What is and how to do 3D echocardiography?

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Introduction

Three-dimensional (3D) echocardiography has a long history with the first 3D-reconstruction of two-dimensional (2D) images in 1974. However, the equipment was impractical and images were unsuitable for clinical use. Over the subsequent decades, several researchers, primarily in biomedical engineering, worked on overcoming technical challenges to make the equipment smaller, yet capable of generating high resolution images from complex transducers. They developed instruments that acquired a series of 2D scans in a linear, fan-like, or rotational manner and consolidated them into a 3D image. However, this was predicated on the assumption that both, the transducer and patient were in a fixed position relative to each other during the acquisition of serial 2D scans. This was the major limitation to the development of real-time 3D imaging. Rotational scanners were then developed, followed by electromagnetic instruments. With improvements in computing power and transducer technology, real-time 3D echocardiography became a reality when Von Ramm and colleagues at Duke University described the acquisition of a complete volume rendition of the heart in a single cardiac cycle.

The transducer used in multiplane TEE, first introduced by Hewlett-Packard in 1990, was an ideal foil to the development of 3D TEE. The multiplane transducer could already rotate from 0 to 180 degrees, and all that was required to enable 3D imaging was an automated acquisition of scan planes at regular intervals through the 180 degrees, followed by offline integration into a 3D image.

The first 3D-TEE was performed in 1992. Initially, this technique was thought to allow a better understanding of both the spatial relationships of cardiac structures as well as of the complex shape of the mitral valve. However, the image quality using early reconstructive techniques was critically dependent on the quality of the 2D images. Minor patient movements (during ventilation) or movement of the heart (during arrhythmia) result in imaging artifacts that could render the image unsuitable for interpretation. Acquisition and reconstruction processes frequently took too much time (15-30 min) thereby restricting reconstructive 3D-TEE to primarily a research role. Some of these limitations were overcome with the development of a sparse array matrix transducer that was first used in the late 1980s. Although this transducer generated different cut-planes from a 3D volume in real time, it was incapable of displaying real-time (RT) rendered 3D images. Further advances in computer and crystal technology led to the introduction of the currently used matrix-array transducer for the use in transthoracic echocardiography (TTE). This transducer uses a large number of elements (> 3000) and is capable of generating 3D images in real time (see figure 1). Further reduction in transducer size led to the introduction of the first echocardiographic system allowing RT-3D-TEE (Philips Medical Systems, Andover, MA).
Image Acquisition

The current RT3DTEE system also provides the conventional modalities such as 2D multiplane imaging, M-Mode, pulsed and continuous wave Doppler as well as color flow Doppler imaging. Earlier systems that had excellent 3D imaging did so at the cost of 2D imaging. However, in the newer 3D systems, the quality of 2D imaging is equivalent to dedicated 2D systems. For 3D imaging, the system offers four imaging modes:

- **Live 3D**: displays a pyramidal dataset with dimensions of approximately 50° x 30° that can be used to display cardiac structures located in the near field.

- **3D Zoom**: displays a truncated but magnified pyramidal dataset of variable size. When selected, the 3D-zoom mode displays a bi-plane preview screen showing the original view and the corresponding (perpendicular plane) orthogonal image. The zoom sector over the region of interest should be placed carefully and sector-width minimized to improve temporal resolution and optimize image quality. This mode is particularly suited for imaging the mitral valve, but may also be used for the tricuspid valve, the left atrial appendage or the inter-atrial septum.

- **Full Volume**: provides a pyramidal data set (up to 100° x 100°) that allows the inclusion of a larger cardiac volume. The wide angle data set is compiled by merging four to seven narrower RT-3D pyramidal wedges obtained over four to seven heartbeats. Imaging artifacts may be avoided in the anesthetized patient by suspending ventilation and avoiding electrocautery use during acquisition of the full volume sequence. Therefore, it is desirable to acquire full volume loops at the beginning of the comprehensive TEE-exam in the operating room prior to the start of surgery. A full volume loop of the left ventricle is based on the 2D midesophageal four chamber view. When selected, the full volume mode displays a biplane image with the four chamber view and the (perpendicular plane) corresponding orthogonal image. The 3D-volume is displayed as a 50% cropped volume mirroring the four chamber view. This is necessary since the full volume image at the outset will not display intraventricular structures like valves, papillary muscles etc. Resetting the crop plane however, allows the whole pyramidal dataset to be displayed. The full volume can be further processed offline by rotating and cropping to visualize specific intracardiac structures. Cropping can be performed by either using one of six available cropping planes selected from a 3D cropping box or by using a freely adjustable plane. Acquired full volumes can also be used for volumetric quantification of the LV using available built-in software (QLAB, Philips Medical Systems, Andover, MA).

- **3D Color Full Volume**: Similar to the acquisition of a full volume the wide angle data set is compiled by merging 7 to 14 narrower RT-3D pyramidal wedges and is similarly prone to artifacts introduced by arrhythmias, movement, or electrocautery. For this mode it is essential to place the area of interest, for example, the regurgitant jet, in the center of the sector. The remainder of the acquisition is identical to that used for full volume acquisition. In the newer software release, the color full volume may be acquired using 1, 2, 4 or 6 separate slices. Once again, one must balance the need for optimal frame rates (more slices) with the tendency for stitch artifacts.

While precise measurements using caliper and trace functions are not currently available in the 3D images, approximate measurements may be made using the 3D-grid with a specified dot-to-
dot distance. The built-in 3D quantification software contains several programs including mitral valve quantification (MVQ), 3D Quantification (3DQ), and 3D quantification advanced (3DQAV).

The MVQ program features a semi-automated analysis package for detailed modeling of the mitral valve, including the mitral annulus, valve commissures, leaflet coaptation, leaflet topography, and aortic orifice to mitral valve angle. The 3DQAV provides data for both global left ventricular function as well as regional wall motion abnormalities and resynchronization therapies (e.g., time to minimal systolic volume). The system relies on automated endocardial border detection and border tracking algorithms that can also be manually edited. Upon completion of the analysis, as many as 17 regional waveforms are displayed simultaneously allowing objective wall motion comparisons. Finally, 3DQ allows simple quantitative assessment of any 3D data set (e.g. area, distance).

**Mitral Valve**

The mitral valve has a complex arrangement and remains one of the most challenging structures to image in 2D echocardiography. It has a saddle shape and a variety of scallops on both its leaflets and additional subvalvular apparatus that make it a three dimensional structure difficult to comprehend with 2D echo images alone. It takes several 2D echo images to conjure up a mental 3D image of the mitral valve. 3D echo takes some of that guesswork away and improves our understanding of the anatomy and pathology of the mitral valve.

A comprehensive 3D assessment of the mitral valve involves the acquisition of 3D zoom, 3D full volume, and 3D color full volume datasets. These can be supplemented by quantitative assessments offline using built-in MVQ software. The midesophageal four chamber view is used as a starting reference and a 3D zoom dataset is acquired keeping the mitral valve in the zoom sector in both the four chamber and orthogonal planes. The resulting 3D volume is then rotated to display the aortic valve at 12 o’clock as the midpoint of the anterior mitral annulus to display the ‘en face’ mitral view. This view mirrors the surgeon’s view from the left atrium down to the MV (figure 1). This sequence usually results in high quality volume-rendered images of the anterior leaflet the top and the posterior leaflet at the bottom of the image as well as the entire mitral apparatus. The mitral valve may then be examined from either atrial or ventricular perspectives by using the trackball to orient the image.

The relationship among the mitral valve, subvalvular apparatus, myocardial walls and left ventricular outflow tract can be appreciated using the full volume dataset. The size and geometry of regurgitant jets can also be assessed, allowing measurement of the effective regurgitant orifice area (EROA) without the need for more complex proximal isovelocity surface area and Doppler velocity equations.

A complete mitral valve exam should also include an assessment of the interatrial septum and the left atrial appendage. This is especially important in the presence of mitral stenosis or when the 2D exam suggests that the left atrium is enlarged or contains spontaneous echo contrast.
indicating sluggish flow. The 3D exam may help differentiate between a bilobed left atrial appendage versus an actual thrombus when the 2D exam is inconclusive.

In mitral stenosis, 3D TEE may help quantify mitral valve area more accurately. However, 3D may add little to management, since the decision to operate on the valve may depend on other factors rather than the calculated area alone. In mixed lesions, 3D echo may help with decision making by identifying valvular pathology such as cleft valves, and immobile scallops that may not be readily appreciated with 2D echocardiography.

**Left Ventricle**

The full volume mode is ideal for assessing left ventricular volumetrics. This requires manual definition of the septal, lateral, anterior, inferior and apical endocardial borders of the endsystolic and the enddiastolic frames, which is followed by an automated border-tracking algorithm. The system then calculates endsystolic as well as enddiastolic volumes by summation of volume pixels ('voxels') within pre-defined endocardial borders (figure 2). Several options are available within the 3DQAV program, including the iSlice and shell views. The software also allows for a 17-segment motion analysis and the popular 'jelly bean' view.

**Aortic and tricuspid valves**

While 3D TEE is ideally suited for imaging the mitral valve, the aortic valve (AV) and tricuspid valve (TV) can also be imaged suitably, albeit not with the image quality of the mitral. The live-3D mode is excellent for both the AV (figure 3) and TV. The presence of thickened or calcified leaflets makes the valves more echodense, thereby enabling easier visualization by 3D TEE. The presence of catheters and wires across the TV can make imaging a bit more challenging due to the presence of numerous ultrasound artifacts. Imaging the AV using live 3D imaging is useful during transcatheter aortic valve implantation, where the echodense prosthetic valve lends itself well to echo imaging.
Prosthetic valves

One of the principal advantages of 3D echocardiography is the improved ability to recognize the spatial arrangement of structures. Malfunctioning prosthetic valves, especially in the mitral position, can be imaged relatively easily and areas of malfunction identified. Lesions such as endocarditis, stuck leaflets, paravalvular leaks and ring dehiscence can not only be identified, but their exact location can be determined to provide the surgeon with more accurate information prior to surgical correction. Color 3D can also be used to identify paravalvular leaks and guide interventional therapy (figure 4).

Recommended Sequence

A recommended sequence for 3D TEE examinations starts with the acquisition of a 3D full volume (four or seven beats) of the left ventricle prior to the start of surgery thereby avoiding electrocautery artifacts. This should be followed by a 3D zoom view of the mitral valve and acquisition of a 3D zoom dataset. In the presence of mitral regurgitation, a 3D color full volume dataset of the mitral valve should be obtained to analyze the shape and location of the jet and to measure a vena contracta or effective regurgitant orifice area. The next step could be the assessment of the LAA and of the aorta again with the 3D zoom mode. Depending on co-morbid conditions, additional images from the aorta, aortic and tricuspid valves may also be obtained. Following acquisition of these independent datasets, the built-in software can be used to perform offline measurements including left ventricular function using 3DQAV, and mitral valve assessment using MVQ.

Limitations

Although RT3DTEE represents an important step in perioperative imaging, significant imitations remain. First, while 3D zoom and live 3D are indeed real-time modes, the acquisition of a 3D full volume as well as a 3D color full volumes are based on automatic reconstruction from subvolumes and are therefore prone to artifacts from arrhythmias, and ventilation – the so-called stitch artifacts. Second, as 3D echo obeys the same physical laws as 2D, poor 2D image quality will likely translate in similarly poor 3D image quality. Unlike the mitral valve, other structures in the far field like the aortic and tricuspid valves are more difficult to visualize using current technology. Third, direct measurements (e.g. caliper, trace) cannot be performed directly in 3D images and require the use of time-consuming software. Fourth, although the built-in software features quantitative assessment of the mitral valve and left ventricle, it would benefit from a more user-friendly interface. Finally, as with most new technology, RT3DTEE will prolong a comprehensive TEE examination, especially when quantitative techniques are employed. However, in the future and with further improvements in technology, RT3DTEE may help to
even expedite a comprehensive TEE examination by using a single 3D view of the mitral valve rather than the five conventional 2D views.

References


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