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Developments in 3D Echocardiography

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Abstract

3D echocardiography (3DE) will gain increasing acceptance as a routine clinical tool as the technology evolves due to advances in technology and computer processing power. Images obtained from 3DE provide more accurate assessment of complex cardiac anatomy and sophisticated functional mechanisms compared with conventional 2D echocardiography (2DE), and are comparable to those achieved with magnetic resonance imaging. Many of the limitations associated with the early iterations of 3DE prevented their widespread clinical application. However, recent significant improvements in transducer and post-processing software technologies have addressed many of these issues. Furthermore, the most recent advances in the ability to image the entire heart in realtime and fully automated quantification have poised 3DE to become more ubiquitous in clinical routine. Realtime 3DE (RT3DE) systems offer further improvements in the diagnostic and treatment planning capabilities of cardiac ultrasound. Innovations such as the ability to acquire non-stitched, realtime, full-volume 3D images of the heart in a single heart cycle promise to overcome some of the current limitations of current RT3DE systems, which acquire images over four to seven cardiac cycles, with the need for gating and the potential for stitch artefacts.

Keywords

Echocardiography, developments, two-dimensional (2D), three-dimensional (3D), realtime imaging, full-volume image acquisition, limitations, clinical application

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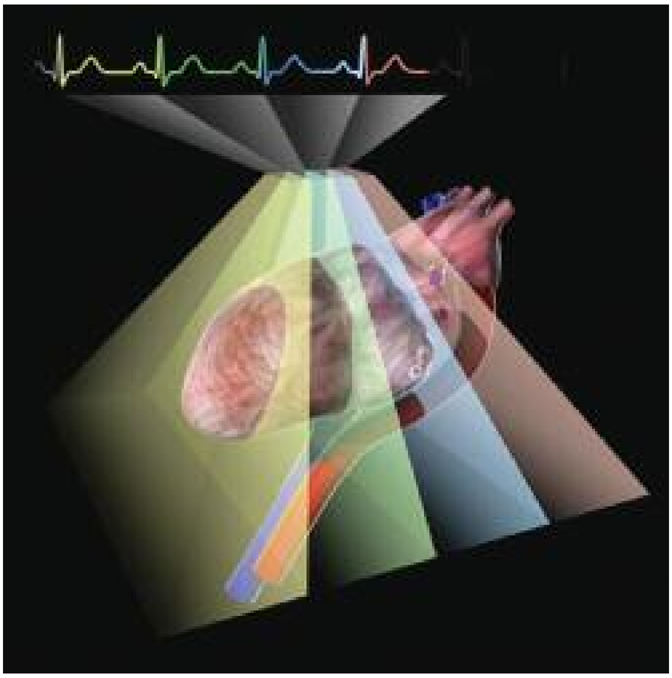
2D echocardiography (2DE) is a common diagnostic and treatment planning tool in clinical cardiology, especially for the assessment of left ventricular (LV) volume and function. However, traditional 2DE is severely limited by its dependence on geometrical assumptions, which can lead to inaccuracies in volume quantification.[1] Because 3D echocardiographic (3DE) imaging eliminates geometrical assumptions and image plane positioning error, the technique offers the potential for more accurate assessment of complex cardiac anatomy and sophisticated functional mechanisms. Early attempts at 3DE using images produced by freehand reconstruction from multiple gated 2D images required spatial tracking of each image. These initial attempts at 3DE of LV volumes and mass and LV ejection fractions (LVEF) produced superior results to 2DE, comparable to those of nuclear magnetic resonance (NMR) imaging.[2,3] Although 3DE has been around for nearly two decades, limitations in the early iterations of the technology prevented their widespread clinical application. While advances in transducer and post-processing software technologies have addressed many issues, it is the most recent advances in the ability to image the entire heart in realtime and fully automated quantification that have poised 3DE to become more ubiquitous in clinical routine. The introduction and increasing availability of realtime 3DE (RT3DE) has the potential to further improve the diagnostic and treatment planning capabilities of cardiac ultrasound. While cardiac magnetic resonance imaging (MRI) is the current gold standard, the imaging modality may require the injection of a contrast agent, is not suitable for patients with implanted cardiac devices and can be more costly.

The Evolution of 3D Echocardiography

The acquisition of the first 3D cardiac ultrasound images dates back to 1974.[4] This was followed by the development of early 3DE techniques, whereby 3DE images were obtained by offline sequential reconstruction of 2D images.[2,3,5] However, these methods had limitations related to acquisition and post-processing: the images obtained were often of a relatively poor spatial and temporal resolution, while the reconstruction of the 2D data sets to produce 3D images was time-consuming and only available offline. More recently, matrix-array transducers have been introduced. These transducers contain an array of piezoelectric elements that are capable of scanning pyramidal volumes rather than 2D thin slices. The matrix-array transducers enable rapid and realtime acquisition of 3D images, without the need for time-consuming offline reconstruction. The initial matrix-array transducers had a sparse array of elements that could obtain a 60°x60° pyramidal volume of data, allowing realtime 3D image acquisition.[6,7] Limitations associated with the earlier transducers included relatively poor image quality, low frame rates and narrow sector volume acquisition.

The next generation of transducers evolved to fully sampled array or provided significant improvements in the quality of the images. A fully sampled matrix-array transducer consists of thousands of simultaneously active ultrasound elements and, together with rapid post-processing, made possible by advances in computer processing power, provide near-realtime volumetric scanning. The images are obtained almost instantaneously and are of a high quality.[8] Such

Figure 1: When System Architecture Limits the Scanning Rate, a 3D Volume Large Enough for the Entire Heart Requires a Number of Electrocardiogram-gated Sub-volumes Stitched Together in a Reconstruction



systems provide several imaging modes, including multiplane (bi-plane and tri-plane), live 3D, 3D zoom, full-volume and 3D colour Doppler. However, although the latter two imaging modes are considered the most important, limitations in system architecture mean that the system requires the acquisition of 3D images through a number of electrocardiogram (ECG)-gated sub-volumes, followed by online reconstruction and presentation of the images. For an acquisition that is large enough for chamber visualisation and quantification, the acquisition of at least four to seven cardiac cycles, gated to the R-wave, followed by stitching of the recordings to obtain a 3D image of the entire heart is required (see *Figure 1*). 3D colour Doppler images are useful for the assessment of valvular regurgitation. With 3D colour Doppler mode, data acquisition is of a smaller sector of the heart, and this requires the recording of up to seven cardiac cycles. The images may be displayed as a surface rendering, orthogonal planes or multiple short-axis views, in order to facilitate viewing and analysis. RT3DE images can also be viewed from any conceivable angle, thus facilitating diagnostic and treatment planning capabilities of cardiac ultrasound.

As well as requiring time-consuming offline post-processing of data sets to produce 3DE images, early 3DE systems relied on manual assessment and quantification of cardiac function. These processes were difficult to carry out and also necessitated significant experience and training. These limitations have been addressed by the availability of software programs for analysis and quantification of 3D data sets. These software programs allow not only direct quantification of cardiac chamber volume and mass, LVEF and systolic dyssynchrony, but also assessment of regional LV wall motion at rest and during stress testing. Another improvement in the post-processing software is the integration of border detection algorithms into the software, allowing endocardial surface detection and enabling semi-automated analysis of the LV without the need to make geometrical assumptions. Increased hard-drive capacity has made it possible to store larger data sets, while improvements in transducer technology, computing power and software have resulted in a substantial reduction in study time and improved workflow compared with earlier techniques.

Clinical Applications of the Current Realtime 3D Echocardiography Systems

The capability of current RT3DE systems to provide near-realtime volumetric images of the entire heart facilitates the assessment of cardiac chamber anatomy and function, as well as evaluation of dyssynchrony, valvular diseases and congenital abnormalities.

Assessment of the Left Ventricle

LV assessment is one of the most common and clinically important applications of echocardiography. Several clinical studies have shown the accuracy and reproducibility of RT3DE in terms of quantification of the LV outcomes to be similar to the current gold standard of MRI.[9–12] RT3DE systems may also be used for the assessment of global LV function. Traditionally, the assessment of global LV function has been performed by visual interpretation to provide an estimate of LVEF. However, this subjective interpretation has limited reproducibility and is comparable to existing quantification methods derived from 2D LV volumes. By contrast, assessment and quantification of LV global function with RT3DE quantification provides a more accurate and reproducible quantification of LVEF.[13,14] Such quantification has a significant impact on clinical decision-making.[13,14] With regard to assessment of LV shape, a quantitative assessment by RT3DE systems provides a 3D-derived sphericity index. This index accurately reflects LV shape and may be an early and independent predictor of LV remodelling after acute myocardial infarction.[15]

RT3DE has also been evaluated for the assessment of other LV measures. It may be useful as part of stress echocardiography testing (dobutamine, vasodilator and even exercise). Preliminary data[16] have shown that 2DE and 3DE have similar sensitivity and specificity but that the latter has a substantially reduced scanning time, which reduces the study time and improves workflow. Stress echo using RT3DE may also allow for a more accurate assessment as the volumetric images could be analysed using multiple axis views, including the standard long-axis and multiple parallel short-axis slices.[17] Temporal resolution is particularly important in stress testing, and current RT3DE systems provide a much better resolution than 2DE.[18] In recent years, the importance of LV dyssynchrony assessment in the selection of candidates and the prognosis (i.e. prediction of success) of cardiac resynchronisation therapy (CRT) has been realised.[18,19] Increasing evidence suggests that LV intraventricular dyssynchrony can be assessed by the analysis of LV regional volumetric changes from 3DE full-volume data sets. It has been proposed that the 3DE full-volume data set may be used to obtain a systolic dyssynchrony index (SDI), which could act as a predictor of response or success with CRT.[20–22] A cut-off SDI value of 6.4% has been shown to have high sensitivity and specificity (88 and 85%, respectively) and good reproducibility.

Assessment of the Right Ventricle

RT3DE has also been evaluated in the assessment of the right ventricle (RV). An accurate assessment of RV size and function is highly desired as these outcomes have important diagnostic and prognostic implications in several cardiac diseases. Historically, assessment of the RV volume has always been difficult based on the complex geometrical shape of the RV and its position in the thorax of the heart. This complex anatomy often results in failure of the geometrical assumptions made by conventional 2DE quantification methods to accurately calculate RV volumes. The currently available RT3DE devices allow for a more accurate and reproducible quantification of RV volumes. The improved results may be due to the RT3DE systems being equipped with post-processing software that can formulate a mathematical cast of the RV to calculate RV volumes and RVEFs. Improved results may also be due to the elimination of geometrical assumptions. Comparisons of 3DE and 2DE images have shown the former method to provide more accurate and reproducible results for RV assessment,[23,24] and to correlate well with the results from MRI.[25,26]

Assessment of Valvular Structures

There has been great interest in the potential of RT3DE for the visualisation of complex structures such as the mitral valve (MV). Data sets obtained from 3DE can be cropped in order to obtain unique 'en face' views from both sides of the valve in realtime. Post-processing software allows visualisation of the MV anatomy in the desired plane of orientation. The availability of several imaging planes is critical for the estimation of valve areas. A single plane measurement of the vena contracta would result in a poor estimation of the effective regurgitant orifice area. The new post-processing software also allows quantification of the MV complex. Assessment of the MV by RT3DE may be helpful for understanding the anatomy and function of the cardiac valves, and initial data from 3DE have provided new insights on the mitral apparatus and the pathophysiology of mitral stenosis and regurgitation.[24,27–30] Pre-operative MV assessment with RT3DE may be used to provide valuable information for the planning of MV repair. Studies point to RT3DE being a feasible, accurate and highly reproducible technique in the estimation of the MV area (MVA) in patients with rheumatic mitral stenosis (RMVS).[31] Furthermore, RT3DE-derived images have been demonstrated to have the best agreement with invasively determined MVA versus other echo Doppler methods that are considered the gold standards.[31] 3D transthoracic imaging has also been shown to be a good non-invasive comparator for pre-operative MV assessment versus the gold standard of 2D transoesophageal echocardiography.[32,33] Clinically relevant supplementary information may also be provided by RT3DE, using colour Doppler flow mapping combined with 3D morphological data. This is especially relevant for patients with valvular regurgitation, where colour Doppler flow mapping can aid in the definition of jet origin and relationship to adjacent structures.[24,34,35]

3D Echocardiography and Congenital Heart Diseases

The ability of RT3DE to provide real-life images of the entire heart and the additional data provided by 3DE compared with 2DE open the door for the use of this technique for the imaging of congenital heart diseases.[36,37] Studies in patients with congenital heart disease have shown that 3DE quantification of LV and RV volumes correlates well with MRI.[38–40] RT3DE has also been shown to reliably define anatomical details of bicuspid aortic valves, tetralogy of Fallot, patent ductus arteriosus, sinus of Valsalva aneurysm, Ebstein's anomaly, subvalvular membranes and several other complex congenital diseases.[41] It is feasible that RT3DE may have an important role within the catheter laboratory as there is an increase in the use of invasive cardiology procedures, such as aortic valve replacement. In such cases, RT3DE could be used as a planimetry tool to allow cardiologists to determine as well as guide the placement of catheters based on the ability of RT3DE systems to provide accurate, almost realtime volumetric images of the heart.[41,42] The benefits of clinical application of RT3DE versus 2DE are summarised in *Table 1*.

Table 1: Some of the Current Clinical Applications of Realtime 3D Echocardiography and Its Advantages Over Conventional 2D Echocardiography

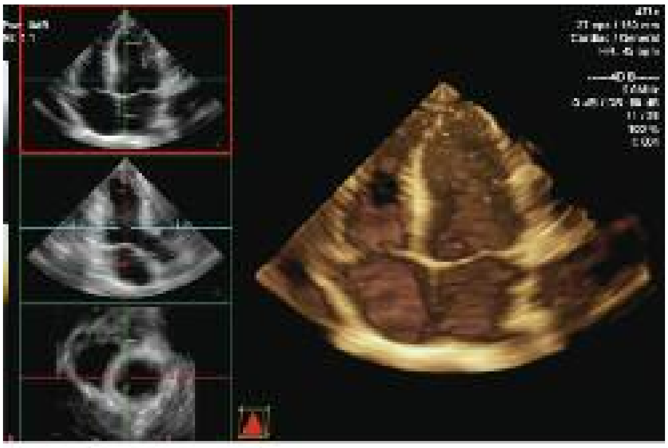
Clinical Application	Advantages of RT3DE versus 2DE
Assessment of LV volumes, mass and ejection fraction	• No need for geometrical assumptions and no errors caused by foreshortened views
Assessment of LV wall motion abnormalities	• The 3D data set contains the complete dynamic information on LV contraction: • faster acquisition (important during stress echocardiography) • more accurate identification of wall motion abnormalities
Assessment of LV dyssynchrony	• Analysis of 16 segments in 1 single acquisition • Semi-automated procedure (more reproducible) • Angle-independent measurement of the composite effect of longitudinal, radial and circumferential contraction • Combination with quantification of LV volumes and function
Evaluation of valve function and diseases	• Unlimited image plane orientation for better understanding of the complex geometry of valves and subvalvular apparatus: • MV and AV stenosis – 'en face' view with more accurate valve area measurement • MV prolapse – accurate identification of the scallop involved • MV and AV regurgitation – identification of the precise mechanism of regurgitation and assessment of the exact size of vena contracta area with colour Doppler • Guide for surgical or percutaneous procedures
Evaluation of congenital heart diseases	• Ability to display complex spatial relationship between cardiac structures • Guide for surgical procedures

2DE = 2D echocardiography; AV = aortic valve; LV = left ventricle; MV = mitral valve; RT3DE = realtime 3D echocardiography; RV = right ventricle.
Adapted from Marsan et al., 2009.[42]

Limitations of the Current Realtime 3D Echocardiography Systems

While there have undoubtedly been significant advances in transducer technology and post-processing software, there are still some barriers to the widespread clinical use of RT3DE. Currently, full-volume 3D image acquisition requires recording of four or more cardiac cycles, gated to the R-wave, followed by stitching of the images to attain the full volumetric image. The use of gating and stitching of images to obtain the full-volume image can result in the appearance of stitch artefacts, especially in images obtained from patients with arrhythmias or respiratory instability. In these patients, the final volume attained from 3DE could be unusable or inaccurate. The difference in the scanning technique required for a gated verses a realtime acquisition also requires additional skill and experience, and the examiner has to rely on post-processed cropped 2D images for qualitative interpretation. Another limitation is that while image acquisition with RT3DE can reduce scanning time versus conventional 2DE techniques, the spatial and temporal resolution of the final image still needs to be improved to rival that of 2DE, while ensuring that the scanning time is still short. There is still a significant need for expertise

Figure 2: New System Architecture Allows Instantaneous Full-volume Imaging with Volumes Large Enough to Capture the Entire Heart without Electrocardiogram Gating



This example is 90ºx90º volume at 16cm deep and 27 volumes/second.

Figure 3: Instantaneous Full-volume Imaging Also Enables Volume Colour Flow Imaging, Capturing Morphology, Function and Haemodynamic Status of the Valve in Realtime

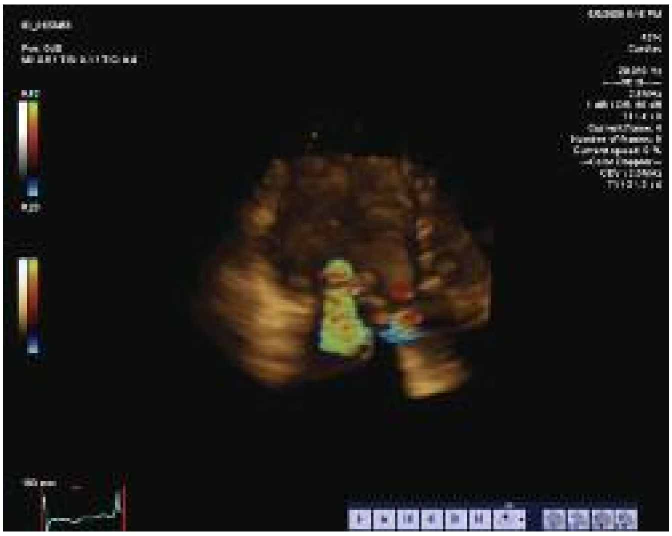
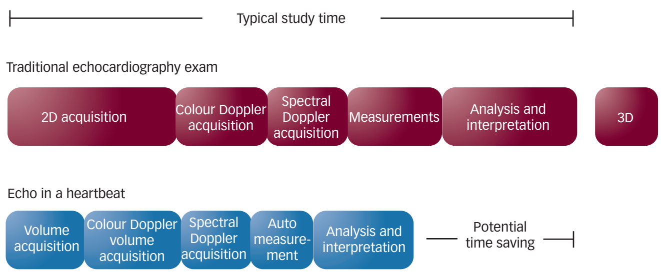


Figure 4: Potential Benefits of Single Cardiac Cycle Realtime 3D Echocardiography Acquisition on Workflow



and training in the manipulation of data sets as post-processing software can only semi-automatically quantify chamber volumes. The importance and need for training was highlighted by a study where the discrepancy in the estimation of volumes by 3DE versus MRI could be overcome if 3DE were carried out by experienced physicians.[43]

Recent Developments in 3D Echocardiography

During the last decade there has been a continuous evolution in 3DE technology, with progress seen every year. The most recent innovation has been a move away from the traditional serial line-by-line acquisition to using simultaneous multiple beams, resulting in the acquisition of non-stitched, realtime, full-volume 3D images of the heart in a single heart cycle. Rapid acquisition of large volumes (90ºx90º) at high volume rates (>20 volumes/second) allows acquisition of the entire heart instantaneously in true realtime in one cardiac cycle, without the need for ECG gating and stitching of multiple cardiac cycles (see *Figure 2*). This speeds image acquisition, removes the problem of stitch artefacts and improves feasibility, image quality and accuracy in a broader range of patients, including those with irregular cardiac cycles (e.g. those with heart failure or arrhythmia) or with breathing difficulties. Furthermore, as the image of the entire heart is displayed continuously in realtime during the image scanning, the orientation within and optimisation of the volume is more intuitive and easier to learn than with the ECG-gated methods.

Other innovations, such as knowledge-based workflow and pattern recognition tools, are now available that allow fully automated extraction and quantification of all of the information needed from a complete study. The use of learned patterned recognition algorithms based on expert databases of real clinical cases in these tools enables the recognition of anatomical patterns as well as fully automatic measurements. Fully automatic data extraction, measurement and analysis will further improve workflow by reducing examination time and intra- and inter-operator variation. Morphological assessment and 3D stress echocardiographic testing may especially benefit from the advanced post-processing software as it allows fast and easy manual rotation throughout the complete 3D data set and rendering of standard cut planes for wall-motion analysis. Doppler is a critical aspect for diagnosis of flow through leaking valves and shunts, and the ability of the new RT3DE systems to depict flow information in 3D with colour Doppler is a major step forward for 3DE (see *Figure 3*). Such imaging capability offers a complete approach for the evaluation of disease, particularly the assessment of valvular problems, allowing a more exact and precise analysis of valve pathologies.

The combination of improved acquisition via the instantaneous full-volume imaging and knowledge-based workflow have the potential to overcome the current limitations that prevent RT3DE being adopted into routine clinical practice. In the future, rather than being added to the 2DE exam, RT3DE will be integrated into cardiac imaging, possibly even replacing part of the 2DE as this could reduce the examination time (see *Figure 4*).

Conclusions

There have been significant advances in RT3DE technology, and post-processing and analysis have generated sufficient evidence to support the adoption of RT3DE for routine clinical use. The current RT3DE systems allow fast acquisition of full-volume images of the heart. Semi-automated post-processing software allows rapid quantification and assessment of chamber volumes and functions. Furthermore, RT3DE has been shown to be comparable to the gold standard of 3D cardiac imaging, MRI, in the assessment of cardiac volumes and function. Nevertheless, there are still limitations associated with the current RT3DE systems. Full-volume acquisition necessitates the imaging of at least four cardiac cycles, gated to the R-wave, followed by stitching of the images to acquire the full volume.

The presence of stitch artefacts and need for prolonged breath-holding and recording of multiple cardiac cycles to acquire the images may result in poorer image quality and inaccurate quantification and assessment of cardiac outcomes. The technique may be particularly unsuitable for patients with dyspnoea or irregular cardiac cycles. Since the post-processing is only semi-automated, there is often a need for expertise and training in the use of the software.

As 3DE technologies continue to advance, RT3DE will be integrated into multimodal imaging workflows. Instantaneous acquisition of the full volume of the heart in one cardiac cycle eliminates the need for prolonged breath-holding and stitched acquisition. Post-processing carried out by a knowledge-based workflow and fully automated quantification and pattern recognition software will also have a positive impact on the current workflow. It is anticipated that the continuing advances in technology will improve exam time, workflow and image quality, as well as the accuracy, speed and simplicity of quantification and assessment of cardiac outcomes, and will help in the integration of 3DE into clinical routine. ■

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