Real-Time 3D: Theory, Knobology and Data Acquisition

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Learning Objectives
At the conclusion of this discussion, the participant will be able to:

1. Define the basic principles of three-dimensional echocardiography
2. Review the technique of real-time 3D transesophageal echocardiography
3. Describe the imaging technique for assessment of the mitral valve and left ventricle

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). More recently, the 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. Significantly though, tissue Doppler imaging has been disabled in the current release. 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.

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 echocardiography may help with decision making by identifying valvular pathology such as cleft valves, and immobile scallops, which 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 end systolic and the end diastolic frames, which is followed by an automated border-tracking algorithm. The system then calculates end systolic as well as end diastolic 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.

Other cardiac structures that may also be assessed include the aortic and tricuspid valves and the thoracic aorta. Further refinements in technology may render RT3DTEE more useful for these structures beyond 2D echo.

**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 limitations 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


Acknowledgement: G. Burkhard Mackensen, MD, PhD, FASE, Duke University Medical Center
**Tips for 3D Imaging**

**Live 3D Mode (no image artifact with irregular heart rhythms)**

- A **real-time** 3D mode.
- Can easily switch from 2D to 3D. Able to check spatial location of 2D image by clicking on live 3D. Good for using 3D to determine location and switching to 2D to make quick measurements.
- Cannot fit the entire mitral valve or left ventricle in the image.
- You must move the probe in live 3D mode to scan the entire valve or ventricle.
- Frame-rates of 20-30Hz (temporal resolution).
- Can change from moderate to high line density for better spatial resolution, but smaller 3D image.
- Start imaging with the lowest frequency (better edge delineation).
- Can actively optimize 3D image (knobology) while in this mode.
- Can guide procedures in 3D (eg. wire guidance in the cath lab).

**3D Zoom Mode (no image artifact with irregular heart rhythms)**

- A **real-time** 3D mode
- Like 2D zoom, able to focus the 3D image on a specific anatomic area.
- Good for evaluating valves (able to fit the entire mitral or aortic valve in the 3D image).
- Determine the size of the 3D data set in the X, Y, and Z planes prior seeing 3D image. Optimize the image on the left (X and Y plane) prior to optimizing the image on the right (Z plane). Only include what is needed for the image to optimize frame rate.
- Start imaging with the lowest frequency (better edge delineation).
- The larger the size of the 3D image, the slower the frame rate.
- Line density can be changed from low, to medium, to high. (greater line density = slower frame-rate)
- Frame-rates range from 5-20Hz depending on image depth, line density, and 3D image size.
- Can actively optimize 3D image (knobology) while in this mode.
- Can guide procedures in 3D (eg. wire guidance in the cath lab).

**3D Full-Volume Acquisition (not real-time 3D)**

- Gated acquisition of a 3D data set.
- Good for viewing larger structures like the entire left ventricle (needed for LV volume assessment).
- Good for obtaining high frame-rate images of the mitral valve.
- Can get stitch artifacts if the patient has an irregular heart rhythm.
- Take the patient off of the ventilator during the acquisition (reduces motion artifact).
- Need at least four heartbeats for a single acquisition.
- Can change to a higher frame-rate mode that requires seven heartbeats for the 3D data set.
- Changing the line density changes the size of the final 3D data set
- Greater line density better resolution, but smaller final 3D data set
- Start imaging with the lowest frequency (better edge delineation).
- Frame-rates range from 20-40Hz in four beat mode (40-50Hz in seven beat mode).
- The higher frame-rates are helpful for valve pathology if the patient has a regular rhythm.
- Must set image optimization parameters prior to acquisition. Set the image on the left and then the image on the right.
- **Optimize 3D gain and compression in Live 3D mode prior to obtaining full-volume data set.** Try to optimize 3D gain at 50% and compression at 30% in Live 3D mode. Do this with the assistance of the time gain compensation levers.
- Limited image optimization once the data set is acquired.

**3D Color Flow Doppler Acquisition**

- Gated acquisition of a 3D data set.
- Can get stitch artifacts if the patient has an irregular heart rhythm.
- Take the patient off of the ventilator during the acquisition (reduces motion artifact).
- Need at least seven beats for a single acquisition.
• Set the line density to low. This will increase the color flow Doppler sector to the largest available size (important for visualizing the entire mitral valve with color).
• Set the Nyquist limit prior to acquisition.
• Must set image optimization parameters prior to acquisition.
• Limited image optimization once the data set is acquired.

3D Exams

3D Valve Exam
• If the patient has a regular rhythm acquire a high-frame rate full volume data set (seven beats) and 3D color flow Doppler data set prior to surgical incision.
• For the mitral exam remember to set the top two time gain compensation levers to the lowest setting to remove the atrial cap from the final image. This will allow imaging the 3D mitral valve without need for cropping.
• For the mitral valve remember to z rotate the image to put the aortic valve at the top of the image (surgeon view)
• Gated acquisitions can be obtained after surgical incision, but the best images are obtained when the surgeon stops electrocautery and moving the heart while the acquisition is performed.
• Real-time imaging modes (live 3D and zoom) are not affected by surgical movement of the heart and ECG artifact caused by electrocautery.
• During the pre-bypass period, obtain live 3D and zoom mode images (especially in patients with irregular heart rhythms where gated acquisitions may not be adequate).
• Scan the valve by advancing and withdrawing the probe in live 3D mode to get a complete picture.
• Obtain 3D zoom mode images of the entire valve.
• Use the 3D images to compliment a complete 2D and Doppler exam to communicate findings.
• Use available software to further define valve pathology if necessary.
• Post-bypass re-evaluate the valve using all available modes. 3D imaging with color is especially helpful for locating perivalvular leaks.

3D Ventricle Exam
• If the patient has a regular rhythm acquire a four beat full volume data set prior to surgical incision.
• Gated acquisitions can be obtained after surgical incision, but the best images are obtained when the surgeon stops electrocautery and moving the heart while the acquisition is performed.
• If the patient has an irregular heart rhythm ventricular data sets may not be accurate.
• Live 3D and zoom modes can be used, but the data sets will not be large enough to fit the entire left ventricle.
• Use the 3D images to compliment a complete 2D and Doppler exam to communicate findings.
• Use available software to further evaluate ventricular function if necessary (Adv 3DQ).
• Post-bypass re-evaluate the ventricle using all available modes.

Suggested Reading