3D Theory, Knobology and How to Acquire and Manipulate a 3D Image
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Introduction
Three-dimensional echocardiography (3DE) refers to the technique of visualizing the heart and its structures and flows in the three-dimensional format either in real-time or after reconstruction from multiple two dimensional images. Only recently, has it gained attention for its utility in the perioperative environment. This is primarily due to faster acquisition times, including real-time imaging, and better methods to analyze the data obtained for patient management and surgical decision-making (1).

We are only beginning to realize how 3DE can improve our understanding of ventricular and valve function. For example, 3DE is providing valuable insight in the complex anatomic relationships that 2DE fails to adequately image (3,4). 3DE provides accurate quantification of left and right ventricular volumes, mass, and ejection fractions without making geometric assumptions as in 2DE (5). There is improved visualization of spatial relations and 3DE provides unique “en face” views and surgical views not previously obtainable by 2DE (5). Below is a brief summary of how 3DE is being used for perioperative surgical planning and diagnosis.

Ventricular Analysis
The utility of 3DE in the evaluation of ventricular function has been looked at in several studies. Qin et al used RT3DE to quantitatively assess changes in LV volume and function after LV reconstruction surgery in patients with ischemic cardiomyopathy (6). Shiota and McCarthy determined that 3DE is valuable in facilitating the communication between echocardiographers and cardiac surgeons in volume reduction surgery for end-stage ischemic heart disease (7). Arai et al determined that RT3DE allows convenient and accurate estimation of LV volume and ejection fraction in patients with wall motion abnormalities (8). 3DE is advantageous in the patients who have ventricles with complex geometry since it does not rely on geometric assumptions to make these calculations (5). The usefulness of RT3DE is also being evaluated in patients with obstructive hypertrophic cardiomyopathy (9, 10). RT3DE is being used to determine the exact location of the systolic anterior motion of the mitral leaflet, the extent of mitral leaflet to septal contact, and the precise area of the left ventricular outflow tract obstruction.

Mitral Valve
Intraoperative surgical planning depends on proper evaluation of the mitral valve apparatus (11). The feasibility, accuracy and value of intraoperative 3DE in valve surgery was studied by Abraham et al (12). Intraoperative 2D and 3D reconstruction TEE examinations were performed on 60 patients undergoing valve surgery. 3D acquisitions were completed in 87% of the patients within a mean acquisition time of 2.8 ± 0.2 minutes and reconstruction time within 8.6 ± 0.7 minutes. 3D echocardiography detected all salient valve morphological pathology (leaflet perforations, fenestrations and masses), which was subsequently confirmed on pathological examination in 84% of the patients. In addition, intraoperative 3D TEE provided new additional information not obtained by 2D TEE in 15 patients (25%), and in 1 case influenced the surgeon’s decision to perform a valve repair rather than a replacement. Furthermore, intraoperative 3DE provided worthwhile and complimentary anatomic information that explained the mechanism of valve dysfunction demonstrated by 2D imaging and color flow Doppler. The ability of 3DE to render new views not previously obtainable by 2DE, such as the “en face” and surgical views of the mitral valve, provide new insight and possible better communication to the surgeon. Ahmed et al evaluated the potential utility of 3D TEE in identifying individual MV scallop prolapse in 36 adult patients undergoing surgical correction (13). Perfect correlation between 3D TEE and surgical findings was noted in 78% of the patients. Being able to “cut” the mitral valve in any plane from both atrial and ventricular views adds a new dimension to its evaluation. In studies comparing 2D vs 3D TEE for measuring MV area and volume in patients with stenosis undergoing percutaneous MV balloon valvuloplasty (PMTV), 3D TEE enabled a better description of valve anatomy including the identification of commissural splitting and leaflet tears post PMTV (14, 15, 16). Two studies have shown that 3DE of the mitral valve allows direct visualization and accurate planimetry of the regurgitant orifice area in patients with mitral regurgitation when compared to the proximal flow convergence method (17, 18). Sugeng et al studied 3DE with color flow Doppler (19). The study looked at 46 patients with mitral regurgitation. 3D color flow Doppler was particularly helpful in patients with paravalvular leaks and eccentric jets.
Several recent studies have highlighted the feasibility and utility of RT3D TEE for evaluating mitral valve disease (20). In 211 patients, including patients with atrial fibrillation, there was excellent visualization of all mitral valve leaflet scallops (anterior and posterior) in 85-91% of patients (21). In 47 patients, intraoperative diagnosis was used to confirm the RT3D TEE exam. Surgical findings correlated in 96% of the patients (22).

### Aortic, Pulmonary, and Tricuspid Valves

3D visualization of the aortic, tricuspid and pulmonary valves is not as good as the mitral valve. Their valve tissue is thinner compared to the mitral valve. In addition, the valves are more anterior and obliquely oriented to the ultrasound beam rendering 3D images that have dropout artifacts. In 211 patients studied using RT3D TEE, each aortic valve cusp was optimally visualized only 18-21% of the time. Each tricuspid valve cusp was optimally visualized only 11% of the time (21). The pulmonic valve was not studied, but from personal experience visualization is often poor. Despite the poorer image quality of the aortic valve in 3D, clinical case reports and studies have been published using the spatial advantages of 3DE. 3D TEE gated-reconstruction with 3D color flow Doppler helped identify the location and extent of aortic valve dehiscence (23). Another case report looked at 3D TEE gated-reconstruction to help determine the location of vegetation and extent of damage caused by endocarditis (24). Since the aortic valve is central to all of the cardiac structures, better diagnosis and communication of aortic valve pathophysiology and its spatial relationship and involvement of related structure could help improve surgical decision-making and planning.

### Congenital Pathology

3DE is being used to evaluate congenital heart pathology, including atrial septal defects and ventricular septal defects. The ability to look at the defect “en face” from both the left and right atrial views and the left and right ventricular views helps to delineate the borders and size of the defect. Lange et al compared preoperative 2D and 3D TTE evaluations with intraoperative findings in 15 patients with atroventricular septal defect morphology (25). 3DE reconstruction provided superior imaging of the MV and tricuspid valve function, a more precise description of primum atrial septal defect (ASD) size, secundum ASD fenestrations and ventricular septal defect (VSD) size. 3DE measurement of ASD size has correlated well with findings obtained intraoperatively or during transcatheter closure (26). Two case reports have demonstrated the accuracy of 3DE in imaging post-infarct VSD’s and pseudoaneurysms (27).

RT3D TEE provides excellent visualization of the atrial septum (21). The fossa ovalis and thicker limbus tissue surrounding the fossa is easily visualized allowing 3D measurement of defects, and with real-time viewing, guidance of percutaneous procedures including transseptal punctures and placement of closure devices.

### Limitations

Although 3DE has shown promise it still has drawbacks that need to be considered. 3D gated reconstruction requires additional time to acquire and reconstruct the images. Any type of motion artifact in the 2D images prior to reconstruction will make the 3D data set suboptimal. Patients with atrial fibrillation or an irregularity in their RR interval will prolong data acquisition and make the 3D reconstruction of poorer quality (stitching artifacts). RT3D TEE is a newer technology. Its ability to visualize near-field structures such as the left atrium, atrial septum, mitral valve and left ventricle appears superior to far-field structures such as the tricuspid and pulmonic valves. Real-time 3D images have slower frame-rates and decreased line density compared to traditional 2D imaging.

There is a learning curve to data acquisition and reconstruction. 3D echocardiography much more than 2D requires a complete understanding of the physics of ultrasound. The ultrasound frequency, line density, depth of the image, sector size, gain, and dynamic range (compression) settings must all be optimized based on the structure and pathology to be imaged. This will maximize both spatial and temporal resolution (frame rate) and minimize image dropout and other 3D artifacts.

### 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.
- 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.
- 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 the density, slower the 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).
- 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 3D gain at 50% and compression at 50%.
- 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.
- Decreasing line density will increase the largest color flow Doppler sector size available (important for visualizing the entire mitral valve with color).
- Set the Nyquist limit prior to acquisition.
- Must set image optimization parameters prior to acquisition.
- Set 3D gain at 50% and compression at 50%.
- Limited image optimization once the data set is acquired.

Rotational-Gated 3D 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).
- Set the number of degrees per 2D image acquisition for the production of the 3D data set.
- Typically set at 3 or 5 degrees per 2D image (60 versus 35 slices needed for 3D data set).
- Less degrees yields more slices and better final 3D image quality (takes more time).
- Define the area of interest prior to acquisition.
- Must set image optimization parameters prior to acquisition.
- Start with the frequency set around 5Hz.
- Limited image optimization once the data set is acquired.
- Can take both color and gray scale in one acquisition.
- Can obtain a larger color flow Doppler area than with the 3D color flow Doppler acquisition.
3D Valve Exam
- If the patient has a regular rhythm acquire a high-frame rate full volume data set and 3D color flow Doppler data set prior to surgical incision.
- The rotational-gated 3D acquisition should also be performed prior to incision (with color).
- 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 the bovie.
- 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 high-frame rate full volume data set and 3D color flow Doppler data set prior to surgical incision.
- The rotational-gated 3D acquisition should also be performed prior to incision (with color).
- 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.
- Post-bypass re-evaluate the ventricle using all available modes.

Bibliography
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