Introduction to 3D Echocardiography

G. Burkhard Mackensen, MD, PhD, FASE
Professor & Acting Chair, Department of Anesthesiology & Pain Medicine
UW Medicine Research & Education Endowed Professor in Anesthesiology
Adjunct Professor of Medicine
University of Washington, Seattle

Objectives and Goals:
At the conclusion of this lecture, the participant should be able to:

1. Understand the principles of three-dimensional echocardiography
2. Understand the basis of image formation and display
3. Appreciate the various modes of the 3D echocardiography

3D Reconstructive Technology versus Real-time 3D Echocardiography

Three-dimensional (3D) echocardiography has a long history with the first 3D-reconstruction of 2D images described in 1974 by Dekker et al. With their approach, the patient was scanned with a transducer attached to a mechanical arm that fed quadrant data to a computer mainframe. However, equipment such as this was impractical and images were unsuitable for clinical use. Over the subsequent decades, biomedical engineers and clinicians 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 reconstructed 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. In an attempt to bring reconstructive 3D echocardiography to the market, rotational methods and electromagnetic instruments were developed alongside freehand methodologies. The rotational approach was designed to permit 3D reconstruction based on a transducer that was held in a cylindric device and rotated in a circular pattern around a fixed axis. Hewlett Packard first developed a rotational transducer in which the entire rotation apparatus was contained within the transducer. The first reconstructive 3D images using TEE were obtained in 1992. However, for years, the image quality using reconstructive techniques has been shown to depend critically on the quality of the original 2D images where minor patient movements (during breathing or ventilation) or movement of the heart (during arrhythmia) may result in artifacts. Due to cumbersome and time-consuming acquisition and reconstruction processes (15-30 min), reconstructive 3D echocardiography remained primarily a research tool. Technologic advances led to improve the acquisition of multiple, gated image planes using electrocardiographic (ECG) and respiratory gating which limits the amount of motion artifacts. Post-processing of acquired images results in 3D images that can be further optimized. One significant drawback of reconstructive approaches to 3D echocardiography is that live, real-time imaging cannot be achieved because the different imaging planes are required sequentially. In the late 1980s, a group at Duke University led by von Ramm developed a transthoracic transducer that used a sparse array matrix transducer containing 256 elements. This system could acquire volumetric data rather than single slices of data, which ultimately permitted the display of volumetric 3D images. While this transducer allowed generating different cut-planes from a 3D volume on-line, it was
not capable to display real-time rendered 3D images.\textsuperscript{5,8,9} Further advances in crystal and computer technology lead to the introduction of matrix-array transducers for the use in transthoracic echocardiography (TTE) shortly after the year 2000. These transducers provided excellent real-time 3D imaging of the beating heart and were only possible due to significant technological developments in hardware (microelectronics, transducer design, computer) and associated software.

Current matrix-array transducers utilize a greater number of imaging elements (> 2500), which are capable to generate real-time (RT) rendered 3D images based on operating frequencies ranging from 2 to 4 MHz (TTE) and from 5 to 7 MHz (TEE).\textsuperscript{10,11} The piezoelectric elements within the transducers are arranged in a matrix configuration and require a large number of digital channels for these fully sampled elements to be connected. To reduce both power consumption and the diameter of the connecting cable, several miniaturized circuit boards are incorporated into the transducer, allowing partial beam-forming to be performed in the probe. To date, the only clinical available RT-3D-TEE transducer is the X7-2t TEE (Philips, Andover, MA) transducer, which combines xMATRIX technology and PureWave crystal technology. This technology permits live biplane (termed Xplane) imaging with two full-resolution planes created simultaneously and, therefore, enables the parallel acquisition of diagnostic data without moving the probe. Importantly, the system supports live volume imaging with unlimited planes in all directions allowing the acquisition and rendering of true real-time 3D full volume data. Of note, 3D-TEE systems provide all conventional modalities such as 2D multiplane imaging, M-Mode, pulsed and continuous wave Doppler as well as color Doppler imaging.

To date, two different methods for 3D echocardiographic acquisition are available: real-time or live 3D imaging (Live 3D or Live 3D Zoom) and electrocardiographically triggered multiple-beat 3D imaging (e.g. full volume acquisition). Real-time or live 3D relies on the acquisition of multiple pyramidal data sets per second during a single cardiac cycle. Most current ultrasound systems have real-time 3D imaging available in the following modes: Live 3D (narrow volume), live 3D zoomed (magnified but truncated dataset), live 3D wide angled, and live 3D color Doppler imaging. While these live 3D modes overcome the limitations imposed by arrhythmias, electrocautery or respiratory motion, their temporal and spatial resolution is limited. However, these live modes permit 3D monitoring and guidance during all kinds of interventional procedures such as transcatheter aortic valve implantations (TAVI), percutaneous mitral valve clip procedures, atrial septal defect closure or closure of paravalvular leaks. In contrast, multiple-beat 3D echocardiography provides images of superb temporal resolution. This is made possible through multiple acquisitions of narrow volumes of data over several cardiac cycles (ranging from two to six or more cardiac cycles) that are subsequently stitched together to create a single volumetric data set. However, gated imaging of the heart is inherently prone to imaging artifacts created by patient movement, respiration or cardiac arrhythmia.

1) \textbf{Live 3D}: This real-time mode displays a fixed pyramidal data set of approximately 50° x 30° by the depth of the initial 2D image that conveniently can be used to visualize any cardiac structure located in the near field. Movement of the TEE probe will result in a live (real-time) change of the 3D image. Live 3D allows for quick 3D imaging and immediate return to a 2D mode. Using Live 3D, a thick slice (90° x 1°) representing an enhanced 2D image may also be displayed and rotated in space. With most recent acquisition packages, color imaging can be added to this Live 3D mode but overall frame rates will be significantly reduced. However, to compensate, acquisition over a number of cardiac cycles will permit the acquisition with higher frame rates.
2) **Live 3D Zoom** displays a magnified but truncated pyramidal data set of variable size. Once activated, this mode displays a biplane preview screen showing the original view on the left and the correspondent orthogonal image on the right. Accurate placement and adjustment of the zoom sector to cover the region of interest while minimizing the sector-width to improve temporal resolution are important to optimize image quality. Live 3D Zoom is preferentially used to display the mitral valve (MV), the tricuspid valve, the left atrial appendage (LAA) or the intraatrial septum. The **en face** view of the MV mirrors the surgical view from the left atrium down to the MV. This view is routinely generated using the live 3D zoom mode based on the midesophageal four chamber view and by rotating the obtained image to display the aortic valve at 12 o’clock as the midpoint of the anterior annulus. Depending on the frame rate and density settings, this routinely results in superior 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 MV apparatus. Live 3D zoom MV images may then be looked at from atrial or ventricular perspectives, another unique feature of 3D imaging. The full volume data set allows assessing the intimate interrelationship among the MV, the papillary muscles, the myocardial walls and the left ventricular outflow tract;

3) The **3D Full Volume** mode allows the acquisition of a pyramidal data set (approximately 65° x 60° up to 100° x 100°) that includes a larger cardiac volume. This wide angle data set is composed by merging a predefined number of narrower RT-3D pyramidal wedges obtained over one to six heartbeats. While artifacts cannot be totally avoided in patients with arrhythmias, artifacts can be minimized in the anesthetized patient by holding ventilation and acquiring full volume loops while electrocautery is not used. With the goal to minimize artifacts, it is recommended to acquire full volume loops at the beginning of the comprehensive TEE-exam in the operating room before the start of surgery. Left ventricular full volume loops are acquired based on the 2D midesophageal four-chamber view. Once the full volume mode is activated, a biplane image with the four-chamber view and the correspondent orthogonal plane is displayed on the screen. Depending on the size of the region of interest, one can select either high, medium or low line density for acquisition which will affect the dimensions of the pyramidal volume from narrow (high density) to wide (low density). Following acquisition of a full volume loop, the 3D-volume is first displayed as auto crop showing only 50% of the volume mirroring the four-chamber view. By resetting the crop plane, the whole pyramidal data set is displayed. The full volume can be further processed offline by rotating and cropping to visualize specific structures inside the pyramid. 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 version 7.0);

4) **3D Color Full Volumes** are acquired similar to the acquisition of a full volume data set. Again, the wide-angle data set is compiled by merging 2 to 6 narrower RT-3D pyramidal wedges and is similarly prone to artifacts introduced by arrhythmias, movement, or electrocautery. It is essential to place the area of interest, e.g. the regurgitant jet in the center of the sector. The remainder of the acquisition is identical to that used for full volume acquisition.

**Limitations:**

Although the introduction of RT-3D-TEE to the operating room has truly added a new dimension to perioperative imaging of the beating heart, a number of significant limitations remain. First, while 3D zoom and Live 3D present truly real-time modes, the acquisition of a 3D full volume as well as a 3D color full volumes are based on automatic reconstruction from multiple subvolumes and therefore are prone to artifacts resulting from arrhythmias, ventilation and other movements.
Second, as RT-3D-TEE obeys the same physical laws as 2D-ultrasound, poor 2D image quality will likely translate in similarly poor 3D image quality that adds little to no value to the overall assessment. Third, image acquisition of 3D full volumes and 3D color full volumes and associated quantification remain time-consuming. Fourth, although built-in software offers a truly novel and promising approach to quantitative assessment of 3D data sets of the MV and LV, this assessment is static and dynamic changes during the cardiac cycle are not reflected. Novel dynamic assessment tools will likely overcome this limitation in the near future. Finally, as RT-3D-TEE technology represents a brand-new technology, its use will naturally prolong a comprehensive TEE examination. This is especially true when more sophisticated quantification using built-in software is performed.

In conclusion, RT-3D-TEE represents a novel clinical and intuitively educational perioperative cardiovascular imaging modality. In addition, live 3D-TEE adds significantly to the perioperative communication between cardiac surgeons and anesthesiologists or echocardiographer. Its unique ability of real-time acquisition, online rendering and cropping capabilities, accurate identification of the precise pathology and location of cardiac disease, together with its ability to promptly quantify 3D data sets using built-in software, will likely help to transition this modality into standard of perioperative care.

References: