Evolving Role of Three-Dimensional Echocardiography in the Cardiac Surgical Patient

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Published online: 30 July 2013
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Abstract The first human three-dimensional transesophageal echocardiography (3D TEE) was reported in 1992. Ever since, technologic advances have revolutionized this echocardiographic imaging modality. Today, real-time 3D TEE (RT-3D TEE) represents a novel clinical and intuitively educational perioperative cardiovascular imaging tool. In addition, live 3D TEE adds significantly to the perioperative communication between cardiac surgeons and echocardiographer. Its unique ability of real-time acquisition and accurate identification of precise cardiac pathology, together with its ability to promptly quantify 3D datasets using built-in software, has greatly helped to transition 3D TEE into the standard of perioperative care. The recent development of percutaneous procedures such as valve implantations and repairs also benefit from 3D TEE quantification and guidance. This article reviews the available 3D TEE acquisition

modes, newest advances in 3D technology, and the utility of 3D TEE in different settings of cardiac procedures.

Keywords Cardiac surgery · Transesophageal three-dimensional echocardiography · Perioperative assessment

Introduction

In the last decade, one of the most important developments in ultrasound imaging of the heart has been the evolution of 3D echocardiography from slow and labor-intensive offline reconstruction to real-time volumetric imaging [1].

In light of these recent and ongoing improvements of 3D echocardiography, echocardiographers are constantly expanding its use in quantifying valvular heart disease, ventricular function, or when assessing complex cardiac anatomy. Intraoperatively, the introduction of RT-3D TEE has quickly been embraced by both cardiac surgeons and anesthesiologists, as this new technology offers superior image quality, greater accuracy, and ever-expanding capabilities. The interventional cardiology suite and the hybrid operating room are other areas where the advent of RT-3D TEE has revolutionized procedural imaging and guidance as well as the immediate diagnosis of related complications.

Significant interest in 3D technology has been sparked in the research community due to its growing availability, its ease of use, and its multiple attractive features, resulting in a large number of related publications and guidelines within the last decade [2, 3•, 4•]. The purpose of this article is to review current 3D imaging technologies and the utility of 3D echocardiography in the perioperative period. Each intraoperative use of 3D echocardiography will be described individually along with its technical limitations.

Electronic supplementary material The online version of this article (doi:10.1007/s40140-013-0025-6) contains supplementary material, which is available to authorized users.

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3D Imaging Modes and Post-Processing

3D images can currently be acquired in two different ways: 3D live or 3D ECG gated imaging. 3D live or RT-3D TEE refers to the acquisition of the image by utilizing multiple pyramidal datasets per second in a single heartbeat. In 3D ECG gated imaging, data acquisition is triggered by the ECG and multiple beats are used to build the final image. There are currently two notable ultrasound systems built for 3D/4D image processing, iE33 xMatrix (Philips Medical Systems, Andover, MA, USA) and Vivid E 9 (GE Healthcare Vingmed Ultrasound, Horten, Norway). The available modes of 3D/4D acquisition are described in more detail below:

Real Time Three-Dimensional Echocardiography (3D Live)

This mode displays in real time 300×600 pyramidal volumes. It can be used to conveniently display cardiac structures located in the near field (Fig. 1). This mode results in superior spatial and temporal resolution permitting accurate diagnoses of complex pathologies. In general, RT-3D TEE or live 3D is preferentially used to display the mitral valve (MV), aortic valve (AV), the left atrial appendage (LAA) and the intraatrial septum.

Focused Sector—Zoom

Also known as 3D Zoom (Philips Medical Systems) or FlexiZoom (GE Healthcare Vingmed Ultrasound), this mode displays a magnified pyramidal dataset of variable size. It permits a focused visualization of a specific cardiac structure or region. It is important to note that, in this 3D acquisition mode, the focused area of interest being imaged is obtained at the cost of the decrease in spatial and temporal resolution. Careful placement and sizing of the zoom sector over the region of interest with minimized sector-width improves temporal resolution and optimizes image quality (Fig. 2). Live 3D color zoom is a new feature available on the most updated version of iE33, Vision 2012 (Philips Medical Systems). In the operative room, this new tool can potentially improve the accuracy in the assessment of postoperative valvular regurgitation. In the interventional laboratory, it helps to assess structural heart defects as well as to diagnose paravalvular leaks after valve deployment in transcatheter aortic valve implantation (TAVI) procedures.

Full Volume

This mode provides the largest pyramidal dataset possible (approximately $65^\circ \times 60^\circ$ up to $100^\circ \times 100^\circ$). When

utilizing the conventional 3D workflow, the wide-angle dataset is compiled by either acquiring data based on a single heart beat or by merging two to six narrower RT-3D pyramidal wedges or subvolumes obtained over two to six heartbeats. Available in the most update version of the iE33, Vision 2012, HVR mode consists of a method of scanning a live 3D volume using subvolumes. Traditionally, a subvolume consists of a contiguous subset of scan lines. An advantage of using contiguous subsets is that there are few locations where the different subsets join and therefore a small number of locations where “stitching” artifacts would be visible. A disadvantage of using contiguous subsets is that, when a given subset is being scanned, there is no information about the remainder of the volume. As such, when there is significant motion of either the patient or the transducer, it is necessary to completely rescan the entire volume to acquire an acceptable full volume. With HVR mode, the volume is scanned with subvolumes that consist of interlocking sparse patterns. An example of a classic interlocking sparse pattern is a chessboard (Fig. 3). This figure shows the difference between the traditional acquisition of the subvolumes and the HVR mode lateral and axial elevation views. An advantage of using interlocking sparse patterns is that, while one pattern is being scanned, it is possible to make a good estimate of the complete volume by interpolating the missing samples. A disadvantage relates to the potential for many “stitching” artifacts given the many locations where the different patterns join. In the HVR mode, scanning alternates between subvolumes. During one cardiac cycle, one subvolume is repeatedly scanned. During the next cardiac cycle, other subvolumes are repeatedly scanned. While one subvolume is being scanned, the missing subvolume is estimated using the surrounding subvolumes.

New software has been developed to help improve the acquisition of large volumes of 3D data. The one beat acquisition available at the Vision 2012 and the 4D views are both “one-touch” options to quickly acquire images of larger structures such as left ventricle.

For the conventional 3D full volume acquisition it is important to minimize artifacts. During the surgical or interventional procedure in the anesthetized patient, full volume loops should be acquired when ventilation is held and electrocautery is not used. In patients with arrhythmia artifacts cannot be totally avoided. After optimization of the two-dimensional (2D) image of the four-chamber view, a full volume loop of the left ventricle (LV) is acquired. 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. The first obtained 3D-volume is displayed as auto crop showing only 50 % of the volume mirroring the original four-chamber view. Resetting the crop plane allows the display

Fig. 1 RT-3D TEE *en face* (or surgical) view of the MV demonstrating the aortic valve at 12 o'clock in the near field. AV aortic valve, MV mitral valve

Fig. 2 3D TEE focused sector images of the MV. 3D Zoom feature (Philips; *top*) and FlexiZoom (GE Healthcare; *bottom*) AV Aortic valve, PL posterior leaflet

of the entire pyramidal dataset. The full volume can be further processed offline by rotating and cropping to visualize specific structures inside the pyramid. Acquired

full volumes can also be used for volumetric quantification of the LV using the available built-in software features explained below.

Fig. 3 HVR mode for full volume acquisition. **a** The contiguous subset of scan lines in axial and lateral elevation views. **b** HVR mode demonstrating how the interlocking space patterns look in the lateral elevation and in the axial view. Reproduced with permission from Philips Healthcare

Full Volume with Color Flow Doppler

The acquisition of the 3D full volume with color Doppler is very similar to the regular full volume data acquisition. It consists of the integration of 7–14 (original version of iE33) or 2–6 individual pyramidal subvolumes gated to the ECG.

Fig. 4 Full volume with color flow Doppler TEE data. Notice the area of interest, *PFO*, in the center of the sector

Similarly to the full volume, this mode is prone to artifacts introduced by arrhythmias, movement, or electrocautery. For this mode, it is essential to place the area of interest, e.g., a regurgitant or patent *foramen ovale* (PFO) jet in the center of the sector (Fig. 4; Movie Clip 1). Most updated software versions of 3D echocardiography allow for the acquisition of full volume with color flow in as few as two heartbeats.

Clinical Applications

Assessment of the Left Ventricle

Perhaps one of the most valuable contributions of 3D echocardiography in the perioperative period may be LV quantification [5]. The 3D echocardiographic assessment of LV volumes and function provides accuracies that approach the accuracy of cardiac magnetic resonance imaging (cMRI) [6–14]. Furthermore, 3D echocardiography for the assessment of LV volumes and ejection fraction (EF) has been currently recommended over the use of 2D echocardiography, due to its accuracy and reproducible measurements [13, 14]. With the advent of the new semi-automated volumetric analysis systems, the global and segmental analysis of the LV has become less troublesome and less time-consuming which makes its intraoperative use more realistic.

One of the most utilized approaches to LV assessment in 3D is the acquisition of a full volume dataset. The software available for the analysis of LV function consists of built-in

quantification features that are based on semiautomated endocardial border detection that allows fast and accurate measurements of global and regional LV function. Examples of available built-in software packages are 3D Quantification Advanced (3DQA) program (Philips Medical Systems) and 4D Auto left ventricular quantification LVQ (GE Healthcare Vingmed Ultrasound). Both vendors offer online as well as offline quantitative analysis.

The Philips 3DQA program consists of a mesh-based surface-tracking mode that provides automatic LV volume and EF. The system requires manual definition of the septal, lateral, anterior, inferior, and apical endocardial border of the LV in the end-systolic and the end-diastolic frames, followed by an automatic border-tracking algorithm. Further, the end-systolic as well as the end-diastolic volumes are calculated. Global stroke volume and EF are then derived. An advantage of this system is the segmental analysis of the left ventricle. The LV shell obtained in semiautomatic fashion is then subdivided in 17 regions, which are analyzed separately by performing the “segmental analysis”. Other viewing modes include the “iSlice” view that displays nine simultaneously moving

short axis views of the LV and allows verifying appropriate endocardial border detection as well as simultaneous wall motion abnormalities (Fig. 5).

An interesting advantage of the 4D is that, by utilizing temporal data, it delivers reproducible results that could be less prone to artifacts and variable heart rhythms for automatic volume and EF.

LV mass has previously been shown to be an independent predictor of incident cardiovascular disease morbidity and mortality [15]. Although rarely used during the peri-operative period, this tool can be used to diagnose LV pathology such as hypertrophic cardiomyopathy [16]. The measurement of LV mass by 3D echocardiography correlated well with cMRI and demonstrated a lower interobserver variability than 2D echocardiography [11, 17–21]. For the 4D LV mass, using the above-mentioned mesh-based surface tracking model, by adding the epicardial border, an LV mass and an LV mass index can be derived from the dataset obtained for the LV EF.

To date, 2D transthoracic echocardiography remains the imaging modality of choice in assessment of LV clot. However increasing evidence in the literature shows that

Fig. 5 3D datasets with different 3D visualization and analysis of the left ventricle (LV). **a** Segmental analysis of the LV with 17 segmental time-volume waveforms are displayed simultaneously offering the

possibility for objective wall motion comparison, **b** “iSlice” 2D tomographic slicing of the LV. **c** “Mesh” of the LV **d** 4D Auto Left ventricular quantification (LVQ) (GE Healthcare Vingmed Ultrasound)

3D technology can be more accurate in intracardiac mass detection and should be considered in the diagnostic process [19].

Assessment of the Right Ventricle

Perioperative right ventricular (RV) dysfunction is one of the most frequent causes of morbidity and mortality in complex cardiac surgical patients. Nevertheless, global assessment of the RV is recognizably difficult mostly due to its geometric complexity. The 2D intraoperative assessment has several limitations, which can be overcome by 3D ECG gated image acquisition. Overall, 3D echocardiography allows the complete assessment of the RV anatomy, geometry, volumes, and EF [3•]. Recent work has shown that 3D TEE assessment of the RV and dedicated RV quantification software can be applied to reliably represent the complex geometry of the RV. Therefore, this approach constitutes a valuable tool for the assessment of the RV function during the perioperative period [22].

Recently, several methods and software packages have been developed to assess the RV. Similar to the LV, a 3D full volume dataset of the ME four chamber view is required. The stored data can be then processed offline. The 3D image of the RV is usually obtained from the ME four-chamber view with the probe slightly rotated to the right side of the patient in order to include the annulus of the RV.

A freestanding software (4D RV-Function; TomTec Imaging software, Unterschleissheim, Germany), dedicated to RV quantification facilitates the analysis of RV volume and function; this can be performed both with 3D TTE as well as with 3D TEE data [23]. After acquisition of the full-volume of the RV, TV and MV annulus, and the LV apex are manually marked (Fig. 6; Movie clips 2–3). These reference points are useful not only to define the tricuspid annulus but also to position the major right heart axis within the 3D dataset. The RV cavity is semiautomatically determined after the identification of the end-systolic and end-diastolic endocardial border. Measurements such as the end-systolic and end-diastolic volumes are automatically derived and the resulting stroke volume and EF calculated. The segmental analysis of the three main sections of the RV including inlet, apex, and outflow segments may be displayed [22].

Until the present time, gold standards methods for RV evaluation such as cMRI or radionuclide ventriculography are not available intraoperatively. Although fasting and hemodynamic changes can make the evaluation of the RV function very challenging, 3D TEE might be the most feasible way to intraoperatively evaluate the function of the right heart.

Mitral Valve Assessment

In the last decade, innumerable studies have been published in the literature comparing 2D versus 3D echocardiography in MV. [24–26] Most recently, Hien et al. demonstrated that 3D TEE is superior to 2D TEE for prolapsed and cord rupture [27]. The superiority of 3D echocardiography might be attributed to the non-planar 3D structure of the MV annulus; it is impossible to visualize it in a single plane using 2D TEE. Additionally, the saddle-shaped configuration of the MV and the complex interrelationships among the MV, chordae, papillary muscles, and myocardial walls mean that 3D imaging is particularly suited to achieve a complete assessment. Therefore, a comprehensive 2D examination requires interrogation of the MV apparatus at multiple planes and TEE probe positions and demands a mental integration of numerous views for accurate assessment which critically depends on observer experience and expertise. A great number of software packages have been developed to assist the intraoperative echocardiographer in the quantitative assessment of the MV [28, 29].

A comprehensive intraoperative evaluation of the MV involves the acquisition of the so-called *en face* view, a full volume and 3D color full volume image. Further analysis of the MV can be achieved by 3D quantitative assessment of the MV using built-in software (MVQ Qlaboratory, Philips Medical Systems; or MVA 2.0, TomTec Imaging software) (Fig. 7).

The *en face* or “surgical view” presents a view of the MV similar to that seen by the surgeon from a left atrial perspective. This view is routinely generated using the 3D zoom mode based on the ME four-chamber view and by rotating the obtained image to display the AV at the 12 o’ clock position as the midpoint of the anterior annulus [30], as previously shown in Fig. 1. The full volume dataset allows assessing the intimate interrelationship among the MV, the papillary muscles, the myocardial walls, and the left ventricular outflow tract (LVOT). 3D TEE has been used to identify the exact location of the pathology of mitral leaflet lesions in MV prolapsed (3 D4 and 5) (Movie Clip 4 and 5) should be here as opposed to (3D 4 and 5), endocarditis, and congenital MV abnormalities to guide the surgeon to optimize the surgical repair. According to a recent study, 3D TEE provided an objective tool for predicting MV repair complexity involving bileaflet repair techniques, requiring multiple resections or patch augmentation, in patients with mitral regurgitation (MR), in which the most predictive models included three predictors: multisegment pathology, prolapsing height, and posterior leaflet angle [31]. RT-3D TEE (94 % accuracy) was superior to RT-2D TEE (71 % accuracy) in accurately identifying abnormal MV segments in patients undergoing MV surgery for MR when compared to the surgical finding as a

a

Volume

60V 125.0
10V 71.5
0V 51.3
EF 42.7

b

Figure 1: A composite image showing three panels. The top panel displays three 2D echocardiographic views (parasternal short-axis, parasternal long-axis, and apical four-chamber) with a color-coded strain map overlaid on the left ventricle. The middle panel shows a 3D reconstruction of the left ventricle with a color-coded strain map. The bottom panel shows a 3D reconstruction of the left ventricle with a color-coded strain map and a list of strain parameters on the right side.

and has been shown to be a suitable technique for monitoring its efficacy and complications [35, 36]. In poor surgical candidates presenting with paravalvular leak, 3D-guided placement of the occluding device has proven to be feasible and superior to 2D [37, 38]. Assuming high-quality 3D datasets, the echocardiographer should not only be able to guide the procedure but also provide accurate

quantitative information about the paravalvular leak to assist in sizing of the occluding device (Fig. 8).

Aortic Valve

Compared with the large body of literature featuring the MV, studies assessing the native AV using 3D echocardiography are limited. The AV can be optimally visualized only in 18 % when using RT-3D TEE, most likely because the AV is an anterior structure with a longer distance from the transducer and with thinner leaflets compared to the MV [39]. However, 3D TEE provides a better understanding of the relationship of the AV and the surrounding structures, such as LVOT, and anterior leaflets of the MV without the need for time-consuming mental reconstruction needed with 2D.

In recent years, the importance of 3D imaging during AV procedures has increased considerably due to the introduction of TAVI. The technique consists of positioning and deployment of a stented bioprosthetic valve over a balloon catheter in the native AV position approached through the retrograde transfemoral or the antegrade transapical access [40–42]. The prosthetic valve is deployed after a balloon valvuloplasty under fluoroscopic guidance. Intraoperative TEE plays an important role to provide (1) accurate measurements of the native AV annular and LVOT for appropriate prosthetic valve sizing, (2) guidance during prosthetic valve positioning, and (3) assessment of the prosthetic valve function and the severity of paravalvular leaks after prosthetic valve deployment [43, 44]. Additionally, 3D TEE is helpful in visualizing the

degree and distribution of calcifications on and adjacent to the AV and in measuring the distance from the AV leaflets to the left main coronary ostium, the angle of the LVOT to the aorta, and the baseline severity of LV size, function, and hypertrophy.

By utilizing the built-in software, the echocardiographer is able to make accurate measurements of the LVOT and the annulus of the AV. Following the acquisition of a full volume dataset, the image should be aligned optimally using the multiplanar reconstruction (MPR) mode. The coronal “green box” on the MPR mode should display the long axis of the AV. Further adjustments with the “red plane” should be made in order to have the “red box” or sagittal plane displaying either the LVOT or the annulus of the AV. Adjustment of the MPR planes is facilitated while playing the cine loop. Great care needs to be taken to avoid inclusion of the anterior leaflet of the MV when assessing the LVOT. After correct identification of the structures to be analyzed, the dimensions and the area of the LVOT and aortic annulus can then be calculated (Fig. 9). Recent guidelines recommend the incorporation of 3D TEE not only for the assessment of the AV but also for guidance of TAVI [3•, 4•].

Left Atrial Appendage

TEE is considered the gold standard imaging modality for detection of LAA thrombi. Despite a relatively high specificity, 2D TEE imaging may overestimate the incidence of thrombi partly due to the complex geometry of multi-lobed LAA. RT-3D TTE or reconstruction 3D TEE

Fig. 8 Three-dimensional TEE color full volume of the paravalvular leak of the MV displayed in three multiplanar reconstruction planes (*green, red, and blue* MPRs). By utilizing built-in software, the measurement of the diameter and area of the paravalvular leak can be obtained (Color figure online)

Fig. 9 3D TEE of the AV displayed in the three multiplanar reconstructions (*green, red, and blue MPRs*) along with the measurements of area and diameters of the aortic valve (*bottom*) (Color figure online)

enables excellent visualization of the LAA anatomy and function, and RT-3D TEE provides a higher specificity in defining LAA pathology than 2D TEE [45–47]. Clinically, 3D echocardiography helps to distinguish thrombi from anatomical variants and might alter the course of therapy for patients with atrial fibrillation and help determine the need for additional surgical interventions such as ligation of the LAA in patients undergoing assisted devices placement. The best way to visualize the LAA is by using the focused sector function (zoom) with the adjacent ligament of Marshall. 3D echocardiography is also helpful for guiding percutaneous interventions involving the atrial septum, such as the Lariat procedure [48, 49]. During this intervention, TEE is used as guidance for positioning a marker balloon at the ostium of the LAA and to confirm acute closure of the LAA [50]. During atrial septum defect (ASD) or PFO closures, 3D TEE provided excellent anatomic detail of the septal defects and continuous visualization of the 3D relationships involved in sheath positioning and device deployment [51].

Tricuspid and Pulmonic Valves

The TV is composed of three leaflets attached to a fibrous annulus presenting a complex three-dimensional shape and thus it is not possible to visualize it in one cross-sectional view using 2D echocardiography. In this context, 3D echocardiography allows users to visualize the whole TV apparatus leading to better understanding of the pathophysiological mechanisms of underlying TV diseases.

While 3D TTE in patients with good-quality 2D images generated optimal 3D images of the TV in 90 % of patients, 3D TEE of TV can be optimally visualized with RT-3D TEE in only 11 % of cases mainly because of its thin leaflets and anterior position [39, 52]. 3D TTE provides incremental diagnostic value over 2D echocardiography with regard to the etiology and location of the abnormal leaflet segments and the exact shape and size of the vena contracta (VC) [53]. The *en face* view of the TV may assist in the diagnosis of TV variants such as the presence of a bileaflet TV which has only been described using 3D-TTE [54]. 3D echocardiography can be helpful in identifying whether pacemaker or intracardiac defibrillator leads contribute to tricuspid regurgitation [55]. Further, 3D color flow Doppler showed that the TV VC is more of an elliptic shape compared to the MV [56].

In general, the morphology of the TV is best assessed using the 3D zoom mode. The 3D full volume mode might add information about the relationship to adjacent structures and help to examine the papillary muscles. Finally, the 3D color full volume is required for the determination of the VC. However, the insufficient visualization of the TV using RT-3D TEE, which may be additionally compromised by the presence of a pulmonary catheter in patients undergoing cardiac surgery, presents a major limitation of RT-3D TEE for assessment of the TV.

Normal pulmonic valves (PV) are barely visualized by 2D TEE, and thus good 3D TEE images are extremely rare because of their anterior position and thin cusps. Intraoperatively, 3D TTE can perhaps provide better scanning of

Conclusion and Future Directions

In conclusion, 3D echocardiography represents a novel clinical and intuitively educational perioperative cardiovascular imaging modality. In addition, live 3D TEE significantly improves the communication of cardiac diagnosis between cardiac surgeons or interventionalists and the intraoperative echocardiographer. However, according to its main critics, the utility of intraoperative 3D TEE is limited to the acquisition of “pretty pictures” rather than its unquestionable impact on surgical decision-making and clinical outcomes. With further technological advances in 3D imaging quality, acquisition speed, and more automated quantification packages, 3D echocardiography is not only here to stay but will become a standard component of perioperative imaging of the patient with cardiac disease.

Ultimately, this technology together with the development of computational capacity and 3D printing tools should open up the door for the creation of precision prosthetics and the establishment of virtual surgery platforms. Although intraoperative 3D TEE is not yet a mature technology, we encourage even the skeptics to embrace it and, more importantly, support its transition towards a standard imaging modality in the perioperative arena.

Disclosures Renata G. Ferreira, Yong Seon Choi, and G. Burkhard Mackensen declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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