Pediatr Cardiol (2013) 34:1525–1531
DOI 10.1007/s00246-013-0718-0

REVIEW ARTICLE

Feasibility and Effectiveness of Three-Dimensional Echocardiography in Diagnosing Congenital Heart Diseases

Saad. Khoshhal

Received: 25 April 2013 / Accepted: 27 April 2013 / Published online: 16 May 2013

Abstract Three-dimensional echocardiography (3DE), a novel approach employed in detecting congenital heart disease (CHD), has gained popularity since it was made commercially available in 2002. This modality is now accepted as an important diagnostic tool for diagnosing CHD. Advancement in transducer technologies and digital data processing allows the use of 3DE in daily clinical practice. In this review, modes of 3DE data acquisition and storage methods in the echocardiogram's machine's hard disk (data processing) are examined. Analysis of the acquired data (cropping or slicing the data set) and methods of illustrating the cropped data set for cardiologists and pediatric cardiovascular surgeons are also discussed. Published literature was searched in PubMed using the keywords "three-dimensional echocardiography", "congenital heart disease", "cropping", and "echoangiogram". This search produced 100 articles, which were further shortlisted to 30 articles. Based on this algorithm, the final selected 30 articles were extensively examined in the current review. The clinical applications of real-time transthoracic 3DE, as well as novel transesophageal 3DE and color flow 3DE data set analyses (echoangiogram) in the routine practice of CHD assessment, are also reviewed. Finally, the limitations 3DE, together with the potential future developments required to improve various techniques of 3DE to make it more readily applicable, are examined.

Electronic supplementary material The online version of this article (doi:10.1007/s00246-013-0718-0) contains supplementary material, which is available to authorized users.

Saad. Khoshhal (✉)
College of Medicine, Taibah University, Almadinah Almunawwarah, Saudi Arabia
e-mail: drsaad68@hotmail.com

Keywords Congenital heart disease · Cropping · Echoangiogram · Echocardiography · Three-dimensional echocardiography

Introduction

Although transthoracic (TT) two-dimensional echocardiography (2DE) is the most common noninvasive diagnostic modality used for CHD evaluation, expert opinions are needed for data interpretation because of the intracardiac complex anatomy and its relationship with the neighborhood structures. This constraint is a limitation when using TT-2DE alone and often leads to varying interpretation by different observers based on their imaginary reconstructions of cardiac structures.The above-mentioned limitations of using TT-2DE alone are overcome by the use of real-time transthoracic three-dimensional echocardiography (RTT-3DE), which provides detailed evaluation of cardiac physiology and anatomy in RT [18, 22]. New techniques of imaging acquisition by advanced transducer technologies and digital data processing allow the application of newer-generation RTT-3DE [7, 14]. RTT-3DE is based on online volumetric scanning and does not require extensive reconstruction after data set acquisition as with computed tomography (CT) and magnetic resonance imaging (MRI) [5].The current RTT-3DE system of matrix-array transducers was developed and has been commercially available for CHD evaluation since 2002. Furthermore, there continues to be extensive advancement of 3DE software, thus allowing better image acquisition and analyses [16]. Compared with the sparse-array transducer, the current RTT-3DE system of matrix-array transducers has more imaging elements in the transducer's head (>3,000 vs. 256) with better resolution, thus making it the technique of choice in 3D data set acquisition and clinical applications [25]. Real time transesophageal three dimensional echocardiography (RTTE-3DE) was developed in 2007 and is now commercially available. The feasibility and usefulness of RTT-3DE, RTTE-3DE, and color flow 3DE data set analyses (echoangiogram) in the daily routine practice of CHD assessment are discussed in this review. The discussion and figures showed in this review are based on the IE-33 echocardiogram (ECG) machine (Philips, Bothell, WA, USA).

Currently there are no widely accepted 3DE protocols. The majority of 3DE studies in several laboratories used (as an afterthought) new echocardiogram machines with advanced software capable of 2D and 3D image acquisition. Typically, complete 2DE is initially performed for all patients followed by RTT-3DE for areas of interest. For instance, if the mitral valve (MV) is found to be abnormal by 2DE with suspicion of cleft MV or MV prolapse (MVP), then 3DE is performed to achieve better imaging of the MV. RTTE-3DE and echoangiogram are usually performed only in selected patients. The greater-frequency X7-2 probe (2–7 MHz) is used in pediatric patients for 2DE, Doppler, RTT-3DE, and echoangiogram. For overweight pediatric patients and adults with CHD, the lower-frequency X3-1 probe (1 and 3 MHz) is used. With these probes, an instantaneous volume scan acquisition can be obtained because it uses a "matrix" transducer (>3,000 active elements available in the probe's head) and offers steering in both azimuth and elevation planes.

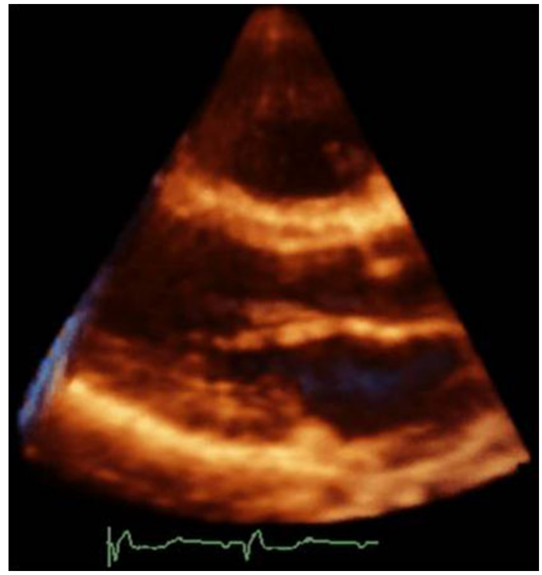

Fig. 1 Still image of Movie Clip 1. RT live 3DE in NA mode

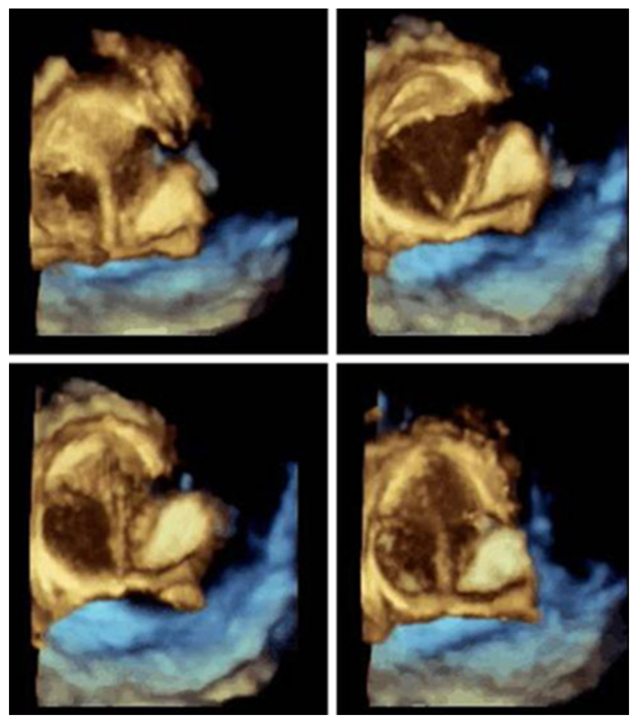

Fig. 2 Still image of Movie Clip 2. Zoom mode (magnified) view shows the aortic valve from above the valve (i.e., within the ascending aorta)

Acquisition Modes

Aquisition modes include the following:

(1) Real-time (live 3DE; narrow-angle [NA]) (Fig. 1, Movie Clip 1)
(2) Zoom (magnified) (Fig. 2, Movie Clip 2)
(3) Full-volume (FV), wide-angle (WA) data sets (Movie Clip 3)
(4) 3D color flow Doppler (50° × 50°) pyramidal volume with tissue and flow information) (Fig. 3)

RT Mode

The RT (live 3DE = NA) mode displays a pyramidal data set of ∼50° × 30°. In addition, it employs familiar 2D-like cut planes and allows RT evaluation of cardiac structures, e.g., in each scanning window, e.g., parasternal long-axis (PSLAx) or apical window scanning started, with this mode of acquisition usually followed by FV acquisition. The advantages of real time 3DE include the following:

- No respiratory holding or Electrocardiogram (ECG) gating is required.
- Live 3DE volume can be easily manipulated using a track-ball to view the lesion from many angles.
- This mode of data acquisition has no risk of motion or stitch artifact formation, which makes it suitable for application in children for whom it is difficult to hold

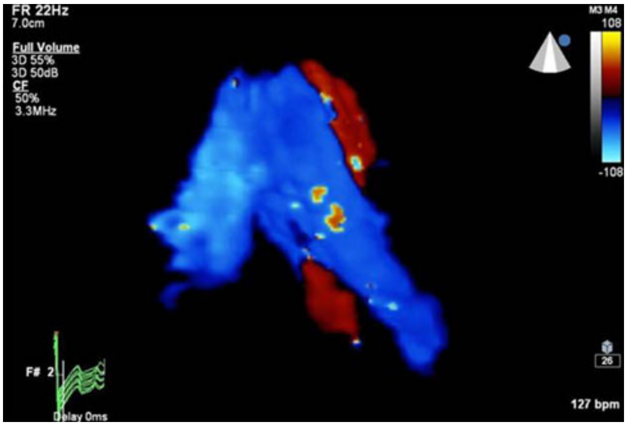

Fig. 3 3DE color flow Doppler mode

the breath during data set acquisition. It can also be performed in patients who had arrhythmia [23]. The main limitation of live 3DE is greater cardiac volumes, e.g., a dilated left ventricle (LV) in cardiomyopathy patient (CMP) cannot be accommodated by this mode of data acquisition.

Zoom Mode

The zoom (magnified) mode it is an excellent mode of 3DE data acquisition and analysis, especially 3DE evaluation of atrioventricular valves and the intratrial septum evaluation during atrial septal defect (ASD) secondum device closure. It provides greater resolution and a magnified pyramidal data set with a scanning angle of 50° × 30°, which can be increased to 90° × 90° if needed [2]. The main limitation of zoom acquisition mode is that it cannot accommodate greater cardiac volumes.

FV Mode

The FV mode provides a pyramidal data set of ~90° × 90° [12], which is suitable for accommodation of greater cardiac volumes because data set acquisition is obtained with ECG gating over four to seven cardiac cycles that are stitched electronically. The main advantage of the FV data set is its broader coverage, i.e., most of the 2DE views (four-chamber, three-chamber, and short-axis) are available in just one FV 3DE data set. Limitations of this mode of 3DE data acquisition include motion artifacts, transducer movement, rhythm abnormalities, and irregular breathing within the acquisition period, all of which can affect the quality of FV-3DE data set acquisition. FV also has lower resolution than live 3DE.

Although the FV mode is an attractive and automatic selection when greater cardiac volumes are required to be scanned, e.g., four-chamber view of a dilated CMP, live 3DE or zoom mode are adequate to guide the interventionist when small structures are planned to be scanned, e.g., secondum ASD closure by device, by providing *en face* view of the ASD from both the left atrium (LA) and the right atrium (RA).

3DE Color Flow Doppler Mode (50° × 50°): Pyramidal Volume with Tissue and Flow Information

In this modality, seven separate NA scans are combined to produce a 50° × 50° "pyramidal wedge", which allows qualitative visualization of structures typically not possible to obtain, such as the Blalock Tausig Shunt (BTS), in a single image with traditional 2DE and allocate the site of atrioventricular valve regurgitation. In addition, regurgitant volume and effective regurgitant orifice area can be estimated using this mode of acquisition qualitatively. Large cardiac structures cannot be accommodated by this mode, which is considered to be its main limitation.

Cropping (Slicing)

Once the acquired RTT-3DE data sets are stored in DICOM format in the machine's hard disk, they can be processed (sliced or "cropped") using Q Lab software (Philips Ultrasound) or off-line data analysis on the machine itself (Figs. 4, 5; Movie Clips 3, 4]. Two methods of cropping have been described:

(1) Direct cropping method: Desired cut planes are obtained by applying direct slicing on FV data sets, e.g., lateral walls of the LA and RA are removed to examine the *en face* view of the ASD from the LA and RA.

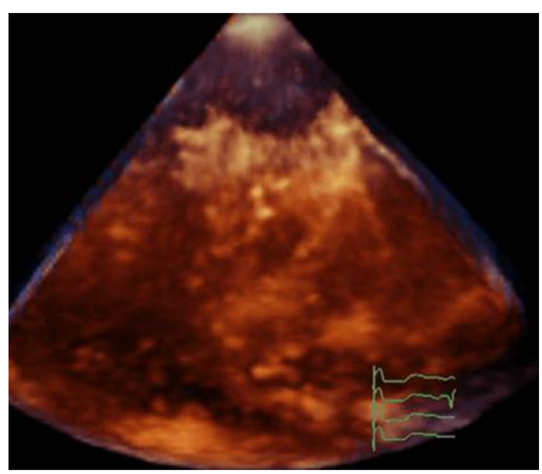

Fig. 4 Still image of Movie Clip 3. Acquired FV 3DE data set. The details of cardiac anatomy are embedded within this data set and thus incomprehensible until cropping is performed

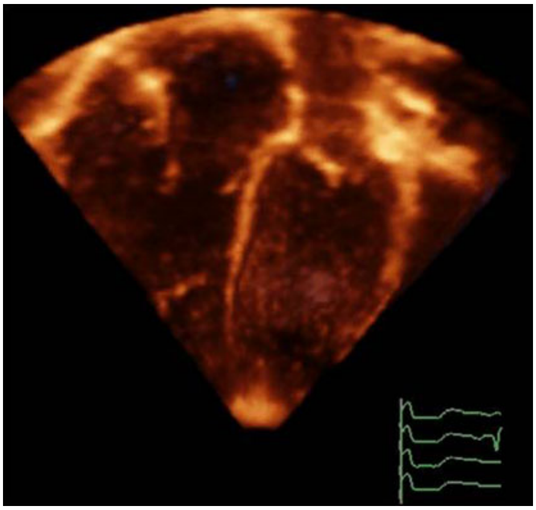

Fig. 5 Still image of Movie Clip 4 illustrating the content within the FV 3DE data set shown in Fig. 4. This is performed by activating the auto crop button in the Q Lab software or directly through the auto-crop feature available on the Echocardiogram machine's screen

(2) Multiplanar reformation (MPR) technique: Once the FV 3DE data set is obtained, the MPR button is pressed (activated) using Q Lab software where three color–coded imaging planes displayed in the Echocardiogram machine screen move spontaneously. Each imaging plane can be evaluated individually by moving the color-coded bar and evaluating the structure of interest in the corresponding color-coded box [3].

Both techniques are used for postprocessing analysis of the acquired 3DE data set. The cropped images (e.g., *en face* views of the valves, septa, Echoangiogram, etc.) are stored in the machine's hard disk in audio–video interleaved and bitmap formats to be shown to cardiologists and cardiac surgeons at a later stage.

Indications

3DE has three main clinical applications in CHD: (1) to define the morphology of CHD with depiction of spatial relationship to surrounding structures; (2) to perform volumetric quantification of chamber sizes, mass, and functions; and (3) to be used in guided intervention, e.g., ASD or VSD device closure, with RTTE-3DE.

Using 3DE to Analyze and Show the CHD Morphology

Historically in valvular heart disease, 3DE has been primarily used in the adult population to assess valvular function, anatomical descriptions, and spatial relationship with neighboring cardiac structures [19, 20, 27]. In contrast, only a few reports have shown the role of 3DE in congenital valvular lesions in children [1, 21, 26].

MVP

In MVP, using MPR technique (by activating the MPR feature in Q Lab software of the Echocardiogram machine in FV mode, i.e., the PSLAx window) permits placing an actual color-coded line physically along the hinge points of the MV parallel to the horizontal axis of the MV. Using this technique, 3DE can show even trivial prolapse in the corresponding color-coded box. Direct cropping (i.e., cutting the edges from upper part of the LA up to the mid-LA cavity slightly above the MV annulus) allows the operator to see the details of the MV from the LA. From below, when the edges are cut up to the mid- or upper third of the LV cavity, the operator can view the details of the MV from the LV. *En face* views of the MV downward from LV and upward from the LA (Fig 6) clearly show an MV prolapsed scallop or segment.

Echocardiographic and surgical views of the MV cleft can be clearly illustrated by 3DE. The MV cleft can be seen on the Echocardiographic view (Fig. 7), and the picture can be flipped 180 degrees to see the cleft by the surgical view (Fig. 8; Movie Clip 5), which enables the operator to show surgeons exactly as it would appear during surgery.

RTT-3DE in MVS stenosis using direct cropping permits viewing the MV view *en face* from the LA, where one can see the calcified, restricted MV opening, and from the LV, where the submitral apparatus, e.g., chordal thickness, can be evaluated [24]. Estimation of the mitral valve area (MVA) by RTT-3DE is more accurate than MVA calculation by TT-2DE [30].

In mitral regurgitation (MR), 3D color flow Doppler illustrates clearly the regurgitation site and origin through the MV. The regurgitant jet vena contracta is nicely visualized through this approach where it appears not to have a

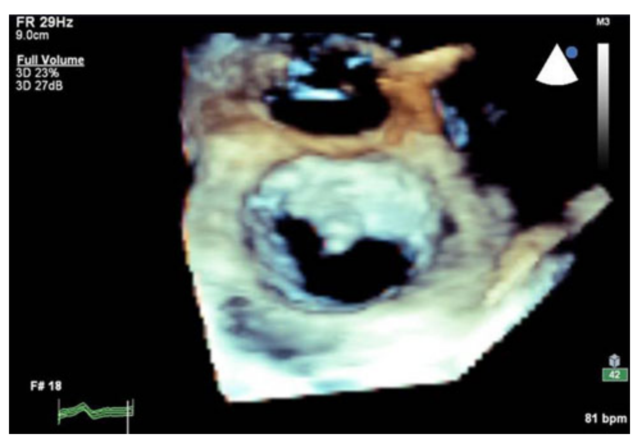

Fig. 6 MVP depicted by direct cropping using TEE-3D

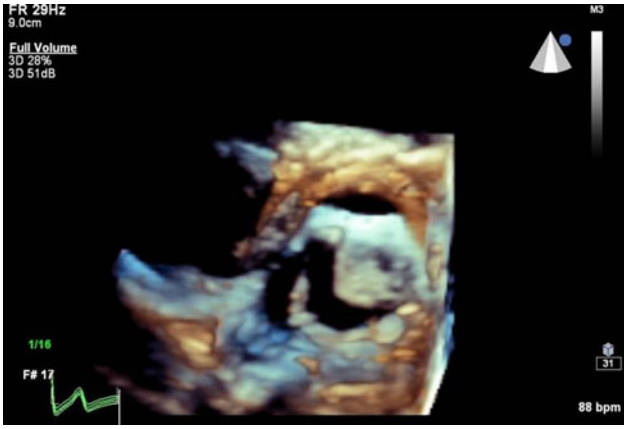

Fig. 7 3D-Echocardiographic view of a cleft mitral valve

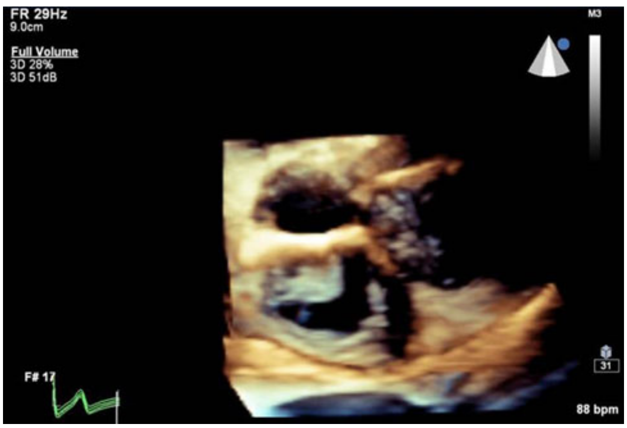

Fig. 8 Still image of Movie Clip 5. 3DE of a cleft mitral valve (surgical view)

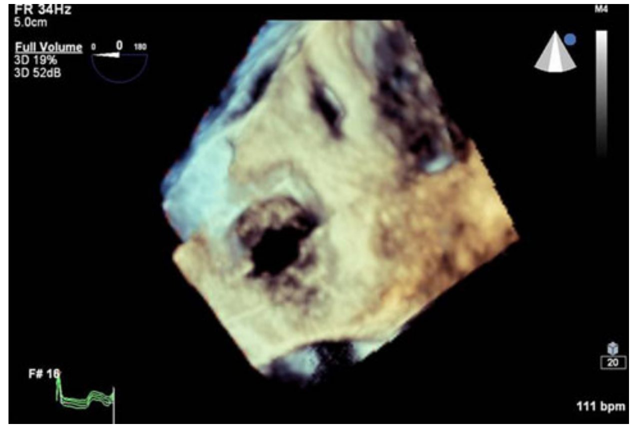

Fig. 9 Still image of Movie Clip 6. RTTE-3DE. The ASD is seen from the LA

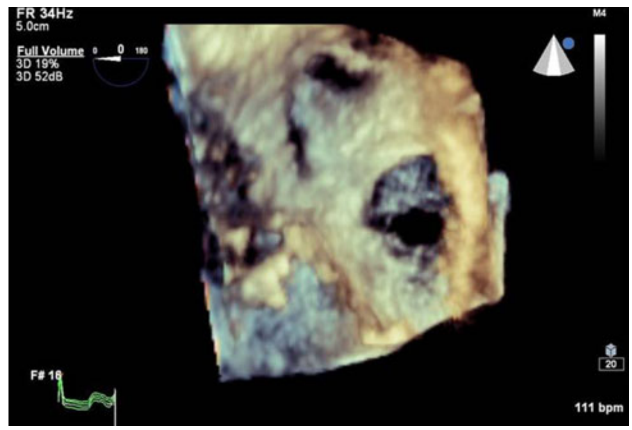

Fig. 10 RTTE-3DE. The ASD is seen from the RA

hemispherical shape, as previously assumed by 2DE color evaluation of MR jet, but rather an irregular shape [5]. Quantification of the vena contracta area by RTT-3DE accurately determines MR severity [13].

Aortic Valve

In aortic valve (AoV) stenosis, MPR technique is used to estimate the AoV area [8]. Direct cropping and *en face* view of the AoV could identify the mechanisms of AR. MPR technique could accurately determine the severity of AR using the AoV FV data set in the apical four-chamber view, the five-chamber view, or the PSLAx window [6].

Tricuspid and Pulmonary Valve Diseases

The mitral and aortic valves, compared with the tricuspid (TV) and pulmonary (PV) valves, are more commonly evaluated by 3DE [11]. On 3DE, the three leaflets of the TV can be displayed in one view, whereas it is difficult to see them simultaneously by 2DE. The prolapsed leaflet of the TV is clearly delineated by 3DE. Vettukattil et al. [29] illustrated the detailed morphological description of the TV anomaly in Ebstein's malformation in TV patients by 3DE. RTT-3DE can accurately determine tricuspid regurgitation (TR) severity by quantitative estimation of the TR vena contract area [28].

ASD and VSD

During transcatheter closure, RTTE-3DE shows the ASD *en face* view as it would be seen from the LA (Fig. 9; Movie Clip 6) and the RA (Fig. 10), > F10 > respectively, which offers significant advantage during intervention planning by determining the tissue rims around the ASD in addition to the number of ASDs, their size, and their relationship to the neighborhood cardiac tissues. After device closure of VSD or ASD, RTTE-3DE evaluates the device location and possible residual shunts and can detect any device impingement of adjacent structures, namely the

MV, TV, inferior vena cava or superior vena cava, pulmonary veins, or coronary sinus.

Conclusion

In this review, we demonstrate the feasibility of using a single 3DE window to delineate cardiac structures, which otherwise requires multiple 2D planes and windows to capture and then mentally reconstruct the spatial relationship of cardiac structures. By using the direct cropping method, the shape and the relationships of cardiac structures are clearly shown without having to imagine the spatial relationships. The main strength of 3DE is to describe the complex anatomical features, e.g., the atrioventricular valve, in AVSD and associated cardiac lesions, such as left-ventricular outflow tract obstruction [15]. 3DE has added additional recordable data compared with 2DE before and even after repair of AVSD cardiac lesions [9, 17, 24].

The method described by Hlavacek et al. [10] for acquisition and analysis of the 3D color Doppler flow mapping data set is commonly used. This reference also outlines various methodologies when using 3DE in assessing vascular abnormalities of the pulmonary arteries, MBTS, and aortic arch [10].

RTT-3DE can also provide volumetric quantification of LV size, mass, and function. This is extremely helpful when deciding whether a specific CHD patient is amenable to biventricular or univentricular type of repair. Ventricular mass and volume estimation by 3DE is realistic and requires no assumption as is the case with estimation using 2DE [4].

The use of 3DE in interventional procedures provides a useful tool in estimating the exact size of septal defects in addition to evaluating the defect's geometric *en face* views from both left and right atrial sides for the ASD and from the LV and RV sides for the VSD as well as determines the defect's relationship to the surrounding cardiac structures.

Limitations of RT-3DE

Although some recommendations have been made in the medical literature as to the utility of 3DE, there is still lack of a uniformly accepted protocol when performing 3DE studies because 3DE technology is still evolving. Respiratory movements and arrhythmia can lead to stitch artifact occurrence during FV data set or 3DE color flow Doppler data set acquisition. Furthermore, this new modality of echocardiography requires training and experience, without which erroneous diagnoses may be made. Further improvements in bioengineering and computer techniques are needed to enhance image quality.

At this time, 3DE is complementary to and not a replacement for 2DE. 3DE can evaluate the heart in RT compared with other 3D modalities of cardiac evaluation, such as CT or MRI, which require extensive off-line processing after acquisition. Although 3D is an innovative ultrasound modality, further clinical studies and technological improvements are needed to expand the list of its appropriate applications by minimizing the disadvantages outlined in this review.

References

1. Barrea C, Levasseur S, Roman K, Nii M, Coles JG, Williams WG et al (2005) Three-dimensional echocardiography improves the understanding of left atrioventricular valve morphology and function in atrioventricular septal defects undergoing patch augmentation. J Thorac Cardiovasc Surg 129(4):746–753
2. Bhan A, Kapetanakis S, Monaghan MJ (2010) Heart 96:153–163
3. Bharucha T, Roman KS, Anderson RH, Vettukattil JJ (2008) Impact of multiplanar review of three-dimensional echocardiographic data on management of congenital heart disease. Ann Thorac Surg 86(3):875–881
4. Bu L, Munns S, Zhang H, Disterhoft M, Dixon M, Stolpen A et al (2005) Rapid full volume data acquisition by real-time 3-dimensional echocardiography for assessment of left ventricular indexes in children: a validation study compared with magnetic resonance imaging. J Am Soc Echocardiogr 18(4):299–305
5. Correale M, Ieva R, Balzano M, Di BM (2007) Real-time three-dimensional echocardiography: a pilot feasibility study in an Italian cardiologic center. J Cardiovasc Med (Hagerstown) 8(4): 265–273
6. Fang L, Hsiung MC, Miller AP, Nanda NC, Yin WH, Young MS et al (2005) Assessment of aortic regurgitation by live three-dimensional transthoracic echocardiographic measurements of vena contracta area: usefulness and validation. Echocardiography 22(9):775–781
7. Franke M, Kohl HP (2003) Second generation real-time 3D echocardiography: a revolutionary new technology. Medicamundi 47(2):34–40
8. Goland S, Trento A, Iida K, Czer LS, De RM, Naqvi TZ et al (2007) Assessment of aortic stenosis by three-dimensional echocardiography: An accurate and novel approach. Heart 93(7):801–807
9. Hlavacek AM, Crawford FA Jr, Chessa KS, Shirali GS (2006) Real-time three-dimensional echocardiography is useful in the evaluation of patients with atrioventricular septal defects. Echocardiography 23(3):225–231
10. Hlavacek A, Lucas J, Baker H, Chessa K, Shirali G (2006) Feasibility and utility of three-dimensional color flow echocardiography of the aortic arch: the "echocardiographic angiogram". Echocardiography 23(10):860–864
11. Hung J, Lang R, Flachskampf F, Shernan SK, McCulloch ML, Adams DB et al (2007) 3D echocardiography: a review of the current status and future directions. ASEJ Am Soc Echocardiogr 20(3):213–233
12. Johri AM, Passeri JJ, Picard MH (2010) Three dimensional echocardiography: approaches and clinical utility. Heart 96:390–397
13. Khanna D, Vengala S, Miller AP, Nanda NC, Lloyd SG, Ahmed S et al (2004) Quantification of mitral regurgitation by live three-dimensional transthoracic echocardiographic measurements of vena contracta area. Echocardiography 21(8):737–743

14. Kisslo J, Firek B, Ota T, Kang DH, Fleishman CE, Stetten G et al (2000) Real-time volumetric echocardiography: the technology and the possibilities. Echocardiography 17(8):773–779
15. Kutty S, Smallhorn JF (2012) Evaluation of atrioventricular septal defects by three-dimensional echocardiography: Benefits of navigating the third dimension. J Am Soc Echocardiogr 25(9):932–944
16. Lang RM, Badano LP, Tsang W, Adams DH, Agricola E, Buck T et al (2012) EAE/ASE recommendations for image acquisition and display using three-dimensional echocardiography. Eur Heart J Cardiovasc Imaging 13(1):1–46
17. Miller AP, Nanda NC, Aaluri S, Mukhtar O, Nekkanti R, Thimmarayappa MV et al (2003) Three-dimensional transesophageal echocardiographic demonstration of anatomical defects in AV septal defect patients presenting for reoperation. Echocardiography 20(1):105–109
18. Pandian NG, Roelandt J, Nanda NC, Sugeng L, Cao QL, Azevedo J et al (1994) Dynamic three-dimensional echocardiography: Methods and clinical potential. Echocardiography 11(3):237–259
19. Pepi M, Tamborini G, Maltagliati A, Galli CA, Sisillo E, Salvi L et al (2006) Head-to-head comparison of two- and three-dimensional transthoracic and transesophageal echocardiography in the localization of mitral valve prolapse. J Am Coll Cardiol 48(12): 2524–2530
20. Schnabel R, Khaw AV, von Bardeleben RS, Strasser C, Kramm T, Meyer J et al (2005) Assessment of the tricuspid valve morphology by transthoracic real-time-3D-echocardiography. Echocardiography 22(1):15–23
21. Seliem MA, Fedec A, Szwast A, Farrell PE Jr, Ewing S, Gruber PJ et al (2007) Atrioventricular valve morphology and dynamics in congenital heart disease as imaged with real-time 3-dimensional matrix-array echocardiography: comparison with 2-dimensional imaging and surgical findings. J Am Soc Echocardiogr 20(7): 869–876
22. Sheikh K, Smith SW, von RO, Kisslo J (1991) Real-time, three-dimensional echocardiography: feasibility and initial use. Echocardiography 8(1):119–125
23. Shirali G (2008) 3D echocardiography. Ann Pediatr Cardiol 1(1):8–17
24. Singh A, Romp RL, Nanda NC, Rajdev S, Mehmood F, Baysan O et al (2006) Usefulness of live/real time three-dimensional transthoracic echocardiography in the assessment of atrioventricular septal defects. Echocardiography 23(7):598–608
25. Sugeng L, Weinert L, Thiele K, Lang RM (2003) Real-time three-dimensional echocardiography using a novel matrix array transducer. Echocardiography 20(7):623–635
26. Takahashi K, Guerra V, Roman KS, Nii M, Redington A, Smallhorn JF (2006) Three-dimensional echocardiography improves the understanding of the mechanisms and site of left atrioventricular valve regurgitation in atrioventricular septal defect. J Am Soc Echocardiogr 19(12):1502–1510
27. van den Bosch AE, van Dijk VF, McGhie JS, Bogers AJ, Roos-Hesselink JW, Simoons ML et al (2006) Real-time transthoracic three-dimensional echocardiography provides additional information of left-sided AV valve morphology after AVSD repair. Int J Cardiol 106(3):360–364
28. Velayudhan DE, Brown TM, Nanda NC, Patel V, Miller AP, Mehmood F et al (2006) Quantification of tricuspid regurgitation by live three-dimensional transthoracic echocardiographic measurements of vena contracta area. Echocardiography 23(9): 793–800
29. Vettukattil JJ, Bharucha T, Anderson RH (2007) Defining Ebstein's malformation using three dimensional echocardiography. Interact Cardiovasc Thorac Surg 6(6):685–690
30. Zamorano J, Cordeiro P, Sugeng L, de Perez I, Weinert L, Macaya C et al (2004) Real-time three-dimensional echocardiography for rheumatic mitral valve stenosis evaluation: an accurate and novel approach. J Am Coll Cardiol 43(11):2091–2096