D images was required (reconstruction technique) and this was very time consuming. However, advances in transducer technology now enable the acquisition of a 3D volume of ultrasound data (volumetric technique) and real-time 3D echocardiographic display. This has brought 3D cardiac ultrasound imaging into the clinical realm. This review will focus primarily on this new volumetric technique.

THE VOLUMETRIC TECHNIQUE FOR 3D ULTRASOUND IMAGING

Volumetric techniques require a specialised rectangular (or matrix) array transducer to collect a pyramidal (or 3D) volume of image data. The transducer elements are typically arranged in a rectangular grid or matrix array and advanced electronics allow beam steering in multiple directions. After transmission of a pulse, the elements simultaneously receive data from multiple lines of sight, enabling reconstruction of a volume of ultrasound data in real-time. At present, due to limitations in processing in most 3D ultrasound systems, a pyramidal 3D ultrasound volume of about 30°×50° can be acquired and displayed in real-time. Thus only a portion of the adult heart is displayed in three dimensions with a real-time acquisition, but, with adjustment of transducer positioning, one can also sufficiently display valves, the right ventricle, complex defects, masses, colour Doppler jets, the infant LV or portions of the adult LV. To optimally visualise such a real-time 3D ultrasound image, one can rotate it and view from all perspectives (figure 1). At present, to display a larger volume with such systems, the acquisition of a series of smaller 3D ultrasound component volumes (or ‘subvolumes’) over a series of cardiac cycles must be performed and then combined to yield a 90°×90° image set. This is commonly known as a ‘full volume’. Similarly, 3D colour Doppler flow mapping is performed with acquisition of a larger number of subvolumes. These ‘fused’ or ‘matched’ subvolumes are subject to motion artefact if there are even subtle alterations in position of the heart during the acquisition of the component images. Such artefact can be minimised by acquiring images with held respiration. Currently, these 3D image sets are obtained at frame rates of 20–25 Hz. Most recently, a new trans-thoracic system has been developed that allows the acquisition of the full 90°×90° volume of ultrasound data in real-time (figure 2). This approach is not subject to the artefact that may be observed from the fusing of multiple smaller volumes.

When a full volume 3D acquisition is first displayed, only an outer surface of the pyramidal ultrasound data set is seen and this is of limited...
value. To visualise the cardiac structures within this volume, one can cut or ‘crop’ it. Multiple dissection planes can be applied to display structures of interest from different perspectives (figure 3). For example, 3D colour flow Doppler acquired with the volumetric technique can be cropped through the major direction of the flow. This can enhance quantification of regurgitant lesions, especially when the jet is eccentrically directed.2

Matrix array transducers can also be used to obtain and display multiple simultaneous 2D image planes of a structure. The user can specify the different image plane angles. This ‘real-time multi-plane’ approach can be used to ensure that 2D images are on axis and is a valuable tool for quantification. For example, the endocardial borders from a series of simultaneous apical views of the LV can be obtained and then automatically or manually traced to calculate the left ventricular volume and systolic function (figure 4). Utilising the matrix array transducer in this fashion results in image quality comparable to that from standard 2D echocardiography.

Advantages of real-time 3D echocardiography
The most obvious advantage of 3D echocardiography is the ability to obtain a full 3D appreciation of cardiac structures and relationships. For those not trained in echocardiography, the images displayed from the 3D technique mirror the true object and thus are simpler to understand than a 2D image plane. Compared to prior approaches for 3D echocardiography, image acquisition with the volumetric method is simpler and potentially faster and thus the time to complete an examination should be shorter. With the real-time 3D and the real-time multiplane display, there is no time needed for off-line reconstruction and display. Since the true structures are displayed, accuracy of quantitation is enhanced.

Disadvantages and current limitations of real-time 3D echocardiography
For the full volume method, image manipulation (cropping) is required in order to find and display the cardiac structures of interest. This can be time consuming, especially for the novice, and require an additional computer workstation for image processing. At present, the image quality on real-time 3D transthoracic echocardiography is inferior.
Interest can be maintained in this zone. The lower frame rates compared to 2D echocardiography also result in reduced temporal resolution. Since reconstruction techniques and most full volume methods combine multiple images gated to the cardiac and sometimes to the respiratory cycle, motion artefacts will occur when the heart rate is irregular, or when the heart moves while the patient is breathing with effort and the sub-volumes obtained are stitched together. These can be minimised by only acquiring 3D full volume images when the cardiac cycle is regular and during held respiration.

Most of these limitations will be overcome with enhancements to transducer design and increased computing power. For example, with the introduction of expanded parallel processing, the number of scan lines transmitted from the transducer will be increased and this will improve the image quality. Also, as previously discussed, full volume acquisitions in a single cardiac cycle are now feasible, thus removing motion artefact.

APPLICATIONS OF 3D ECHOCARDIOGRAPHY

Left ventricular volume and function

Numerous studies in humans have shown the improved accuracy of left ventricular volume quantitation by 3D echocardiography compared to those measured from 2D echocardiograms and other modalities. Compared to cardiac magnetic resonance imaging (cMR), LV volumes calculated from contrast enhanced 3D transthoracic echocardiography are equivalent while the LV volumes from non-contrast enhanced 3D echocardiography are slight underestimations. On the other hand, volumes calculated from non-contrast 2D echocardiography can underestimate the cMR volume by more than 30% (table 1). In addition, measurement variability is reduced compared to 2D echocardiographic methods (table 2).

The improvement in accuracy is explained by the fact that a more accurate representation of the left ventricular endocardial surface occurs with the 3D echocardiogram than the 2D echocardiogram. 2D echocardiographic volume calculation uses formulae that rely on assumptions of the

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>LVEDV (ml)</th>
<th>LVESV (ml)</th>
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</thead>
<tbody>
<tr>
<td>cMR</td>
<td>207±79</td>
<td>117±71</td>
</tr>
<tr>
<td>2DE</td>
<td>125±54*</td>
<td>73±44*</td>
</tr>
<tr>
<td>CE-2DE</td>
<td>172±58*</td>
<td>100±51*</td>
</tr>
<tr>
<td>3DE</td>
<td>177±64</td>
<td>100±57</td>
</tr>
<tr>
<td>CE-3DE</td>
<td>196±96</td>
<td>111±59</td>
</tr>
</tbody>
</table>

Values are mean ± 1 SD.

*Statistically significant compared to the corresponding cMR value (p<0.05). Adapted from Jenkins, C. et al.©

CE-2DE, contrast enhanced two dimensional echocardiography; CE-3DE, contrast enhanced three dimensional echocardiography; cMR, cardiac magnetic resonance imaging; 2DE, two dimensional echocardiography; 3DE, three dimensional echocardiography; LVEDV, left ventricular end diastolic volume; LVESV, left ventricular end systolic volume; SV, stroke volume.

Figure 3 Three dimensional volume of ultrasound data (lower right) has been cropped into coronal (upper left), sagittal (upper right) and transverse (lower left) planes. Coronal image is viewed from front, the sagittal image is viewed from the lateral aspect, and the transverse image is viewed from the left ventricle apex.

Figure 4 Three apical transthoracic echocardiographic images can be obtained simultaneously with the matrix array transducer. The image planes are adjusted to obtain four chamber (upper left), two chamber (upper right), and long axis images (lower left). The endocardial borders were traced to obtain the left ventricular volume. CO, cardiac output; EF, ejection fraction; HR, heart rate; LVEDV, left ventricular end diastolic volume; LVESV, left ventricular end systolic volume; SV, stroke volume.
symmetry and geometry of the left ventricle. The volume of the left ventricle by the 3D echocardiographic technique, on the other hand, is calculated from the entire 3D left ventricular endocardial surface without assumptions of shape. In addition, the 2D methods are subject to underestimation if the images used for the quantitation are foreshortened. In contrast, the image planes displayed from the 3D echocardiographic dataset can be adjusted so that the true length of the LV is included. Furthermore, multiple methods for volume calculation can be used with 3D echocardiographic datasets. These include a method of discs, where multiple short axis planes are derived to create a series of component volumes of the left ventricle which are summed from base to apex. Another method directly sums the volume elements (voxels) enclosed by the endocardial borders of the 3D structure.

As noted above, compared to cMR, left ventricular volumes are slightly smaller when calculated from 3D echocardiography, but this can be corrected with the use of contrast. Echocardiographic images obtained from the apical transducer position may underestimate the left ventricular cavity slightly due to the ultrasound point-spread function and beam width. To compensate for this, one can trace the middle of the endocardial echocardiographic signal rather than the inner edge of the signal. In addition, there are differences in how the endocardial border is defined with echocardiographic and cMR techniques. With 3D echocardiography the spatial resolution currently is not high enough to allow differentiation of the myocardium from its many trabeculations, so the border that is traced is different from that on the cMR and usually excludes the trabeculations from the LV cavity, while cMR tracings tend to include the trabeculations as part of the LV cavity. Thus, either modifications to the conventions used to trace the ventricular borders or use of ultrasound contrast agents for improved endocardial border delineation can reduce this discrepancy.

**Right ventricular volume**

Accurate quantitation of right ventricular volume and function can be challenging by 2D echocardiography because its inflow, outflow and apex do not all align within a single 2D plane. However, this is solved with 3D imaging and the need for geometric assumptions or standardised imaging planes is eliminated. Numerous 3D echocardiographic validation studies of right ventricular volume show excellent correlation coefficients, standard errors, biases, precision and percentage inter-observer variability (table 2).

**Atrial volume**

Left atrial size is a marker of diastolic function and left atrial volume has also been shown to be associated with risk for stroke, cardiac events and, of course, atrial fibrillation. Due to the lack of symmetry of the atria, 3D echocardiography is ideally suited for accurate quantitation of left and right atrial volumes. The methods are similar to that for calculation of ventricular volume by 3D echocardiography, and in studies comparing it to cMR the volumes are more accurate than those from 2D echocardiography (table 2). Importantly, compared to 2D echocardiography, the test-retest variability, and the inter- and intra-observer variability are much lower with 3D echocardiographic measures of left atrial volume, thus improving the ability to detect significant changes over time.

**Left ventricular mass**

Left ventricular mass is utilised in the management of hypertension and valve diseases and is important in the prediction of prognosis. It is commonly calculated as the product of the volume of the left ventricular myocardium and the specific gravity of cardiac muscle. Since there are fewer assumptions about the geometry of the myocardium, the LV mass calculated by 3D echocardiography is more accurate and subject to less measurement variability than 2D echocardiographic methods. Left ventricular mass measurements by 3D echocardiography have been shown to be equivalent to those from cMR (table 2).

**Valvular heart disease**

3D echocardiography is well suited for assessment of cardiac valve disease due to its ability to image non-planar valve leaflets, demonstrate the spatial relationships of all components of the valve and surrounding structures, and depict colour Doppler flow in three dimensions. This is of particular value in the preoperative and intraoperative ultrasound evaluation of patients being considered for repair and replacement of valves.
Mitral valve
Since its early development, 3D echocardiographic approaches have been utilised to understand the complex geometry of the mitral valve and mitral annulus, thus improving the diagnosis of mitral valve prolapse.\(^w9\)

Mitral stenosis
Accurate planimetry of mitral valve area requires an image plane that is perpendicular to the long axis of the smallest mitral orifice. With 2D echocardiography, this can be a challenging task when the valve orifice is asymmetrically narrowed. In such cases, deviations from the ideal image plane positioning will lead to significant overestimations of the valve area. With the 3D volumetric technique, the best image of the valve can be cropped and rotated to display ‘en-face’ the best plane for planimetry.\(^1^1\) Since the commissures of a mitral valve affected by rheumatic fever may be asymmetrically fused, the image plane required to view and planimeter the mitral orifice may not be truly perpendicular to the long axis of the LV. Yet the 3D method can provide the necessary display of the orifice that may be difficult from a standard 2D echocardiogram (figure 5). Since multiple 2D ultrasound planes can be created simultaneously with a matrix array probe, another method for accurate planimetry of the mitral valve area is to obtain a long axis view of the mitral valve and then position a second intersecting 2D imaging plane that is perpendicular to the limiting orifice.\(^1^2\) Mitral valve area by real-time 3D echocardiography is more precise than 2D measurements and comparable to that of the pressure half time technique.\(^1^1\)

Mitral regurgitation
3D echocardiography can be utilised in several ways during the assessment of mitral regurgitation (MR). These include quantification of MR severity and the delineation of specific anatomic lesions associated with various causes of MR such as degenerative disease, myxomatous valve disease, congenital lesions and endocarditis.\(^1^3\) Quantitative 3D echocardiography has provided insights into the mechanisms responsible for functional and ischaemic MR.\(^1^4\) Mitral regurgitation can be quantified by the proximal isovelocity surface area method or the vena contracta area method.\(^w1^2,w1^3\) For each of these techniques, the 3D image of the colour flow Doppler velocities of the mitral regurgitant flow converging on the regurgitant orifice and exiting the regurgitant orifice, respectively, are displayed and cropped so that the true areas are depicted. The measurements can then be made without the assumptions of shape typically used in the 2D method. In addition, similar to planimetry of stenotic valve orifices, a direct measurement of the regurgitant orifice area by 3D echocardiography is feasible and may overcome some of the limitations of the calculation of this area by the other methods.\(^5\)

Aortic valve
3D echocardiography may have value in the assessment of aortic valve disease since all aspects of the three leaflets of the aortic valve cannot be visualised in a single 2D plane, and the 2D ultrasound imaging plane often is oblique through the stenotic or regurgitant aortic orifice. Direct planimetry of the aortic valve in aortic stenosis, description of valve morphology (ie, number of leaflets), localisation and description of subvalvular obstruction (both discrete membranes and hypertrophic septum/LV outflow tract obstruction), quantification of aortic regurgitation, and assessment of aortic root pathology have all been demonstrated with 3D echocardiography.\(^w1^4\) The vena contracta and proximal isovelocity surface area methods as described for quantitation of MR above can be applied to aortic regurgitation.

Other applications
3D echocardiography can be applied to any of the current uses of 2D echocardiography. Reports of its
Use highlights improved diagnosis, improved display of complex spatial relationships, and shorter time for image acquisition. Use of 3D echocardiography has been described in a variety of diseases and procedures including hypertrophic cardiomyopathy, infective endocarditis, congenital heart disease, aortic dissection, right ventricular biopsy, percutaneous cardiac interventions, pericardial effusions, cardiac masses and left ventricular mechanical dysynchrony. For most of these applications it is premature to determine if 3D echocardiography provides additional information that alters diagnosis or outcome, or whether it is just that the information is obtained in a simpler or faster fashion.

3D TRANSESOPHAGEAL ECHOCARDIOGRAPHY

3D display of transoesophageal echocardiographic (TOE) images has been performed with single and multiplane transducers by reconstructing gated, 2D cross-sectional images obtained from known transducer positions. There are several limitations to this technique including the time required for processing and image display, and the presence of motion artefacts.

Recently, a full matrix array transducer for transoesophageal imaging has become commercially available. In addition to its capacity to perform standard 2D multiplane imaging, this transducer has the ability to provide real-time 3D, full volume, and 3D colour Doppler imaging similar to a transthoracic matrix array transducer. It is also capable of displaying two simultaneous 2D imaging planes. Similar to comparisons of 2D TOE with 2D transthoracic echocardiography, the real-time 3D TOE images demonstrate improved image resolution compared with the real-time 3D transthoracic approach. This technology overcomes many of the practical limitations of reconstructed 3D TOE, thereby making it potentially more useful in the clinical arena. Initial experience with real-time 3D TOE suggests value in the clinical evaluation of structural heart disease, intraoperative assessment, and guidance of interventional procedures that require real-time imaging. This real-time technique is relatively new so the peer reviewed published literature using this approach is limited. Most published reports of the utility of 3D TOE utilise the reconstruction method.

3D TOE imaging provides unique echocardiographic views of the mitral valve, allowing visualisation of this valve from both the atrial side and ventricular side (figure 6). These ‘en-face’ views of the mitral valve are familiar to surgeons and pathologists, and may provide additive information for the assessment of a surgical repair in complex myxomatous mitral valve disease by characterising the location and extent of leaflet prolapse (figure 7). 3D TOE provides an accurate assessment of mitral valve morphology and is highly predictive of the valve pathology directly identified in patients undergoing mitral valve surgery. Studies have shown that real-time 3D TOE more accurately identifies the segments involved in some types of mitral valve prolapse compared with standard 2D TOE.

As with the transthoracic approach, 3D TOE also provides useful information in mitral stenosis through a detailed analysis of leaflets, leaflet commissures, valve orifice area and subvalvular apparatus.

Another value of the novel 3D display with this TOE technique is in patients who have undergone prior mitral valve replacement. In these patients, it is often easier to detect the exact site or full extent of paravalvular leaks or vegetations with 3D compared to 2D TOE (figure 8).

Planimetry of aortic valve area by intraoperative 3D TOE (reconstruction technique) has been shown to be accurate compared with invasive (Gorlin equation) and Doppler (continuity
Thus, real-time 3D TOE may help in the delivery catheter. (D) View of right atrial portion of the occluder device in position but still attached to the delivery catheter.

**Three dimensional echocardiography: key points**

- Understanding of the complex shapes and spatial relationships of various cardiac structures is enhanced with three dimensional (3D) echocardiography.
- 3D echocardiography eliminates the need to assume a specific geometric shape of the left ventricle or right ventricle when quantifying volume and ejection fraction.
- 3D echocardiography has the potential to reduce the time required for echocardiographic image acquisition.
- 3D ultrasound can be acquired as either a series of 2D images requiring reconstruction into a 3D image or as a 3D volume of ultrasound.
- The reconstruction technique requires image acquisition, registration, reconstruction and rendering before display.
- The volumetric technique requires a rectangular (matrix) array transducer and the images are best displayed after off-line cropping of the 3D ultrasound dataset.
- Multiple 2D image planes can be obtained simultaneously with a matrix array transducer.
- 3D echocardiographic quantitation of left ventricle volume, ejection fraction, mass and right ventricle volume are more accurate than the 2D approaches, and these measurements derived from 3D echocardiography have reduced measurement variability.
- In congenital heart disease, significant benefits of 3D echocardiography over 2D echocardiography have been noted in patients with atrial septal defect, ventricular septal defect, atrioventricular septal defects and L-transposition of the great vessels.
- An important enhancement to the current 3D transthoracic echocardiographic technique required before broader clinical applications includes higher volume or frame rate acquisitions to improve image quality and resolution.
- Real-time 3D transoesophageal echocardiography provides high quality images of the mitral valve and some other cardiac structures in a format that is easy to understand by those familiar with cardiac anatomy.

**CONCLUSIONS**

3D echocardiography is a technique undergoing rapid evolution. It has many advantages over 2D echocardiography including improved visualisation of complex shapes and spatial relations between cardiac structures, improved quantitation of cardiac volumes, mass and function, improved visualisation of colour Doppler flow fields, improved display and assessment of valve dysfunction, and decreased time for image acquisition. For the real-time volumetric approach, technical improvements including those that will lead to better transthoracic image quality and those that will make image display easy and intuitive are required for its widespread clinical use and for it to replace 2D echocardiography. Image quality with real-time 3D TOE is satisfactory for clinical use, and it is anticipated that it will provide cardiac structural information at the bedside faster and in a manner that can improve comprehension. Specifically, in current clinical practice, 3D transthoracic echocardiography can be utilised with confidence for measurement of LV volumes, ejection fraction, mass and right ventricle volume.
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mass and left atrial volume in addition to display of cardiac valve anatomy. The clinical roles for 3D TOE include display and assessment of mitral valve anatomy, display and quantitation of cardiac defects such as ASD, and the real-time guidance of percutaneous cardiac interventions.

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► One of the original studies demonstrating the accuracy of left ventricular volume determination by 3D echocardiography.


► Validation study of real-time 3D echocardiographic quantification of LV volume.


► A multicentre study demonstrating the reliability of 3D echocardiographic derived LV volumes and their high correlation with cMR. This paper explores some of the reasons that 3D echocardiography can underestimate LV volume when compared to cMR.


► Study showing the value of 3D echocardiography for serial assessment of cardiac structure and function. Compared to 2D echo and echocardiographic methods, reduced test-retest variation with 3D echocardiographic measurement of LV volume, EF, and mass measurements is demonstrated.


► Early report of the accuracy of real-time 3D transthoracic echocardiography for the quantification of mitral valve area in mitral stenosis.


► Demonstration of the feasibility and reproducibility of 3D guided measurement of the mitral orifice area in mitral stenosis.


► Nicely illustrated study demonstrating that the precise location of mitral valve prolapse defects can be visualised better on real-time 3D transthoracic echo and 3D transesophageal echo (by reconstruction technique) compared to 2D methods.


► Study highlighting the feasibility and accuracy of 3D transesophageal echocardiography to image and assess the morphology of native and prosthetic heart valves.