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**ABSTRACT**

Over the past two to three decades echocardiography has come a considerable distance from the early M-mode machines, and has become an indispensable diagnostic tool in any cardiovascular department. It has long been proved to be safe and cost-effective, and its clinical versatility has steadily increased with the continued integration of newer techniques, such as two-dimensional and harmonic imaging, Doppler and much more. One of the more recent developments in the field is three-dimensional echocardiography (3DE). 3DE, in various forms, has been used as a research tool for many years now, but lately improvements in software and transducer technology have begun to facilitate its integration into clinical practice. As with any technique, 3DE has its strengths and weaknesses, and these must be fully appreciated if it is to be utilised effectively.

Cardiac ultrasound has become an integral part of cardiovascular medicine, and as it has evolved so have its indications and applications. Three-dimensional echocardiography (3DE) (sometimes referred to as “four-dimensional echo”: three spatial dimensions plus time) is one of the latest manifestations of this evolution. Three-dimensional (3D) ultrasound as an idea, and even as a plausible technique, has been with us for a considerable time now. However, the past decade or so has seen an explosion in focussed research of the technology and its uses. Along with this has come its increasing integration into clinical practice, to the point now when, for certain techniques, it is on the threshold of widespread acceptance. This shift has mainly been facilitated by the introduction of “real-time” imaging, which has dispensed with the need for involved image acquisition protocols and protracted off-line reconstruction.

However, for those not using 3DE on a regular basis there is still some confusion over its exact role, its benefits and limitations, and furthermore, how it fits into the gamut of contemporary cardiac investigations.

The techniques available within 3DE are similar to traditional two-dimensional (2D) techniques. These include grey-scale imaging, colour Doppler, stress and even contrast. The most researched and established area is quantification of left ventricular morphology and function (ie, volumes, mass and ejection fraction). There is, however, growing evidence for more specialised applications such as the assessment of left ventricular intraventricular dyssynchrony, particularly as a predictor of response to cardiac resynchronisation therapy (CRT), as well as valvular interrogation. Furthermore, quantification of the right ventricle and left atrium are possible, and there is also a considerable amount of ongoing research in more niche applications.

**HISTORY**

It was all the way back in 1961 that 3D ultrasound was first used successfully to image the orbit. Clearly, 3D imaging of a highly mobile structure, such as the heart, would pose a considerably tougher challenge. Nevertheless, just over a decade later, in 1974, acquisition of the first 3D cardiac ultrasound images was reported. These acquisitions, and those that followed for a number of years, were based around the idea of constructing, or reconstructing, a 3D dataset from a number of 2D acquisitions. This was initially performed by very careful freehand scanning and then made more reliable by the introduction of rotary motorised transducers, whose location in space was continually tracked. Unsurprisingly, such images required time-consuming offline reconstruction and vast computing power, meaning that they tended to be confined to dedicated research departments. Nevertheless, in the right hands they appeared to provide accurate volumes and impressive images. Indeed, it was this type of imaging that first demonstrated the complex saddle shape of the mitral annulus, and altered our diagnostic criteria for mitral valve prolapse.

Gradually, 3D-rendered images were created from smaller and smaller incremental slices and gating to ECG and respiration were introduced, which led to improved image quality. However, the potential for clinical integration of 3DE has only really come with the advent of “real-time” 3D imaging, allowing rapid acquisition of a 3D volume in no more than a few cardiac cycles.

The first transducer capable of this form of imaging was a sparse matrix array, which consisted of 256 individually activated elements. This could acquire a 60° by 60° pyramidal volume, over a single cardiac cycle, which was subsequently presented using two orthogonal long axis views and two to three parallel short axis views. This technology provided accurate volumes but the problems regarding clinical applicability were still apparent. A large transducer footprint, not to mention a sizeable, cumbersome machine, made acquisition challenging, and eventual image quality left a little to be desired. Furthermore, the on-line display of 3D-rendered images remained illusive.

This capability was made possible in the early 1990s with the introduction of a fully sampled matrix array, while tandem developments in 3D software allowed advanced post-processing and the all-important ability for quantification of these images.

Subsequent to this the technology was cleverly miniaturised, to such an extent that it could be incorporated into a transoesophageal probe.

Even more recent advances in electronics as well as microprocessing have led to transducers capable
of single-beat acquisitions, which have recently been introduced.

**THE TECHNOLOGY**

The introduction of matrix array technology has really been the step that has promised clinical integration of 3DE. The elements, which now number in excess of 3000, are set out in a grid-like fashion within the head (fig 1), and are capable of parallel processing, allowing pyramidal datasets to be rapidly acquired. The sheer number of elements means that some processing needs to be performed within the head of the transducer otherwise the cable would be impossibly heavy. Consequently, the transducers themselves are considerably larger than 2D probes, although the footprints themselves are only marginally so (fig 2).

In addition to conventional 2D and Doppler imaging, broadly speaking matrix array transducers allow five types of 3D acquisition, each of which will be briefly discussed below. These differ in spatial and temporal resolution capacity as well as the number of cardiac cycles required. Furthermore, the exact specifications of these modes and their availability vary from vendor to vendor.

These modes are (fig 3):

- Multiplane (bspine and triplane)
- Live 3D
- 3D zoom
- Full volume
- 3D colour Doppler.

Although all termed “real-time” this is only strictly true for the multiplane, live 3D, and 3D zoom settings. The other modes capture a number of ECG gated subvolumes, over consecutive cardiac cycles, followed by almost instantaneous online reconstruction and presentation. However, the very latest generation of 3D scanners is capable of creating a full volume dataset (incorporating the whole heart) within one cardiac cycle.

Multiplane imaging allows the simultaneous presentation of a number of 2D slices (usually two or three) captured during a single cardiac cycle. The exact angle of the slices can be manipulated to a certain degree depending on the orientation and size of the structure being imaged.

A live 3D image capture allows a beat-by-beat volumetric dataset (of approximately 50° by 50°), which can be cropped live. 3D zoom is similar, but allows magnification of a specific area and the scanning angle can sometimes be increased to approximately 90° by 90°, although this is at the expense of frame rates. These two modes are particularly good for imaging smaller structures such as valves.

For chamber visualisation and quantification, however, a full volume is usually required. This mode allows a dataset of approximately 90° by 90°, although on some systems reducing the line density can widen this to just over 100° by 100°. Apart from on the very latest scanners, acquisition is performed over at least four to seven cardiac cycles, gated to the R wave. Images can then be displayed as a volumetric dataset or as a number of 2D cut planes, in order to facilitate viewing and analysis.

Finally, the 3D colour Doppler setting allows the acquisition of a smaller sector (approximately 50° by 50°) and can take up to seven cardiac cycles. It combines grey-scale imaging with colour Doppler in 3D and is mainly aimed at assessing valvular regurgitation.

All images are acquired in a similar fashion to 2D imaging. The left lateral decubitus position is preferred, with suspended respiration during image capture. A multiplane (usually biplane) image is used to position the heart within the scanning angle and optimise the image.

The rules of image optimisation are the same for 3D as they are for 2D, with careful attention required to gain controls, depth and sector size and the use of harmonics to maximise image quality and frame rates.

**THE CLINICAL ROLE OF THE TECHNIQUE**

3DE is simply an advancement of ultrasound technology like, for example, tissue Doppler, and should be seen as such, as opposed to an isolated technique. It offers additional information in many situations, but we are a considerable way away from completely replacing our standard current 2D techniques.

The majority of research and clinical applications are unsurprisingly focused on the left ventricle, as assessment of this is one of the most clinically important applications of echocardiography. However, 3DE is much more versatile than this and has been successfully applied in a number of other situations, some of the more accessible of which will be discussed.

**Left ventricular volumes, mass and ejection fraction**

A direct volumetric assessment of left ventricular size is preferable to calculations made from 2D or M-mode, because it can guard against image foreshortening and does not require any geometric assumptions. 3DE assessment of left ventricular mass, volumes and ejection fraction now has a solid research
base comparing it favourably with the current gold standard of magnetic resonance imaging (MRI). 7–13

Left ventricular mass has long been known to be an important prognostic marker in both those with, and without, coronary disease. However, on a day-to-day basis it is infrequently measured by echo, probably because of the relatively complex calculation required and the inaccuracy of 2D and M-mode measures. Current 3D software packages allow
mass to be calculated from a 3D full volume dataset. The dataset is lined up in a multiplane reconstruction viewer and anatomically correct apical four and two-chamber views are used to obtain epicardial and endocardial volumes (fig 4). From this a muscle mass is calculated. This technique is not only quick but has been proved to be accurate and reproducible when compared with MRI. 14 15

Left ventricular function is one of the most common reasons for an echocardiogram to be requested and there is a continual demand to improve accuracy and reproducibility. This is particularly important when small differences in ejection fraction can mean the difference between offering and withholding established therapies (CRT, implantable cardioverter defibrillators and, more recently, chemotherapeutic agents). A number of software programs are now available to calculate 3D volumes. This involves opening the dataset within the program and using semi-automated border tracking techniques to create a mathematical cast of the whole of the left ventricle throughout the cardiac cycle (fig 5). From this cast, volumes and ejection fraction are derived. 3D ejection fraction using these techniques can improve confidence and, with superior interobserver as well as test–retest variability, it is ideal for situations in which calculations on serial scans are required. It has also been proved to alter clinical decision-making in such situations when compared with 2D imaging.16

Most vendors now offer on-line packages to perform 3D left ventricular analysis. For left ventricular volumes, with a little practice, these take not much longer than a standard 2D biplane Simpson’s measurement.

Regional function and dyssynchrony
The field of dyssynchrony assessment by echocardiography has been thrown into confusion recently by the publication of the PROSPECT study.17 This clearly demonstrates that echocardiographic quantification of dyssynchrony has a long way to go. The field is really wide open when it comes to the best technique of assessment for CRT and the prediction of its success. Left ventricular intraventricular dyssynchrony can easily be assessed using a 3DE full volume dataset, and is supported by a growing body of evidence.18–20 The mathematical cast created from a volumetric analysis discussed previously can be divided up into the American Society of Echocardiography 16 or 17 left ventricular segmentation model (fig 6). The regional ejection fraction, and/or time to minimum volume of each segment, can then be calculated. The standard deviation of the time to minimum volume, corrected for RR interval can then give a systolic dyssynchrony index, which can be used to guide therapy.18

Furthermore, these timings can then be colour-coded on a dynamic bulls-eye plot giving a visual parametric representation of specific areas of delay (fig 7); a technique known as contraction front mapping. In the future this type of display could potentially be used to guide left ventricular lead placement in CRT.

Stress echocardiography
The idea of a 3D left ventricular dataset acquired during stress echocardiography (dobutamine, vasodilator and even exercise) is an attractive one. It promises to speed up examination times and also allow for accurate left ventricular chamber quantification before and during stress. It is possible to ensure that
reproducible scan planes are obtained at each stage of stress and, in addition, modified views to detect localised areas of ischaemia can be obtained from 3D datasets. Furthermore, advanced techniques could be added, such as contraction front mapping, potentially to increase accuracy and measure ischaemic burden. However, there are still some technical issues such as frame rates and use with contrast that need to be overcome to facilitate general clinical use.

Right ventricle
One of the major difficulties of right ventricular assessment for 2D echo, is its complex geometrical shape and position in the thorax. 3DE now offers the ability to formulate a mathematical cast of the right ventricle, similar to that for the left ventricle, which gives volumes and ejection fraction, without the need for any geometric assumptions (fig 8). This is still predominantly a research tool; however, a clinically feasible software package is now available and there is some interesting evidence supporting its use and showing a good correlation with MRI.

Left atrium
Left atrial size is known to be an important prognosticator in cardiovascular disease, and a volume measurement has been shown to be better than a diameter measurement. As with any volume calculations from 2D echo, geometric assumptions are required. Direct volumetric measurement can be performed using a left atrial full volume dataset (fig 9) and has been shown to be feasible and reproducible. Its accuracy has been proved but its clinical role is yet to be fully determined.

Valves
3D assessment of valvular structure and function is also possible and there is increasing interest in this field because of the ability to visualise true valve geometry. Investigation has predominantly focused on regurgitation through the mitral valve, and particularly in the assessment of leaflet prolapse. As mitral valve repair becomes more commonplace and more widely available, accurate preoperative imaging is becoming increasingly important. The current gold standard for pre-operative mitral valve assessment is 2D transoesophageal echocardiography, however, good 3D transthoracic imaging has now been shown to be a good non-invasive comparator in this situation. In particular, when compared with 2D transthoracic, it is adept in detecting pathology at the leaflet edges (P1, A1, P3 or A3). Furthermore, recent software allows quantification of the mitral valve complex, although the clinical applications of this remain to be defined. Applications for other valve lesions include the use of 3D planimetry.

Figure 5 A left ventricular analysis. Semi-automated border detection is used to create a mathematical cast of the left ventricle. Volumes and ejection fraction can be derived from this.
**Figure 6** The mathematical left ventricular cast can be subdivided into 16 or 17 segments and the regional function quantified. DISPES, dispersion; EDV, end-diastolic volume; EDSI, end-diastolic splenicity index; EF, ejection fraction; ESSI, end-systolic splenicity index; ESV, end-systolic volume; MES, mean end-systolic time; SDI, systolic dyssynchrony index; SV, stroke volume.

**Figure 7** Contraction front maps offer a visual representation of contraction propagation. The areas coloured red are those that contract later. The left-hand map demonstrates a delay predominantly in septal contraction. The right-hand map is from a patient with coronary artery disease and previous myocardial infarcts. The contraction map shows a very heterogeneous pattern of activation with multiple remote delayed areas.
Figure 8  A three-dimensional volumetric right ventricular analysis. Global volumes and ejection fraction can be measured. The mesh represents the end-diastolic volume (EDV). A time volume curve is on the bottom left and volume figures on the right. EF, ejection fraction; ESV, end-systolic volume; SV, stroke volume.

Figure 9  A three-dimensional volumetric left atrial analysis. EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; SV, stroke volume.
using multiple planes to obtain a geometrically accurate effective orifice/valve area, as well as measurements of the left ventricular outflow tract\textsuperscript{32,33} to enhance calculations using the continuity equation.

3D colour Doppler can be employed to assess regurgitant lesions and these have been characterised in 3D, mainly in the mitral valve.\textsuperscript{34,35} Furthermore, the 3D proximal isovelocity area for mitral regurgitation has undergone in-vitro validation.\textsuperscript{36} These techniques, however, currently still remain very research orientated.

3D contrast echocardiography

This is one of the most experimental 3D techniques. It can be performed both in left ventricular opacification settings and more recently in low mechanical index myocardial perfusion settings. Preliminary work has been done in the clinical use of this technique\textsuperscript{37–39} but it is still a way off widespread use. It does, however, offer the potential to measure the volume, as opposed to the area, of perfusion defects.\textsuperscript{40}

Figure 10  Three-dimensional (3D) transoesophageal echocardiography in interventional procedures. Top row: Monitoring and guidance of intracardiac wires/catheters. The left-hand picture is taken during a transfemoral transcatheter valve implantation, showing a guide wire passing through the native aortic valve and into the left ventricle. The right-hand picture shows, from the left atrial view, an attempt at transcatheter closure of a mitral paraprosthetic leak. A guide catheter (black arrows) is seen to curl around the left ventricle and is being positioned in an area of paraprosthetic dehiscence (white arrows). Bottom row: A 3D dataset is used to orientate an atrial septal defect correctly. Measurements of area and length are shown. The right picture shows an Amplatzer atrial septal defect device in situ as seen from the left atrium.

3D transoesophageal echocardiography

This is a recent addition to 3DE and currently the technique capable of supplying the most impressive pictures. Intense research is ongoing to delineate a clinical role, but this appears to lie in valvular assessment,\textsuperscript{41} particularly prosthetic valves and guidance of percutaneous interventions,\textsuperscript{42–44} which are becoming more widespread and increasingly complex (fig 10).

CURRENT PROBLEMS WITH THE TECHNIQUE

Many of the limitations of 3DE are the same as for 2D echocardiography. Patients with poor acoustic windows secondary to body habitus, chest deformities or lung pathology remain a challenge. A limited scan size means that by and large currently single chambers at a time can only be reliably acquired for quantification, but this is sufficient for a separate analysis of the left atrium, left ventricle and right atrium.

Temporal and spatial resolution can still be an issue, especially when trying to image larger ventricles and/or at higher heart rates, but these are improving all the time.
So-called stitching artefacts (“lines” that appear in the knitted dataset from any motion of the whole heart relative to the transducer) can be a major limitation in patients with significant arrhythmia, or those unable to breathhold for a sufficient period. The next generation of single-beat acquisition systems promise to help overcome this.

Currently 3D transthoracic transducers are independent of their 2D cousins. With the exception of the transoesophageal array, the 2D capabilities of matrix array probes are markedly inferior to the dedicated 2D transducers, meaning that transducers must be exchanged if 3D images are to be obtained. However, it is anticipated that the next generation of transthoracic 3D transducers will also be capable of generating 2D images that are equal in quality to those obtainable from dedicated 2D probes.

There is no widely available stress echo viewer for 3D echo, although these are currently being introduced (fig 11), and offer the promise of dedicated 3D stress capabilities. These need to become more widespread, with the integration of quantification tools and parametric displays. Frame rates will need to be maximal, especially important at the latter stages of stress.

The software, although relatively simple, can initially appear a little complex, but updates are continually simplifying and streamlining workflow.

**Table 1** Some of the strengths and weaknesses of 3DE when compared with 2D echocardiography

<table>
<thead>
<tr>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
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<tbody>
<tr>
<td>Inclusion of the whole heart within a dataset allows for correction of foreshortening/off axis views</td>
<td>Additional training and software required</td>
</tr>
<tr>
<td>Rapid on-line direct volumetric analysis; no requirement for geometric assumptions</td>
<td>2D imaging from 3D transducers is currently not as good as for dedicated 2D probes</td>
</tr>
<tr>
<td>Greater accuracy for left ventricular mass volumes and ejection fraction, when compared with MRI</td>
<td>Reduced temporal and spatial resolution</td>
</tr>
<tr>
<td>Improved inter, intra and test–retest variability</td>
<td>Not currently as widely available as 2D imaging</td>
</tr>
<tr>
<td>Regional volumetric analysis capabilities</td>
<td>Not yet fully integrated with data storage systems used for 2D echo</td>
</tr>
<tr>
<td>Improved anatomical assessment of valves</td>
<td>“Stitching” artefacts, particularly in those with significant arrhythmia</td>
</tr>
<tr>
<td>Similar excellent safety profile</td>
<td>Not fully incorporated into major society guidelines</td>
</tr>
<tr>
<td>Ability to obtain global and regional data from one analysis (volumes, ejection fraction and dyssynchrony)</td>
<td>Differences in data derived from different software packages need to be further delineated</td>
</tr>
</tbody>
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MRI, magnetic resonance imaging; 2D, two dimensional; 3DE, three-dimensional echocardiography.

**Figure 11** An example of a recently introduced three-dimensional stress viewer. Three long-axis (across the top) and three short axis views (bottom) can be manipulated in all planes and datasets at different stages can be compared side by side.
Large volumes of raw data are created with 3DE and these require careful storage. Ideally, online techniques of long-term data storage are necessary with seamless integration of dedicated software. This will be required to make 3DE fully integrated.

Quantification of left ventricular volumes is currently the most clinically applicable 3DE technique. Although there is a good correlation with MRI, there appears to be a significant underestimation of volumes by 3DE. In a recent study, this discrepancy appeared to be largely overcome by experience and was independent of the software used for each technique. This is mainly thought to be due to the difficulty in differentiating left ventricular trabeculations from true myocardium, which is a result of differences in spatial resolution.

Guidelines/imaging protocols are helpful, particularly for those less familiar with the technology, and some have instigated these. So far there is a lack of involvement of 3DE in major national and international guidelines; this is soon to change because the European Association of Echocardiography and the American Society of Echo are currently working on joint guidelines for 3DE. Along with this we need widely agreed cut-off values for certain analyses. Results supplied by different software programs for specific analyses, such as dysynchrony, may not be interchangeable and therefore any cut-off values should be defined with this in mind. Table 1 highlights some of the strengths and weaknesses of 3DE when compared with 2D echocardiography.

**HOW THE TECHNOLOGY WILL DEVELOP IN THE FUTURE**

One transducer capable of high quality 2D imaging as well as 3D would help facilitate further clinical integration. This is currently possible in the matrix array transoeseophageal echocardiography so is clearly conceivable for transthoracic echocardiography.

As processing power continues to increase, there will be continual improvements in temporal and spatial resolution, which promise to improve image quality even further. As mentioned earlier, transducers capable of single-beat acquisitions have recently been introduced and these will help to eradicate stitching artefacts, and will hopefully offer higher and higher volume rates; the ultimate goal being the acquisition of the whole heart in one cardiac cycle, with high frame/volume rates. This could lead to a scan being performed rapidly with one or two full volumes, followed by offline analysis of chambers and valves done after the patient has left the department.

Software will also develop, with semi-automated quantification giving way to fully automated, artificially intelligent analysis capabilities that could further improve reliability and reproducibility.

Dedicated 3D stress viewers will allow a single acquisition at each stage and more accurate reproducibility of viewing planes. In addition, 3D left ventricular analysis during stress will increase the quantitative capacity of stress echo.

3D myocardial contrast echocardiography, while still very experimental, has the potential to offer volumetric quantification of myocardial perfusion defects.

Advanced myocardial imaging such as deformation imaging is also now possible, although not widely available as yet. Further investigation is required but this promises to offer true 3D deformation including torsion, and may speed up deformation analyses.

**CONCLUSION**

The areas in which the accuracy and reproducibility of 3DE have been proved without a doubt are left ventricular mass, volumes and ejection fraction. With regard to volumes it is beginning to become a comparator to MRI, but without the additional expense and inconvenience. Evidence is growing for its use in dysynchrony as well as valvular assessment, and more specialised techniques such as stress and myocardial contrast offer a great deal of promise. Quantification of other chambers is becoming increasingly straightforward, although their clinical role is yet to be determined. Ongoing improvements are reducing the limitations, but as with any imaging modality it must not be seen in isolation, and is complementary to other techniques, all of which are rapidly advancing.

Furthermore, true volumetric acquisitions open up the opportunity for co-registration and fusion, which could enhance our ability for simultaneous intermodality imaging of anatomy and function; an exciting prospect for cardiovascular imaging.

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