CME

Three-Dimensional Transesophageal Echocardiography Is a Major Advance for Intraoperative Clinical Management of Patients Undergoing Cardiac Surgery: A Core Review

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Echocardiography is a key assessment tool for the evaluation of cardiac structure and function. The ability to image cardiac structures using 3-dimensional (3D) echocardiography is evolving. In this article, we present some of the key features of the emerging 3D technology and review its applications with an emphasis on real-time 3D transesophageal echocardiography. (Anesth Analg 2010;110:1548–73)

Transesophageal echocardiography (TEE) is a powerful diagnostic modality used to assess cardiac anatomy and function.¹ Intraoperative TEE has become commonplace during cardiac surgery reflecting the mounting complexity of surgical technique and patient pathology. The skill and expertise of the intraoperative echocardiographer, now often a TEE-trained anesthesiologist,² are constantly evolving to provide timely and accurate information to the surgeon and aid perioperative patient management.

Advances in technology presently permit real-time (RT) 3-dimensional (3D) echocardiography using a transthoracic (TTE) or transesophageal matrix array ultrasound probe that provides detailed on-line 3D images.^{3–5} Analytical software allows for prompt off-line reconstruction of 3D datasets as 3D models affording improved assessment of mitral valve (MV) structure and quantification of left ventricular (LV) function. Unlike 2D TEE, which relies on standard imaging planes,⁶ 3D TEE uses volume datasets. The echocardiographer must attain new basic skills to manipulate the 3D datasets and appropriately orient the 3D images. Normal or pathologic cardiac structures can now be viewed from multiple perspectives. This is an invaluable visual aid that enables the echocardiographer to better appreciate individual patient anatomy.

This article presents some key features of the emerging 3D technology used in echocardiography and reviews the current applications of 3D echocardiography with an emphasis on RT 3D TEE.

3D TECHNOLOGY

A considerable challenge in ultrasound image interpretation has always been the ability to mentally visualize a 3D

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Accepted for publication December 25, 2009.

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structure based on 2D images. Given the complexity of cardiac anatomy and the steep learning curve required in accurately interpreting cardiac ultrasound images, there has always been an intense desire to display "live" 3D images.⁷ Time-consuming acquisition, off-line reconstruction, and poor image quality have previously limited the use of 3D echocardiography. A familiarity with the new technology that overcomes some of these limitations will aid the echocardiographer in performing RT 3D echocardiography.

Analogous to the creation of a 2D image, a 3D ultrasound image of the heart involves 4 steps⁸: data acquisition, data storage, data processing, and image display (Fig. 1).

Data Acquisition

Initial 3D data acquisition involves obtaining echocardiographic information about a volume of tissue using either a 2D scanning or volume scanning technique.⁹

The 2D scanning technique consists of acquiring, then reconstructing off-line, a series of 2D images (or slices) of an anatomic structure with a standard TTE or TEE ultrasound probe. In the free-hand method,¹⁰ the TTE probe is tracked by a sophisticated mechanical or electromagnetic system as it is manipulated to different echocardiographic windows. In the sequential linear method,¹¹ the TEE probe handle (monoplane or multiplane) is attached to a motor (stepper) that moves the probe in equal longitudinal millimeter steps to provide a series of parallel equidistant 2D images similar to a computerized tomography (CT) scan (Fig. 2A). The rotational scanning method¹² is performed using a single echocardiographic window; the ultrasound probe (TTE or multiplane TEE) is held immobile while the ultrasound scanning plane rotates on its main axis to scan a conical-shaped volume at fixed angle increments (Fig. 2B).

For all 2D scanning techniques described above, the acquisition of each image (slice) is timed to the same portion (R wave) of the electrocardiogram (ECG). This practice is called ECG gating and allows data reconstruction synchronous with the ECG. It works best for any regular paced or native rhythm. In addition, when the time to obtain multiple 2D images is longer than a tolerable breath hold, respiratory gating is used to acquire images during the same portion of the respiratory cycle. This improves image quality because the distance between the TEE probe and the heart varies with respiration.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.anesthesia-analgesia.org).



Figure 2. Data acquisition. Techniques used in transesophageal echocardiography to acquire raw 3D data include (A) sequential (linear) 2D scanning, (B) rotational 2D scanning, and (C) volume scanning. (Courtesy of Michael Corrin, MscMBC, with permission.)



3D Echocardiographic Imaging

The volume scanning technique requires the use of stationary TTE or TEE ultrasound probes with special matrix array transducers (Fig. 2C) that steer the ultrasound beam to scan a pyramid-shaped volume.^{13,14} Data acquisition occurs over a significantly shorter time (single or multiple heart beats) and may involve ECG gating but not respiratory gating.

Data Storage

Data storage is required to maintain data flow from initial data acquisition to the next step of data processing. During the 2D scanning technique, the raw data are stored on a memory medium such as optical disks or magnetic tapes and subsequently exported to a powerful external computer for processing (off-line). The lack of small, capable, and affordable memory media had been an important limiting factor to the development of 3D echocardiography for many years.¹⁵

While performing the volume scanning technique, the data are streamed through a random access memory for temporary data storage within the computer on the ultrasound machine. This permits immediate data acquisition, storage, and processing concurrently (on-line) within the ultrasound machine.

Data Processing

Data processing is the transformation of the scanned raw data for a specific volume into a code (3D dataset) necessary to generate a 3D object. Typically, data processing consists of 2 sequential processes: conversion and interpolation, which are separate steps for the 2D scanning technique, but integrated during the volume scanning technique.

Regardless of the data acquisition technique used, during conversion, all acquired raw data are placed into a Cartesian volume with each point assigned x-y-z coordinates and an echo-intensity value. Images obtained with the 2D scanning technique are realigned in space at the same position and orientation they were acquired (Fig. 3A). The product of this step is a group of points with distinctive echogenic characteristics and a known position in space.

Interpolation fills the gaps between all the known points in space with data points of similar characteristics. For the 2D scanning technique, this consists of filling the space between the 2D slices (Fig. 3B). Interpolation generates a 3D dataset that comprises voxels or volume elements for a specific volume in space. A voxel is a (vo)lume of pi(xels) that encrypts the physical characteristics and location of the



Figure 4. Three-dimensional display. Graphic rendering involves using different techniques to make 3D datasets visible as shown here for the left ventricle. A, The wireframe technique connects a series of points with lines to form a rudimental endocardial left ventricular cast. B, The surface-rendering technique generates a more detailed endocardial 3D surface with a hollow core. C, The volume-rendering technique displays a virtual dissection of the inner structure of the left ventricle.

smallest cube in a dataset, which is used for 3D display. The accuracy of the 3D image depends on the size of a voxel (similar to pixel size in 2D image resolution). Large voxels are generated when raw data are available for fewer points in the space and interpolation has to fill wider gaps.

The volume scanning technique^{13,14} generates a data stream using the computer random access memory and creates voxels while scanning, with near simultaneous conversion and interpolation. The matrix array probe scans over the elevational axis resulting in a pyramid-shaped volume with a curved base.

3D Display

The process of making a 3D dataset visible is termed 3D display and results in either multiple 2D image planes or the creation of a 3D graphic reproduction.¹⁶

Multiple 2D planes can be virtually cut from a 3D dataset and the relative 2D views3-9 displayed on 1 screen,¹⁵ without the creation of a visible 3D object.

Three-dimensional graphic reproduction is the product of graphic rendering, a 2-step computer graphics technique. The first step is segmentation, which separates within the 3D echocardiographic dataset the object to be rendered from surrounding structures by specifically differentiating cardiac tissue from blood, pericardial fluid, and air. Given their diverse physical properties and different ability to reflect ultrasound, segmentation is achieved by setting a threshold of echo intensity. Any point with echo intensity equal or lower than blood will be excluded from further processing. This step delineates the 3D surfaces of cardiac tissue.

After segmentation, the 3D dataset undergoes 1 of the 3 increasingly complex rendering techniques to create a visible 3D object: wireframe rendering, surface rendering, or volume rendering.

The simplest technique is wireframe rendering, which defines and connects equidistant points on the surface of a 3D object with lines (wires) to create a mesh of small polygonal tiles. Smoothing algorithms can refine the narrow angles and make the rudimental object appear more real. This technique is used for relatively flat surface structures such as the LV and the atrial cavities (Fig. 4A) (Video 1, see Supplemental Digital Content 1, http://links.lww.com/AA/A82; see Video 1 legend at Appendix 1, http://links.lww.com/AA/A104). It cannot display structures with complex shapes, such as the cardiac valves that require greater anatomic detail for meaningful analysis. This technique processes a small amount of data, thus it is fast and can be efficiently performed on basic computers.

The surface-rendering technique is similar to the wireframe technique but defines more points on the surface of a 3D object making the lines joining them invisible. It displays the details of a 3D surface and makes morphologic assessment of the corresponding anatomic structure feasible. Surface rendering generates 3D objects with rendered surfaces and a hollow core (Fig. 4B, Video 1, see Supplemental Digital Content 1, http://links.lww.com/AA/A82; see Video 1 legend at Appendix 1, http://links.lww.com/AA/A104).

The volume-rendering technique displays a 3D object with a rendered surface and details of its inner structure.



Figure 5. Transesophageal echocardiography (TEE) probes. A, A standard multiplane TEE probe uses a linear phased array to rotate a 2D plane through 180°. B, A matrix array TEE probe contains 2500 piezoelectric elements to scan a 3D pyramidal volume. (Courtesy of Michael Corrin, MscMBC, with permission.)

Volume rendering of a 3D dataset enables the potential display of every voxel of the 3D object permitting a "virtual dissection" (Fig. 4C) (Video 1, see Supplemental Digital Content 1, http://links.lww.com/AA/A82; see Video 1 legend at Appendix 1, http://links.lww.com/AA/A104).⁸

Although composed of voxels, 3D objects are seen on the screen as pixels of a 2D image. As in old paintings, perspective, light casting, and depth color coding are used to give a visual sense of depth and reality. Stereoscopic displays¹⁷ and holograms¹⁸ may display a 3D rendered object more realistically but are currently used only for research purposes. Any volume-rendered 3D object can be freely rotated on the display screen to be viewed in any orientation either as a static or a moving object. A moving (dynamic) 3D object is often referred to as 4D, with time considered the fourth dimension.

TEE PROBES

Monoplane and biplane TEE probes have been replaced by the 2D multiplane TEE probe, introduced into clinical practice in the early 1990s, and the recently released matrix array TEE probe.

The 2D multiplane TEE probe consists of a phased array transducer that contains 64 to 128 piezoelectric crystals placed side by side forming a square. Sequential (phased) activation of individual crystals generates an ultrasound beam that is steered back and forth over a 90° angle to sweep a flat, "pie-shaped" scanning plane or sector.¹⁹ The transducer is mechanically or electrically rotated within the probe handle in 1° increments, 180° clockwise (0°–180°), and counterclockwise (180°–0°) to scan a conical-shaped volume (Fig. 5A).²⁰ As described above, it is possible to create 3D images using a standard 2D multiplane TEE probe, but it is time consuming and requires off-line processing.

Early "sparse" or matrix array probes¹³ were composed of 128 to 512 crystals intermittently arranged over the transducer surface. Although capable of a volumetric scan, they only produced on-line 2D images. Modern matrix array transducers contain a grid of 50 rows and 50 columns for a total of 2500 independent piezoelectric crystals that cover the transducer surface. They are encased in the size of a standard multiplane TEE probe tip.

Integrated circuits adjacent to the piezoelectric crystals manage part of the ultrasound beam forming and steering within the probe tip, substantially decreasing the number and size of cables to and from the probe handle.¹⁴ Individual piezoelectric crystals are activated and generate an ultrasound beam that can be steered in the azimuthal (x-y) and the elevational plane (x-z) over a 90° angle to cover a pyramidal scanning volume (Fig. 5B). The sum of returning acoustic information from each crystal (fully sampled) is processed to voxels, which are immediately displayed as a volume-rendered 3D image.

The matrix array probe also functions as a standard 2D multiplane TEE probe (Fig. 5A) including 2D, spectral, and color Doppler modes.²¹ In addition to basic 2D and 3D TEE image acquisition, the stationary matrix array TEE probe (X7-2t, Philips Medical Systems, Andover, MA) can scan and display 2 independent 2D scanning planes simultaneously (xPlane mode), albeit at a reduced frame rate (<40 Hz). By default, the initial 2 planes are at a 90° angle to each other, and the images displayed (Fig. 6A) (Video 2, see Supplemental Digital Content 2, http://links.lww.com/AA/A83; see Video 2 legend at Appendix 1, http://links.lww.com/AA/A104) as left (baseline) and right panels. Alternatively, the image on the right panel display changes by rotating the multiplane angle (Fig. 6B) or moving the cursor line to alter the angulation (Fig. 6C) (Video 2, see Supplemental Digital Content 2, http://links.lww.com/AA/A83; see Video 2 legend at Appendix 1, http://links.lww.com/AA/A104). In the xPlane mode, color Doppler can be displayed in both images although with poor temporal resolution from an extremely low frame rate (<10 Hz).

Another TEE system capable of RT 3D images has been described.²² It assembles multiple groups of phased array transducers within a long probe head. Although it generates good-quality 3D images, it has not yet been considered for clinical use.

3D IMAGE MODES

The acquisition and display of 3D images occurs instantaneously (on-line) using the matrix array probe, "live" over a single heart beat or gated over multiple heart beats. During "live" acquisition, the displayed 3D TEE image can change on-screen but only with physical probe movement (turning or advancing) and not by adjusting the multiplane angle. Gated images are a loop of merged subvolumes that is displayed on-line but not "live" so is unaltered on-screen by probe manipulation. For the purposes of this article, both "live" and gated acquisition



Figure 6. xPlane mode. The xPlane mode images two 2D planes independently and displays both simultaneously. On the left of each display is the standard transgastric (TG) mid short-axis and on the right: (A) TG 2-chamber at 90°, (B) TG long-axis (125°), or (C) TG 2-chamber at an angulation of 18°. In (B) and (C), the aortic valve is seen in the lower right corner of the display. The circle on the display indicates the relationship of the planes. (Courtesy of Michael Corrin, MscMBC, with permission.)

using matrix array probes are considered RT, resulting in volume-rendered 3D images.

As with all forms of ultrasound imaging, RT 3D echocardiography has all the limitations of frame rate, sector size, and image resolution interdependence.¹⁴ An increase in 1 of these 3 factors will cause a decrease in the other 2. The best imaging compromise to allow anatomic definition is sufficient spatial (image) resolution with an adequate temporal resolution. In RT 3D imaging, this is best achieved using a small 3D dataset. Temporal resolution (frame rate) is maintained in 3D echocardiography by parallel processing, limiting scan lines, small volume, and gated acquisition. Good 3D image quality always starts with optimization of the 2D image because any 2D artifact will persist in 3D.

Single button activation occurs for specific 3D imaging modes (Philips Medical Systems) using both TTE and TEE matrix array probes.²³ Selecting between modes for specific clinical applications is a balance between choosing pyramidal images of variable dimensions and frame rate (Table 1).

- 1. 3D live (Fig. 7) (Video 3, see Supplemental Digital Content 3, http://links.lww.com/AA/A84; see Video 3 legend at Appendix 1, http://links.lww.com/AA/A104) displays a live RT narrow angle 3D volume of the initial 2D view for 1 or multiple heart beats. Rotation of this 3D volume to any orientation on screen in RT is a valuable quick check of 3D image settings that can then be adjusted. Physical probe movement is required to image structures in their entirety. This mode can image pathology from the standard TEE views at a 20- to 30-Hz frame rate and can help guide interventional procedures in RT.²⁴
- 3D zoom (Fig. 8) (Video 4, see Supplemental Digital Content 4, http://links.lww.com/AA/A85, see Video 4

Table 1. Three Dimensional (3D) Imaging Modes			
	Live	Zoom	Full volume
Dimensions ^a	$60^{\circ} \times 30^{\circ} \times$ by the depth of the 2D image	$20^{\circ} imes 20^{\circ}$ to $90^{\circ} imes 90^{\circ}$ by a variable height	$90^{\circ} \times 90^{\circ}$ by the depth of the 2D image
Real time	Yes	Yes	No (gated)
Frame rate	20–30 Hz	5–10 Hz	20–40 Hz (4 beats)
Temporal resolution	Good	Lowest	40–50 Hz (7 beats)
Spatial resolution	Mid	Highest	Lowest
Cardiac structure	Any 2D image	Cardiac valves, Interatrial septum, Left atrial appendage	Mitral valve, Left ventricle
Clinical application	Guide interventional procedures	Examine anatomy	Left ventricular function color Doppler
Figure	7	8	
Video	3	4, 5	6, 7

 a Dimensions are described by °width \times °thickness by depth.



Figure 7. Three-dimensional live mode. A 2D transesophageal echocardiography (TEE) standard midesophageal 4-chamber view (A) is compared with 3D live "thick slice" (B) and 3D live views (C) both rotated (arrow) to be seen from the side. Note the relative sector angle and thickness differences between the 3D images. FR = frame rate; C = compression.

Figure 8. Three-dimensional zoom mode. Acquisition of a mitral valve (MV) 3D dataset using the 3D zoom mode is shown. A, Boxes are adjusted in a biplane preview for size (X, Y axes) and elevational width (Z axis) to include the entire MV and obtain a pyramid-shaped 3D image. Inclusion of the aortic valve (AV) helps orientate the 3D volume. B, This 3D image is rotated downward and clockwise on-screen to position the AV at 12 o'clock. C and D, The gain is reduced to optimize an en face display of the MV in the surgeon's orientation comparable with this intraoperative picture. Individual posterior (P1, P2, P3) and anterior scallops (A1, A2, A3) of the MV leaflets can be easily identified. AC = anterior commissure; AMVL = anterior mitral valve leaflet; FR = frame rate; LAA = left atrial appendage; PC = posterior commissure.



legend at Appendix 1, http://links.lww.com/AA/A104; and Video 5, see Supplemental Digital Content 5, http://links.lww.com/AA/A86, see Video 5 legend at Appendix 1, http://links.lww.com/AA/A104) displays a live RT magnified subsection of 3D volume of varying dimensions. The 3D volume can be adjusted using orthogonal biplanes so that it can be centered on a specific region of interest (e.g., any valve, interatrial septum [IAS]) and minimized to optimize frame rate (although < 10 Hz) and image definition.

3. 3D full volume (Fig. 9) (Video 6, see Supplemental Digital Content 6, http://links.lww.com/AA/A87; see legend at http://links.lww.com/AA/A104) is an ECG (4-7 beats) gated acquisition of a large 3D



Figure 9. Three-dimensional full-volume mode. A, The 3D full-volume mode uses electrocardiogram-gated acquisition over 4 consecutive heart beats. Shown here is a full-volume 3D dataset obtained from a midesophageal 4-chamber view without autocropping. B, Each subvolume is stitched together in 1 cardiac cycle to form a large pyramidal 3D image. The 3D volume from (A) is rotated (arrow) to be viewed from the side. C, A stitch artifact presents as a demarcation line between subvolumes in the 3D image. A 3D full-volume, compared with a 3D zoom (Fig. 8C), acquisition for the mitral valve has a higher frame rate (FR) but may show stitch artifacts (arrow) and poorer spatial resolution. A central mitral regurgitant jet is shown with 2D color Doppler (D) and 3D full-volume color Doppler (E). In xPlane, the color Doppler box can only be adjusted lengthwise, but not widened. As shown here, temporal resolution decreases from full volume > color Doppler full volume >3D zoom and the opposite is true for spatial resolution.

volume created from subvolumes stitched together and synchronized to 1 cardiac cycle. Full-volume acquisition can be optimized to volume size (7 beats over large sector), ECG (4 beats over large sector), or frame rate (7 beats over small sector). Arrhythmias, electrocautery artifacts, and probe movement cause a demarcation line, termed a stitch artifact, to be evident between the subvolumes distorting the anatomic structures and impeding adequate analysis. Stitch artifacts are unavoidable in patients with arrhythmias, but these ECG-generated artifacts can be mitigated by gating acquisition over an estimated heart rate. In this case, each subvolume is acquired with a time delay that equals the RR interval of the manually set heart rate. To minimize patient movement during gated acquisition, it is good practice to suspend mechanical ventilation or ask the patient to hold their breath.

4. 3D full-volume color Doppler (Fig. 9, D and E) (Video 7, see Supplemental Digital Content 7, http://links.lww.com/AA/A88; see Video 7 legend at Appendix 1, http://links.lww.com/AA/A104) is a gated acquisition of a small 3D volume with superimposed 3D representation of color Doppler. Similar to 3D Zoom, color sectors are centered using 2 orthogonal 2D color Doppler views to render 3D blood flow. The 8 3D wedge-shaped subvolumes acquired over successive heart beats are stitched and synchronized to the same cardiac cycle. Stitching artifacts are common. Given the amount of information (3D volume and 3D color flow), current technology can create only small (up to 60° wide $\times 60^{\circ}$ thick) 3D full-volume color Doppler datasets with poor temporal resolution (frame rate <10 Hz).

POSTPROCESSING ORIENTATION AND CROPPING

A new challenge for the echocardiographer is to skillfully manipulate and orient the 3D images to analyze anatomic details from a particular surgical orientation. Any stored 3D image can be rotated, either on-line or off-line, with the easily recognized aortic valve (AV) used as a reference to orient the 3D cardiac image in space. Alternatively, the reference 2D orthogonal planes can be displayed to guide 3D image orientation (Fig. 10A). Any stored 3D dataset can generate a 3D image that can be cropped (or sliced) along the 3 axes (X, Y, Z) using 6 standard orthogonal planes (Fig. 10B). A seventh arbitrary cropping plane can be freely maneuvered in space and aligned to any anatomic structure of interest. Although cropping can be performed on-line without using analytical software, it cannot be completed in RT because it uses stored 3D images.

Current 3D technology does not allow even simple on-line measurement of length and area within the 3D



Figure 10. Three-dimensional orientation and cropping. A, A 3D image of a descending aorta atheroma is displayed with the original 2D short-axis (0°) and long-axis (90°) views for orientation purposes. B, This 3D full-volume image of the left ventricle can be rotated to be viewed from any perspective or cut along any predetermined axis (red, green, or blue plane) or with a mobile cropping plane (purple). C, A measurement grid (5 mm) to estimate size is overlaid on a 3D zoom image of the mitral valve.

image. A grid of dots (5 mm apart) can be overlaid in an RT (live or zoom) mode or on any stored 3D image (Fig. 10C) to estimate dimensions. Quantitative assessment of the 3D image requires exporting the 3D dataset into dedicated analytical software.

SPECIFIC APPLICATIONS

A complete echocardiographic examination assesses cardiac anatomy and hemodynamic status. Currently, RT 3D echocardiography is a qualitative technique with excellent spatial resolution but limited temporal resolution that complements but does not replace 2D echocardiography. Lacking a formal protocol, the indication to use RT 3D TEE is as a focused examination of specific pathology rather than performing a comprehensive 3D examination.

There is very limited information available for the use of RT 3D TEE in the perioperative setting. The majority of studies published in the past decade on the clinical application of 3D echocardiography were conducted using offline 3D reconstruction for TEE (3D TEE) and TTE (3D TTE) or RT 3D TTE. This literature is confounded by the use of the term "real-time," which has previously described dynamic 3D images obtained with off-line reconstruction of 3D datasets. Although many of the recent RT 3D TTE studies validate the current matrix array 3D technology, the implicit extension of TTE findings to TEE is a problem. Nevertheless, this large body of literature provides important information that may guide future clinical applications of RT 3D TEE, as described in the following sections.

MITRAL VALVE Imaging

The relative position of the MV within the heart and its relationship to the esophagus allows perpendicular alignment of the TEE ultrasound scanning plane making the MV an easily imaged structure using TEE.

Off-line 3D MV reconstruction using the 2D rotational scanning method with a standard TEE probe²⁵ remains cumbersome and time consuming, so it is mostly confined to research purposes. The recently available matrix array TEE probe (X7-2t, Philips Medical Systems) consistently provides optimal on-line volume-rendered 3D images of the MV in a larger percentage of patients⁴ than RT 3D TTE.²⁶ The MV can be easily imaged using all the 3D imaging modes previously described: live, zoom, and fullvolume modes.

A 3D live acquisition from standard 2D midesophageal views through the MV can be rotated to be viewed from the left atrium but yields only a portion of the MV. Despite a 10-Hz frame rate, 3D zoom²⁷ is the modality of choice to view detailed anatomy of the entire MV with adequate temporal and spatial resolution. The zoom acquisition begins with imaging the entire MV in 2D, preferably with the AV in view (Fig. 8) (Video 5, see Supplemental Digital Content 5, http://links.lww.com/AA/A86; see Video 5 legend at Appendix 1, http://links.lww.com/AA/A104). The displayed pyramid-shaped 3D image can be manipulated on-screen in RT to view the MV from any perspective. Typically, the MV 3D image is presented "en face" in the surgeon's orientation as viewed from the left atrium with the AV at the top of the image and the left atrial appendage (LAA) to the left. Stored MV 3D images can be cropped on any plane to further delineate leaflet morphology (Fig. 11).

Full-volume acquisition of the MV (Fig. 9C) (Video 6, see Supplemental Digital Content 6, http://links.lww.com/AA/A87; see Video 6 legend at Appendix 1, http://links.lww.com/AA/A104), using the frame rate option (7 heart beats over a small volume), can achieve a higher (>25 Hz) frame rate. Starting from a 2D midesophageal 4-chamber view that is magnified to display a full screen view of the entire MV, full-volume mode is selected. Stitch artifacts and reduced spatial resolution may limit analysis compared with the zoom mode.

MV Anatomy

The MV is no longer considered in isolation but instead forms part of a complex anatomic structure that can be described as 3 subunits: the annulus, the leaflets, and the subvalvular apparatus.²⁸

The MV annulus is a saddle-shaped incomplete fibrous ring that changes shape continuously during the cardiac cycle. The annulus is divided into anterior and posterior portions according to the attachment of the corresponding MV leaflets. The posterior MV leaflet attaches to 70% of the annulus and has 3 indentations (scallops): lateral (P1),



Figure 11. Mitral valve cropping. A, A 3D zoom image of the mitral valve viewed from the left atrium showing a cropping plane positioned perpendicular to the mitral valve commissure. B, The cropping plane is advanced to cut different sagittal planes through each part of the mitral valve leaflets. Each plane can be rotated to better demonstrate leaflet position in relation to the annulus.

larger middle (P2), and smaller medial (P3). The anterior MV leaflet has the same surface area comprising a smaller base and a leaflet height twice that of the posterior leaflet. The Carpentier nomenclature describes the anterior MV leaflet as 3 segments: lateral third (A1), middle third (A2), and medial third (A3) that correspond to the posterior MV leaflet scallops. A variable amount of commissural tissue, or even separate leaflets, bridge both MV leaflets and is important for MV function. The combined surface area of the MV leaflets is twice that of the mitral orifice, permitting at least a 30% leaflet coaptation area. The subvalvular apparatus includes the chordae tendineae, papillary muscles, and LV wall.

MV Pathophysiology

Normal MV function depends on the integrated role of the various components of the MV apparatus. Failure of any one of the components can result in mitral regurgitation (MR).²⁹ Carpentier et al.³⁰ classified the mechanisms of MR into 3 types according to the range of leaflet motion, which can be readily assessed using echocardiography.

There are numerous etiologies of MV disease, so a clear understanding of individual patient MV pathology is imperative in surgical planning. It is important for the echocardiographer to provide the surgeon with detailed information of MV pathology.³¹ When feasible, MV repair has become the treatment of choice for MR.³² The use of 3D echocardiography has significantly contributed to a better understanding of normal MV anatomy and the pathophysiology of MV dysfunction.³³ The role of RT 3D TEE is expanding to become a powerful tool in guiding surgical MV repair.³⁴

To identify the complexity of MV repair, it is important to distinguish between degenerative MV disease due to myxomatous disease (complex repair) and fibroelastic deficiency (simple repair).³⁵ Barlow disease is characterized by an excess of myxomatous tissue, prolapsed redundant leaflets, elongated thickened chordae, severely enlarged annulus, and an end-systolic mitral regurgitant jet. Fibroelastic deficiency is a connective tissue disorder, which often affects a single MV segment or scallop with ruptured chordae, flail leaflets, and a holosystolic mitral regurgitant jet.

Mitral Regurgitation

The TEE assessment of MR begins with a systematic evaluation of MV morphology followed by quantification of MR severity. Currently, 2D TEE has a high accuracy for identifying prolapsed or flail leaflet (90%-98%) segments^{36,37} and a lower accuracy for cleft, perforation, or commissural MV disease. The assessment of MV morphology using RT 3D TTE^{38,39} and off-line reconstruction 3D TEE^{40,41} showed similar accuracy in defining leaflet prolapse but a higher intraobserver agreement compared with 2D TEE.41 Two recent studies have demonstrated the feasibility^{27,42} of intraoperative assessment of MV morphology by RT 3D TEE (Fig. 12) (Video 8, see Supplemental Digital Content 8, http://links.lww.com/AA/A89, see Video 8 legend at Appendix 1, http://links.lww.com/AA/A104; and Video 9, see Supplemental Digital Content 9, http://links.lww.com/AA/A90, see Video 9 legend at Appendix 1, http://links.lww.com/AA/A104), with a superior accuracy to 2D TEE in defining leaflet pathology when both were compared with surgical findings. In both studies, TEE was performed by experienced echocardiographers with specific RT 3D training⁴³ necessary to effectively acquire, manipulate, and accurately interpret MV 3D datasets.

MV Models

Detailed quantitative analysis of individual MV structure is obtained by off-line construction of a 3D MV model (Fig. 13) using an analytical software package. The 2 software packages commercially available, QLAB MV Quantification (MVQ) (Philips Medical Systems) and TomTec44 4D MV-Assessment (Munich, Germany), create MV models using zoom and full volume, TTE or TEE MV 3D datasets. An advantage of the QLAB software is the convenience of having it built into the Philips ultrasound machine. Although the TomTec software requires a separate workstation, it can analyze 3D datasets acquired from any vendor.

Creation of the MV model requires specific software training. The process is time consuming (15–20 minutes)

Figure 12. Mitral regurgitation. A series of 3D zoom images of the mitral valve (MV) viewed from the left atrium (upper) in the surgeon's orientation and left ventricle (lower) with corresponding MV models (mid) are shown during systole. The left ventricle orientation is obtained from horizontal rotation of the left atrial image. Compare (A) a normal MV, (B) prolapse/ flail of the posterior leaflet (P2), and (C) central malcoaptation from tethered MV leaflets in ischemic cardiomyopathy. A = anterior; AL or AC = anterolateral commissure; Ao = aorta; AV = aortic valve; LAA = left atrial appendage; P = posterior; PM or PC = posteromedial commissure.





Figure 13. Mitral valve models. A, Using proprietary software (QLAB Mitral Valve Quantification; Philips Medical Systems, Andover, MA), a 3D model of the mitral valve can be constructed by tracing the mitral valve leaflets and points of coaptation. B, A number of discrete measurements, as indicated, are automatically generated from the reconstructed 3D model. C, In addition, more detailed calculations of areas and volumes can be made. A or Ant = anterior; AL = anterolateral commissure; AMVL = anterior mitral valve leaflet; Ao = aorta; P or Post = posterior; PM = posteromedial commissure; PMVL = posterior mitral valve leaflet.



Figure 14. Mitral stenosis. A, A transesophageal echocardiography (TEE) 3D zoom image of the mitral valve (MV) viewed from the left atrium shows restricted opening during diastole from severe rheumatic mitral stenosis. Compare orifice with normal MV during middiastole in Figure 8C. B, The 3D dataset is imported into analytical software (QLAB Mitral Valve Quantification; Philips Medical Systems, Andover, MA). The cropping plane is positioned to cut through the narrowest MV orifice in 2 orthogonal views. The anatomic MV orifice area (MVA) of 1.09 cm² is directly planimetered from the left atrial perspective. AV = aortic valve.

and subjective because it first involves the manual identification of 15 to 20 points on the MV leaflets and annulus from the 3D dataset (Fig. 13A). Interpolation of all the manually entered points generates the MV model. A broad spectrum of measures are automatically displayed, such as MV leaflet length and areas, tenting volume, coaptation length, annular dimensions, and angle with the aorta (Fig. 13, B and C). Given the intraoperative time limitations, the clinical role of the MV model may best be suited for the perioperative setting.

MV Annuloplasty and Prosthesis

Accurate dimensions of the MV annulus obtained off-line using RT 3D TTE correlate well with magnetic resonance imaging (MRI).⁴⁵ Assuming its high accuracy in determining mitral annular size, a 3D TEE rendered en face MV image has been used as a virtual model for perioperative sizing of MV annuloplasty ring.⁴⁶ The off-line construction using RT 3D TEE datasets of a 3D MV model that quantifies annular dimensions and geometry may assist in surgical planning.

RT 3D TEE of prosthetic MVs (mechanical or tissue) provides optimal 3D images, from the left atrial and LV orientation, and allows detailed assessment of areas of dehiscence^{42,47} and clot formation.⁴⁸ The size and location of paravalvular leaks⁴⁹ can be quickly defined using all 3D imaging modes, including 3D color Doppler, while the live mode is also a valuable tool in guiding percutaneous closure of the leak.⁵⁰ Low temporal resolution or inadequate gain settings in the zoom and full-volume modes may underestimate or miss a paravalvular gap even when viewed from the LV aspect. The use of 3D color Doppler may help differentiate a paravalvular dehiscence from artifact.

Mitral Stenosis

Mitral stenosis is usually quantified using echocardiography by estimation of MV area with planimetry or from the pressure half-time (PHT) of the MV inflow spectral Doppler trace.⁵¹ The PHT can be influenced by hemodynamic factors such as heart rate and cardiac output; however, planimetry is not always accurate because of suboptimal imaging of the actual MV orifice.⁵²

Assessment of the MV area by RT 3D TTE planimetry, even in the presence of severe calcific mitral stenosis,⁵³

better correlates to invasive catheter measurement using the Gorlin formula⁵⁴ or 2D PHT. In addition, RT 3D TTE can consistently identify MV commissural fusion and predict the success of MV balloon valvuloplasty.⁵⁵ Indeed, some authors have proposed planimetry by RT 3D TTE as a "gold standard" in the assessment of mitral stenosis.⁵⁶

Two methods have been described to planimeter⁵⁷ the anatomic MV orifice using the matrix array probe. The on-line xPlane method simultaneously displays a transgastric 2-chamber view at 90° with a second 2D plane positioned in RT through the true MV orifice in short axis to allow planimetry. The off-line cropping method requires importing an MV zoom or full-volume 3D dataset into an MV analytical software package described above. The 3D dataset is cropped by an arbitrary plane, parallel to the MV annulus, cutting through the smallest true MV orifice that is planimetered (Fig. 14) (Video 10, see Supplemental Digital Content 10, http://links.lww.com/AA/A91; see Video 10 legend at Appendix 1, http://links.lww.com/AA/A104). MV planimetry for mitral stenosis by 3D TTE and 3D TEE has never been compared.

TRICUSPID VALVE

Imaging

The 3 leaflets of the tricuspid valve (TV) can only be imaged simultaneously using 2D TEE in a modified transgastric basal short-axis view of the right ventricle (RV). Compared with TTE, TEE imaging of the TV is made difficult by its thin leaflets, anterior position, and the unfavorable angle of incidence of the ultrasound beam. Off-line reconstruction⁵⁸ and RT⁵⁹ 3D TTE in patients with good-quality 2D images generated optimal 3D images of the TV in 90% of patients.

A full-volume acquisition from the midesophageal 4-chamber view can be rotated to display the detailed anatomy of the base of the heart (Fig. 15) (Video 11, see Supplemental Digital Content 11, http://links.lww.com/AA/A92; see legend at http://links.lww.com/AA/A104). When viewed from the atria, the relationship of the TV with the remainder of the valves can be appreciated. The TV can be entirely visualized, in a small percentage of cases,⁴ from a single midesophageal view using the zoom mode (Fig. 16A) (Video 12, see Supplemental Digital Content



Figure 15. Base of the heart. A and B, Using a gated 4-beat full-volume acquisition of a midesophageal 4-chamber view, the base of the heart is seen by rotating (arrows) the image to view it from the atrial side as shown during systole. C, The 3D full-volume image of the base of the heart can be compared with a dissection of a pig heart in the same orientation. AV = aortic valve; MV = mitral valve; PV = pulmonic valve; TV = tricuspid valve.



Figure 16. Tricuspid valve (TV). The TV can be imaged using the 3D zoom or full-volume modes by including the entire TV from midesophageal 4-chamber or right ventricular inflow-outflow views. A, A transesophageal echocardiography (TEE) 3D zoom image of the TV is rotated to show all 3 leaflets en face from the right atrium (RA) in the surgeon's orientation. B, Surgical view of a tricuspid annuloplasty ring from the RA at the time of implantation. C, A TEE 3D full-volume image of a tricuspid annuloplasty ring (arrow) is shown in situ from the RA. Ant = anterior; AV = aortic valve; IAS = interatrial septum; LVOT = left ventricular outflow tract; Post = posterior; Sept = septal.

12, http://links.lww.com/AA/A93; see Video 12 legend at Appendix 1, http://links.lww.com/AA/A104). Prosthetic valves in the tricuspid position are less reliably imaged using RT 3D TEE than in the mitral or aortic position.⁴²

The assessment of the TV annulus by RT 3D TEE for intraoperative surgical decision making⁶⁰ has never been investigated. However, changes in the shape and geometric assessment of the TV annulus by 3D TTE is feasible, correlates well with cardiac MRI,⁶¹ and helps improve the understanding of TV pathophysiology.⁶²

The oval shape of the tricuspid annuloplasty ring (Fig. 16B) can be displayed by RT 3D TEE using both zoom and full-volume modes (Fig. 16C) (Video 12, see Supplemental Digital Content 12, http://links.lww.com/AA/A93; see Video 12 legend at Appendix 1, http://links.lww.com/AA/A104). A 3D reconstructed model of the TV is not part of the analytical software packages.

TV Pathology

Assessment of tricuspid stenosis using zoom or fullvolume modes consists of a description of TV morphology and direct measurement of the TV orifice area. Planimetry of the TV orifice area requires off-line cropping through the smallest TV orifice using analytical software. No studies have described the use of RT 3D TEE in the assessment of tricuspid stenosis. However, RT 3D TTE provided optimal images of the entire TV structure in the presence of rheumatic tricuspid stenosis and allowed off-line measurement of the TV orifice area in all patients.⁶³

TV leaflet morphology has been described in the presence of tricuspid regurgitation by RT 3D TTE⁶⁴ but not RT 3D TEE.

AORTIC VALVE

Imaging

The normal AV is difficult to image with RT 3D TEE because of its relative anterior position and thin pliable cusps. Complete visualization of the AV cusps in the zoom mode is possible in only a small number of patients.⁴ Reliable imaging of the AV cusps is best obtained using the live or full-volume modes from midesophageal AV short-axis and long-axis views, respectively. The same imaging modes for the native AV are used in the assessment of AV prosthesis by RT 3D TEE.

Aortic Stenosis

The TEE assessment of aortic stenosis (AS) comprises a description of cusp morphology, AV function, and quantification of AS severity.⁵¹ Thickening and calcification of AV cusps facilitates imaging by all 3D modes. The 3D images show restricted cusp mobility, although echo dropout from calcification may still limit image quality.

Off-line planimetry of the anatomic aortic valve area (AVA) requires cropping by an arbitrary plane through the smallest AV orifice using zoom or full-volume 3D datasets exported to analytical software. This technique, with RT 3D TTE AV datasets, was found to correlate well with catheter measurement of AVA by the Gorlin formula and be more accurate and reproducible⁶⁵ than 2D TEE AVA planimetry.⁶⁶ The continuity equation⁶⁷ is an accepted method to indirectly estimate the effective AVA¹ and is based on the formula:

$$SV_{LV} = SV_{AV}$$

 $VTI_{LVOT} \times CSA_{LVOT} = VTI_{AV} \times AVA$

The LV stroke volume (SV_{LV}) is calculated, assuming the LV outflow tract (LVOT) cross-section to be circular. The noncircular shape of the LVOT cross-section has been demonstrated by RT 3D TTE and has raised the question of the accuracy of this method.⁶⁸

RT 3D TEE can overcome this limitation by directly measuring SV_{LV} (as discussed below), thus avoiding the need to estimate LVOT diameter. Dividing the 3D measured SV_{LV} by the AV velocity time integral obtained by 2D spectral Doppler yields the effective AVA. This method by RT 3D TTE has been reported to be more accurate than any 2D TTE measurement⁶⁹ but has not been studied using RT 3D TEE.

Aortic Insufficiency

The role of 2D TEE in the morphologic and functional assessment of aortic insufficiency (AI) has been described.⁷⁰ Imaging of normal AV cusps by RT 3D TEE is unreliable and its use is, therefore, limited in this setting.

PULMONIC VALVE

The pulmonic valve is the most anterior, and its cusps are the thinnest of all cardiac valves. Normal pulmonic valve cusps are barely visualized by 2D TEE, and good 3D TEE images are extremely rare. Intraoperative assessment of the pulmonic and TVs by RT 3D epicardial echocardiography (EE) should be considered in selected cases. The assessment of pulmonic stenosis by RT 3D echocardiography has not been reported.

HEMODYNAMIC ASSESSMENT OF REGURGITANT VALVES

Quantification of native valve regurgitation severity has been well described for 2D TEE using a number of different variables.⁷¹ The use of 3D echocardiography is limited by the lack of spectral Doppler mode and the inability to easily perform on-line linear or area measurements. However, 3D color Doppler does allow alternative ways to assess variables, such as vena contracta cross-sectional area, regurgitant jet volume, and proximal isovelocity surface area (PISA).

The measurement of the regurgitant jet vena contracta width is a simple method frequently used to grade regurgitation severity.⁷¹ It relies on the assumption that the minimal width of the regurgitant jet has a circular shape. Off-line use of a 3D color Doppler dataset permits cropping on a plane perpendicular to the regurgitant jet and direct planimetry of the vena contracta cross-sectional area. The shape of the vena contracta cross-sectional area of a tricuspid regurgitant jet⁷² is ovoid and that of a mitral regurgitant jet varies according to MV pathology and can become rather irregular.⁷³ Cropping of the LVOT on a plane parallel to the aortic annulus allows direct planimetry of an AI jet vena contracta area for comparison with the LVOT area.74 Direct measurement of regurgitant jet vena contracta area by RT 3D echocardiography may be more precise than 2D echocardiography because it does not rely on any geometrical assumption.⁷⁵ This is yet to be studied and may be limited by the poor temporal resolution of 3D images that could miss the optimal frame for accurate assessment.

Multiplying the vena contracta cross-sectional area measured as described above by the regurgitant velocity-time integral obtained by 2D spectral Doppler estimates the regurgitant volume. This technique using RT 3D TTE is feasible and reliable for MR,^{75,76} tricuspid regurgitation,⁷² AI,⁷⁴ and pulmonic insufficiency.⁷⁷

Calculation of the effective orifice area (EROA) by the PISA method assumes a perfect hemisphere. Studies using 3D color Doppler have demonstrated that PISA is not always hemispheric and this geometric assumption may underestimate the EROA.^{78,79} In vitro estimation of EROA by RT 3D TEE using the PISA method in a laboratory model of MR is feasible, precise, and highly reproducible⁷⁸ but awaits in vivo testing.

Transcatheter Aortic Valve Implantation

Transcatheter AV implantation is a new treatment option for patients with symptomatic AS deemed too high risk for conventional AV surgery.⁸⁰ The technique consists of positioning and deployment of a stented bioprosthetic valve over a balloon catheter in the native AV position approached through the femoral artery (retrograde)^{81,82} or a minithoracotomy (antegrade).⁸³ The prosthetic valve is deployed after a balloon valvuloplasty under fluoroscopic guidance.

The role of intraoperative TEE (Fig. 17)(Video 13, see Supplemental Digital Content 13, http://links.lww.com/AA/A94, see Video 13 legend at Appendix 1, http://links.lww.com/AA/A104; and Video 14, see Supplemental Digital Content 14, http://links.lww.com/AA/A95, see Video 14 legend at Appendix 1, http://links.lww.com/AA/A104) is to confirm the diagnosis of AS, provide accurate native AV annular measurement for appropriate prosthetic valve sizing, guide valve positioning, and assess prosthetic valve function after deployment.84,85 The xPlane and 3D live modes (Fig. 17C) display long-axis views of the AV that provide valuable complementary information to guide

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Figure 17. Transcatheter aortic valve (AV). The transapical approach for the transcatheter AV procedure before (A–C) and after (D–F) valve deployment is shown. A, The stenotic AV is identified in a 3D zoom dataset obtained from the midesophageal (ME) AV long-axis (LAX) view rotated to show the AV in short-axis (SAX) view from the aorta. The aortic annulus is best measured using 2D ME AV LAX or deep transgastric views. B, A 3D live ME AV LAX view guides a balloon valvuloplasty, which dilates the native AV to facilitate passage of the catheter-mounted stented prosthetic valve. C, Accurate positioning requires alignment of the prosthetic valve equator slightly below the native AV annulus (arrow). In this 3D transesophageal echocardiography (TEE) live ME AV LAX view, the valve is positioned too low and will need to be advanced before deployment. D, The deployed Edwards SAPIEN stented prosthetic valve (Edwards Lifesciences, Irvine, CA) shows good coaptation of the cusps during diastole using 3D zoom. E, The xPlane color Doppler mode helps assess and localize any paravalvular leak (arrows) showing the ME AV LAX and SAX views in the same display. F, Postdeployment valvular and paravalvular regurgitant leaks (arrows) are shown using 3D TEE full-volume color Doppler obtained from transgastric views. LVOT = left ventricular outflow tract.



Figure 18. Sinus of Valsalva aneurysm. A, A patient with a sinus of Valsalva aneurysm of the noncoronary sinus (arrow) shown in a 2D transesophageal echocardiography (TEE) midesophageal aortic valve (AV) short-axis view with color Doppler. B and C, The windsock (arrow) expands during systole in this 3D full-volume image orientated to the comparable intraoperative surgeon's view from the aortic root and the right atrium. NCC = noncoronary cusp; RCC = right coronary cusp; TV = tricuspid valve.

positioning of the prosthetic valve.^{86,87} The same artifacts present in 2D TEE such as reverberation from the wires and shadowing from AV calcification limit the use of RT 3D TEE, making accurate positioning of the prosthetic valve using TEE alone challenging. RT 3D TEE color Doppler is useful in defining the location and assessing the severity of paravalvular leaks after prosthetic valve deployment (Fig. 17, E and F) (Video 14, see Supplemental Digital Content 14, http://links.lww.com/AA/A95; see Video 14 legend at Appendix 1, http://links.lww.com/AA/A104).

Aortic Root and Aorta

The ascending aorta, aortic arch, and descending aorta can be examined using all 3D imaging modes. The wider sector of the zoom mode more completely images aortic pathology than the live mode from standard 2D TEE views. The



Figure 19. Left atrial appendage (LAA). A, A 3D zoom image of the LAA rotated to be viewed from the left atrium in the surgical orientation for the mitral valve. This 3D dataset is obtained by positioning boxes in a biplane preview to encompass the orifice of the LAA from a 2D midesophageal LAA view (typically at 30°-60°). Inclusion of the mitral valve (MV) helps orientate the 3D volume. B, A thrombus (arrow) is present at the orifice of the LAA in this patient. AV = aortic valve.

distal ascending aorta and proximal aortic arch remain difficult to image by RT 3D TEE in the blind spot created by air in the trachea and right bronchus. Given the size and thin walls of a root aneurysm, the full-volume mode achieves better image quality.

RT 3D TEE can provide detailed images of complex pathology of the aortic root and aorta including aortic aneurysm, aortic dissection, pseudoaneurysm⁸⁸ of the intervalvular fibrosa, and sinus of Valsalva aneurysm (Fig. 18) (Video 15, see Supplemental Digital Content 15, http://links.lww.com/AA/A96; see Video 15 legend at Appendix 1, http://links.lww.com/AA/A104). The diagnosis of aortic dissection by RT 3D TTE was found to integrate and potentially increase the accuracy of 2D TTE for this specific application.89

The TTE matrix array probe has been successfully used to perform RT 3D epicardial echocardiography (EE) intraoperative scanning. RT 3D EE can overcome the limitations of RT 3D TEE for imaging the most anterior structures of the heart, such as the AV and the aortic root.⁹⁰ Compared with 2D TEE and epiaortic scanning, RT 3D epiaortic imaging provided better topographic definition of atheromatous disease⁹¹ of the ascending aorta before surgical cannulation.92 The use of RT 3D TEE in detecting aortic plaque has not been reported.

LEFT ATRIUM

The left atrium cannot be entirely visualized by TEE and 3D TEE does not overcome this limitation, thus left atrial volume cannot be accurately measured by RT 3D TEE. Off-line measurement of left atrial cross-sectional area by RT 3D TEE requires importing a 3D zoom or full-volume dataset of the MV into analytical software and cropping the left atrium on a plane parallel to the mitral annulus. Although this measure seems more precise than the anteroposterior diameter measured by 2D TEE,93 its value in clinical practice has not been investigated. This contrasts with the accurate estimation of left atrial volume by RT 3D TTE,94 which was successfully used to predict survival in patients with previous stroke and congestive heart failure.95

The LAA has a pyramidal shape and its geometry can be imaged by RT 3D TEE using the zoom mode (Fig. 19A) (Video 16, see Supplemental Digital Content 16, http://links.lww.com/AA/A97; see Video 16 legend at Appendix 1, http://links.lww.com/AA/A104) as accurately as by cardiac CT.⁹⁶ Although 2D TEE is considered the "gold standard" for the assessment of LAA thrombus, RT 3D TEE (Fig. 19B) (Video 16, see Supplemental Digital Content 16, http://links.lww.com/AA/A97; see Video 16 legend at Appendix 1, http://links.lww.com/AA/A104) provides a higher specificity in defining LAA pathology than 2D TEE.97,98 The use of RT 3D TTE99 provides similar accuracy but lower specificity than TEE in excluding LAA thrombus.

LEFT VENTRICLE

Adequate assessment of the LV should include an estimate of LV volume, global and regional wall motion, mass, and synchronicity. In the operating room setting, the LV is still often assessed by qualitative "eyeballing" from 2D TEE images. Quantitative 2D TEE assessment of LV function⁹³ is time consuming and may be limited by geometric assumptions and foreshortened views.

In the normal heart, the LV is the largest cardiac structure. A 3D full-volume acquisition is the only imaging modality that can capture the entire LV volume at sufficient frame rate (25 Hz) that allows dynamic assessment. This begins from an optimized 2D midesophageal 4-chamber view. Unfortunately, RT 3D TEE does not overcome the limitation of ultrasound, thus poor endocardial definition on the baseline 2D TEE image will result in a poor-quality full-volume dataset. Little information is present from the initial full-volume 3D image of the LV epicardium until cropping reveals the endocardial cavity. More useful analysis is obtained by exporting the dataset into analytical software that enables semiautomated volumetric and dynamic quantification of global and regional LV function.

Global LV Function and Volume

LV volumes can be measured with RT 3D TEE using 2 off-line methods: 3D-guided biplanes or direct volumetric analysis. The 3D-guided biplane method more easily positions 2 perpendicular 2D planes to accurately cut the LV along its long axis at the true apex (Fig. 20A). Ideal midesophageal 4-chamber and 2-chamber 2D views are simultaneously displayed, and the LV volume, ejection fraction, and mass are calculated by applying the modified Simpson biplane method of disks to the end-systolic and end-diastolic frames.93 Although this method minimizes foreshortening of the LV when using TEE, it still relies on geometric assumptions.

Direct volumetric analysis consists of rendering a cast of the LV cavity to measure its volume throughout a cardiac



Figure 20. Left ventricular function. A, Global left ventricular function can be assessed with a 3D full-volume dataset using the biplane technique. The modified Simpson method of disks is applied to both ideal 2-chamber and 4-chamber 2D transthoracic views. B, Analytical software (QLAB; Philips Medical Systems, Andover, MA) can surface render a 3D cast of the left ventricular cavity and divide it into 17 subvolumes. C, Comparative illustration of a left ventricular cast showing the 17-segment model from the American Society of Echocardiography. D, The change in each of the left ventricular subvolumes over time is displayed as a graph to assess left ventricular regional wall motion and dyssynchrony. The basal inferior wall is clearly dyssynchronous in this patient. TMSV = time to minimal systolic volume. (Figure part C courtesy of Michael Corrin, MscMBC, with permission.)

cycle. This process requires the initial identification of 4 LV walls and the apex from 2D LV views derived from the full-volume 3D dataset. Semiautomated endocardial border detection creates a dynamic cast of the LV endocardial cavity (Fig. 20B) (Video 17, see Supplemental Digital Content 17, http://links.lww.com/AA/A98; see Video 17 legend at Appendix 1, http://links.lww.com/AA/A104). The end-diastolic volume and end-systolic volume are measured, and the stroke volume and ejection fraction are calculated. This method more accurately quantifies LV volumes particularly in patients with an abnormal ventricular shape or regional wall motion abnormalities. This in part relates to better alignment through the cardiac apex, inclusion of more endocardial surface during analysis, and the lack of geometric shape assumption.

No studies have been published on the use of RT 3D TEE for the assessment of global LV function. When compared with 2D TTE, LV volume quantification by RT 3D TTE is more reproducible, has a high test-retest correlation,¹⁰⁰ and

correlates well with cardiac MRI in the measurement of both normal¹⁰¹ and abnormal LV volume.^{100,102–105} Nevertheless, RT 3D TTE tends to consistently slightly underestimate LV volume compared with MRI. This is possibly explained by the different quantification software used to process MRI and 3D TTE datasets and the variable experience of the echocardiographer performing the LV quantification.¹⁰⁶ Commercially available analytical software for RT 3D TTE and TEE datasets were found to offer the same level of accuracy and reliability in the measurement of LV volume.¹⁰⁷

LV Mass

LV mass is a frequently used measure for the diagnosis and follow-up of LV pathology in the perioperative setting. LV mass is calculated by multiplying the volume of the LV myocardium by its weight.⁹³ Myocardial volume is determined by the difference between epicardial and endocardial volumes at end-diastole. Myocardial volume can be measured off-line from an LV full-volume 3D dataset by 2 methods: 3D-derived biplanes and 3D direct volumetric analysis. A biplane estimate of myocardial volume is obtained from tracing the LV epicardial and endocardial end-diastolic volumes in optimized midesophageal 4-chamber and 2-chamber views. The 3D direct volumetric analysis calculates the difference in enddiastolic volumes from rendered endocardial and epicardial LV casts to estimate the volume of LV myocardium.

The measurement of LV mass by RT 3D TTE using both these 3D methods correlates well with cardiac MRI.^{102,108} Furthermore, RT 3D TTE showed a lower interobserver variability than 2D TTE.¹⁰⁹ The use of RT 3D TEE in the assessment of LV mass has not been studied.

Regional LV Function

For the assessment of regional LV wall motion, the 3D LV cast is automatically divided into 16 wedges plus an apical cap, resembling the 17 segments of the American Heart Association/American Society of Echocardiography model (Fig. 20C). The RT 3D TEE assessment of regional LV wall motion is based on a change in LV chamber volume over time from altered segmental myocardial contractility. Unlike standard 2D TEE, there is no direct measurement of myocardial thickening or displacement of individual segments. Graphic display of a single cardiac cycle for each of the 17 subvolumes allows rapid detection of abnormalities in systolic endocardial motion with simultaneous assessment of all 17 segments (Fig. 20D) (Video 17, see Supplemental Digital Content 17, http://links.lww.com/AA/A98; see Video 17 legend at Appendix 1, http://links.lww.com/AA/A104).

Sensitivity and specificity of RT 3D TTE in the detection and follow-up of LV regional wall motion abnormalities have been reported to be very high.¹¹⁰

Tissue Doppler imaging (TDI)¹¹¹ has not yet been integrated in commercially available 3D matrix array probes, but the evaluation of possible applications of simultaneous multiple planes 3D TTE TDI is under investigation.¹¹² Comparing RT 3D TTE and 2D TTE strain for the assessment of LV ejection fraction and volumes provided a similar degree of accuracy and reproducibility but the latter seemed to be less time consuming.¹¹³ The application of 2D strain technology to RT 3D echocardiography is under development.¹¹⁴

A full-volume 3D dataset of the LV can be cut in multiple 2D planes and displayed simultaneously. Using this feature, the LV can be displayed as a series of parallel short-axis planes similar to a typical MRI view, allowing assessment of all LV segments in 1 display. The use of this modality in the assessment of LV function has not been studied.

LV Dyssynchrony

TDI is considered the standard for the assessment of LV dyssynchrony using 2D TTE.¹¹⁵ The technique has a high temporal resolution but is angle dependent and cannot be used with TEE for this specific reason.

Regional synchronicity assessed by RT 3D TEE measures blood ejection (subvolumes) and not tissue motion. Graphic representation of each of the 17 subvolumes from the reconstructed 3D LV model allows prompt assessment of LV synchronicity in a single screenshot (Fig. 20D) (Video 17, see Supplemental Digital Content 17, http://links.lww.com/AA/A98; see Video 17 legend at Appendix 1, http://links.lww.com/AA/A104).

The standard deviation (SD) of the time to minimal systolic volume of all 17 LV segments is a measure of LV dyssynchrony. The time to minimal systolic volume is the time from the ECG R wave to the minimal systolic volume. The SD is calculated as a percentage of a cardiac cycle. RT 3D TEE for the assessment of LV dyssynchrony has not yet been investigated.

In the normal population, RT 3D TTE has defined normal ranges for dyssynchrony indices in 91.6% of subjects with a low interobserver variability.¹¹⁶ RT 3D TTE correlated well with single positron emission CT in the assessment of LV dyssynchrony¹¹⁷ and has been used to guide resynchronization therapy.^{118,119} Correlation between RT 3D TTE and 2D TDI has been reported to be good^{120,121} in some studies and fair in others.¹²² A possible explanation for this poor correlation is that they measure longitudinal and radial LV timing, respectively,¹²² and thus cannot be compared.

RIGHT VENTRICLE

The crescent shape of the RV (Fig. 21A) makes 2D echocardiographic measurement of RV size, volume, and function difficult. As recently reviewed, a number of different echocardiographic indices can assess RV systolic, diastolic, global, and regional function.^{123–125}

RT 3D TEE overcomes some of these limitations and allows acquisition of full-volume 3D datasets of the RV with off-line measurement of RV volume and function (Fig. 21B) (Video 18, see Supplemental Digital Content 18, http://links.lww.com/AA/A99; see Video 18 legend at Appendix 1, http://links.lww.com/AA/A104) using special analytical software (4D RV-Function© application; TomTec Imaging Systems GmbH, Munich, Germany).

Although the use of RT 3D TEE in the assessment of RV function has not been investigated, data from the RT 3D TTE literature reported feasibility of this technique.^{126–128} Recent studies have shown good correlation between 3D TTE and cardiac MRI^{126,127} with better reproducibility than by 2D TTE¹²⁷ for the assessment of RV volume and function in adults and children.¹²⁹

CONGENITAL HEART DISEASE

Three-dimensional representation of cardiac anatomy may provide a better understanding of complex congenital heart disease.¹³⁰ RT 3D TTE¹³¹ and TEE¹³² imaging of the cardiac valves and assessment of ventricular function in this patient population have been reported. The lack of a pediatric 3D TEE probe has limited study to patients >15 kg in weight.¹³²

Interatrial Septum

The IAS is imaged using the zoom or full-volume modes with orientation to show the IAS from the left atrium or right atrium. This can facilitate demonstration of common



Figure 21. Right ventricular function. A, A cast of the right ventricle shows the complex geometry of the right ventricular cavity. B, Off-line reconstruction of the right ventricular cavity using TomTec analytical software (4D RV-Function© application; TomTec Imaging Systems GmbH, Munich, Germany) demonstrates this complex geometry. (Figure part A courtesy of Michael Corrin, MscMBC, and figure part B courtesy of TomTec Munich, Germany, www.tomtec.de, with permission.)



Figure 22. Atrial septal pathology. The interatrial septum (IAS) can best be imaged using 3D zoom or full-volume modes starting from midesophageal bicaval or right ventricular inflow views. The 3D volume can be orientated to be viewed from the left atrium (LA) or in the surgeon's perspective from the right atrium (RA). A, A sinus venosus defect (asterisk) of the superior vena cava (SVC) type with partial anomalous pulmonary venous drainage (PAPVD) of the right upper pulmonary vein (RUPV) is shown in this modified bicaval view. B, The same defect (asterisk) with PAPVD of the RUPV (arrow) is shown using 3D zoom of this area from the RA in the surgeon's orientation. C and D, A patent foramen ovale (PFO) is defined by a gap between a flap of the septum secundum and septum primum, without an absence of tissue as shown in 3D full volume from the (C) left atrial and (D) right atrial perspectives. E and F, Almost complete absence of the IAS is seen in the xPlane view and 3D zoom view in the surgeon's orientation from the RA. IVC = inferior vena cava.

pathology (Fig. 22) (Video 19, see Supplemental Digital Content 19, http://links.lww.com/AA/A100; see Video 19 legend at Appendix 1, http://links.lww.com/AA/A104), such as a patent foramen ovale or atrial septal defect (ASD).

Septal defects in the adult congenital population have been extensively studied using 3D echocardiography.^{133–138}

An en face surgical view of different types of ASDs by 3D TTE was reported more than a decade ago.¹³⁸ Off-line



Figure 23. Sarcoma. A patient with a sarcoma at the junction of the inferior vena cava (IVC) and right atrium (RA) is imaged using (A) 2D transesophageal echocardiography (TEE) midesophageal bicaval view and (B) 3D TEE zoom image orientated to be viewed from the RA. The 3D zoom image was obtained from orthogonal biplanes positioned to encompass the mass in the bicaval view. C, Surgery consisted of resection of the tumor together with part of the IVC and RA under circulatory arrest. RAA = right atrial appendage; TV = tricuspid valve.

3D TEE correlates well with an invasive balloon technique, in the measurement of the ASD diameter, and provides a more precise localization of multiple ASDs.¹³⁷

Assessment of an ASD using RT 3D TTE is more accurate than 2D TTE and better correlates with intraoperative surgical measurement.^{135,136} RT 3D TTE showed similar accuracy to 2D TEE in determining ASD suitability for device closure and in guiding device size selection.¹²² RT 3D TEE better defines the shape¹³⁹ and the spatial relations of the ASD and the surrounding structures such as the AV and the great vessels. The use of RT 3D TEE to guide placement of percutaneous device closure of ASDs has been well described.^{134,140}

Interventricular Septum

Similar to an ASD, ventricular septal defects (VSDs) are imaged by RT 3D TEE using zoom and full-volume modes. The 3D images can be rotated to display a view of the VSD from either the RV or LV. No studies have been reported on the use of RT 3D TEE in the diagnosis or management of a VSD. Assessment of a VSD by RT 3D TTE is feasible, provides high-quality images, and has high correlation with intraoperative surgical findings.^{133,136,138}

MASSES

RT 3D TEE can accurately assess location, attachment, and size of intracardiac masses to facilitate surgical planning (Fig. 23) (Video 20, see Supplemental Digital Content 20, http://links.lww.com/AA/A101; see Video 20 legend at Appendix 1, http://links.lww.com/AA/A104). Depending on their size, masses are imaged using the live or zoom (smaller masses) and full-volume (larger masses) modes.

The role of 3D TEE has been compared with standard 2D TEE and in 37% of the cases it provided unique information and in 27% of the cases complemented 2D TEE findings.¹⁴¹ Despite the intuitive advantages of RT 3D TEE in the operative management of intracardiac masses, no study has been reported for this specific application. RT 3D TTE has been reported to be more accurate in the measurement of the size of intracardiac masses than 2D TTE and 2D TEE.¹⁴²

HYPERTROPHIC OBSTRUCTIVE CARDIOMYOPATHY

Hypertrophic obstructive cardiomyopathy often presents with an asymmetric interventricular septal hypertrophy and narrowing of the LVOT. Surgical resection of the interventricular septum is a therapeutic option that results in relief of LVOT obstruction, improving symptoms and patient outcome.¹⁴³

Intraoperative TEE has been successfully used during surgical septal myectomy. Surgical resection is guided by measures taken in a single 2D plane perpendicular to the interventricular septum. The LVOT is, however, a tubular structure that is difficult to accurately describe using 2D images alone.

The perioperative application of 3D TTE in this setting has shown that it may be a useful tool to improve understanding of the LVOT anatomy and guide surgical intervention.¹⁴⁴ The intraoperative role of RT 3D TEE has not been investigated (Fig. 24) (Video 21, see Supplemental Digital Content 21, http://links.lww.com/AA/A102; see Video 21 legend at Appendix 1, http://links.lww.com/AA/A104). Systolic anterior motion of the anterior MV leaflet, causing significant MR, is frequently associated with asymmetric septal hypertrophy in the presence of hypertrophic obstructive cardiomyopathy. The RT 3D TEE live mode and en face view¹⁴⁵ of the MV can effectively display systolic anterior motion. Of note, RT 3D TTE showed a very high correlation with cardiac MRI in the measurement of LV volume, mass, and wall thickness in this subset of patients.146

MINIMALLY INVASIVE SURGERY AND CATHETER-GUIDED INTERVENTIONS

The possibility of generating high-quality 3D images with a high frame rate makes RT 3D TEE suitable to guide minimally invasive cardiac procedures.^{24,147} The ability to rotate the 3D image in any orientation and reproduce the anatomic view provides effective and reliable guidance to the operator.

RT 3D TEE has been successfully used to guide the percutaneous closure of MV paravalvular leaks^{49,50,148} (Fig. 25) (Video 22, see Supplemental Digital Content 22,



Figure 24. Hypertrophic obstructive cardiomyopathy. A and B, The hypertrophied intraventricular septum (IVS) in a patient with hypertrophic obstructive cardiomyopathy is shown (arrow) through the aortic valve from a surgeon's orientation (A) at the time of surgery and (B) using 3D full volume of the aortic root. C, The hypertrophied IVS (arrow) with systolic anterior motion (SAM) is shown in this 3D live image of the midesophageal long-axis view. D, A surgical myectomy is performed. E and F, Comparable postmyectomy full-volume view from the (E) aortic root and (F) 3D live image of the midesophageal long-axis view during systole are shown. LCC = left coronary cusp; NCC = noncoronary cusp; RCC = right coronary cusp.



Figure 25. Paravalvular leak. A, A patient with a bioprosthetic mitral valve and paravalvular leak is shown in a 2D transesophageal echocardiography (TEE) midesophageal color Doppler view at 53°. B, The gap (arrow) causing the paravalvular leak is seen in the 3D TEE zoom image orientated to be viewed from the left atrium. Two catheters are visible; one through the paravalvular leak (*) and the other in the right atrium (**). C, The leak was closed percutaneously using 2 Amplatzer devices (AGA Medical, Plymouth, MN). AV = aortic valve.

http://links.lww.com/AA/A103; see Video 22 legend at Appendix 1, http://links.lww.com/AA/A104), MV clipping,¹⁴⁹ ASD device closure,^{134,140} and LAA device occlusion.¹⁵⁰ The development of new minimally invasive cardiac surgical techniques¹⁵¹ combined with the advances in RT 3D TEE technology have permitted the integration of both into experimental robotic surgery workstations.¹⁷ This technology uses stereoscopic rendering of RT 3D TEE imaging to guide the beating heart

intracardiac procedure.¹⁷ This technique has shown promising results in ASD¹⁵² and VSD¹⁵³ closure in an animal model.

The 2 main limitations to current 3D technology are low frame rate with poor temporal resolution of large 3D datasets and artifacts generated by the metallic surgical instruments. Integration of systems to track the position of the surgical instruments in space and RT 3D TEE imaging is under development.

FUTURE IMPROVEMENTS

Intraoperative RT 3D TEE has elevated TEE to a new fascinating and challenging dimension. Spectacular pictures, ease of use, and simplification of challenging diagnoses are combined in a tool that has not yet revealed its full potential. The continued evolution of current RT 3D TEE technology should aim to satisfy the needs of the fast and hectic intraoperative environment. Quicker acquisition of 3D full volume and 3D color Doppler combined with on-line automatic 3D LV and RV reconstruction would provide the cardiac anesthesiologist with the most precise tool to assess and monitor LV and RV volumes. Integration of spectral Doppler and TDI should be incorporated into the next generation of 3D TEE probes.¹⁵⁴

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