

3D Echo in Routine Clinical Practice – State of the Art in 2019



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Three-dimensional (3D) echo has been around for almost five decades. Recent advances in ultrasound, electronic and computing technologies have moved 3D echo from the research environment to everyday clinical practice. Real time 3D echo and full volume acquisition are now possible with transthoracic as well as transoesophageal probes. The main advantages of 3D echo are the infinite cut planes possible, allowing direct, *en face*, and anatomical views of cardiac structures, avoiding foreshortening and circumventing the geometric assumptions of the cardiac chambers inherent in any 2D echo techniques. Three-dimensional echo is still dependent on image quality, subjected to ultrasound artifacts and faces the compromise between spatial and temporal resolution. In routine clinical practice in 2019, we recommend a focussed 3D examination after a full 2D echo study. The area where 3D echo has been consistently shown to have superior accuracy and reproducibility over 2D echo is in the assessment of left ventricular (LV) volumes and ejection fraction. We recommend obtaining a full volume 3D echo data set from the apical window, from which LV volumes and LV global longitudinal strain can be measured. Further 3D examination can be performed depending on the pathologies identified on 2D examination. Three-dimensional echo is superior to 2D echo in the assessment of mitral valve pathologies and atrial septal defects. Furthermore, real time 3D transoesophageal echo is a very useful technique in guiding structural cardiac intervention, both before, during and after the procedure. While 3D echo is not the holy grail of echocardiography, it does represent a useful technique in selected areas of cardiac imaging.

Keywords

Three-dimensional echocardiography • Left ventricular function • Cardiac Imaging

Introduction

Since its first description in the 1960s, three-dimensional echocardiography (3D echo) has gone through major advances. Initially, 3D echo was performed by acquiring a series of two-dimensional (2D) tomographic images, either by manual rotation of the transducer with external references or later by multi-plane transoesophageal echocardiography (TOE). Three-dimensional echo images were then generated by off-line reconstruction. The process was cumbersome and time consuming, thereby precluding its use in routine clinical practice. Through advances in ultrasound, electronic and computer technologies, real time display of 3D rendered images of the heart is possible with both transthoracic echo

and TOE, enabling its more widespread use in routine clinical practice.

Numerous studies have demonstrated the utility and, in many cases, the superiority of 3D over 2D echo in the assessment of almost all cardiac structures and function. These include assessment of left ventricular (LV) and right ventricular (RV) volume and function and wall motion, left and right atrial volume, LV mass, valvular heart disease, congenital heart disease, LV synchrony, guidance of interventional procedures and in volumetric colour Doppler imaging. In this article, we do not aim to give a full review of the technical aspects and all possible applications of 3D echo. Instead, we focus on areas where, in our opinions, 3D echo should be used in routine clinical practice in 2019.

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Advantages of 3D echo

The main advantages of 3D over 2D echo lie in the fact that a sector or a full volume dataset can be obtained in three dimensions. Like computed tomography and cardiac magnetic resonance imaging (CMR), this allows infinite cut-planes of the whole dataset both on- and off-line. Therefore, limitations of 2D echo like image foreshortening and off-axis cuts can be circumvented. Together with image cropping and rotation, *en face* views of cardiac structures can be obtained, allowing more anatomically orientated views easily understandable by cardiac surgeons and interventional cardiologists. Furthermore, real time 3D volume allows imaging of the left ventricle in a single heart beat allowing simultaneous assessment of all LV walls. This will shorten the time for image acquisition post exercise for evaluation of inducible ischaemia and for more reliable assessment of LV volume and function.

Limitations of 3D Echo

It needs to be emphasised early on that we do not consider 3D echo to be the holy grail of echocardiography. Despite all the technical advances, 3D echo is still an ultrasound-based technique and all the limitations of echo still apply. The image quality of 3D echo is dependent on that of 2D echo, being subjected to the same type of artifacts as dictated by the physics of ultrasound.

Despite the advances in transducer and computer technologies, one of the main limitations of 3D echo is the frame rate. Image acquisition and display in echo is always a compromise between temporal and spatial resolution. In achieving real time 3D display capabilities, frame rate is often sacrificed. For 2D echo, a frame rate of >100 Hz is commonly achieved giving high temporal resolution at a level not achievable with other imaging modalities like computed tomography or CMR. With real time 3D echo, a frame rate of, at most, 20–25 Hz is commonly obtained. With the addition of colour Doppler with 3D echo, frame rate frequently drops below 20 Hz, thereby limiting its usefulness. This limitation is imposed by the physics of ultrasound, and there is a limit as to how much temporal resolution may be improved with technical advances. We feel that this unique advantage of high temporal resolution of echo over CT scan or CMR may be compromised in the pursuit of 3D capabilities.

Stitching artifacts are unique to 3D echo. A full volume 90° × 90° 3D dataset can be obtained with electrocardiograph (ECG) gating and breath hold. Stitching artifacts may be seen in patients with irregular heart rate and inability to breath hold. This can be avoided in real time 3D mode or zoomed mode. However, a narrower sector will be available for viewing.

Image Display and Manipulation

The standard echo views of 2D echo are familiar to all of us. During our echo training, we were taught to think and view

the heart in these tomographic planes from standard echo windows. However, as these echocardiographic windows are not anatomical, they may be difficult to comprehend for those not familiar with echo. For example, cardiac surgeons view the heart differently to echocardiographers and finding a common language may be difficult.

Three-dimensional echo images can be acquired and displayed in several ways: real time 3D, zoomed 3D and full volume. These are fundamentally different to that of 2D echo, therefore, further training and familiarisation are necessary. This fundamental difference, together with the additional time needed for image acquisition, may be an impediment to the more widespread uptake of 3D echo in clinical practice. Furthermore, online and/or offline image manipulation and cropping are often necessary in 3D echo, presenting additional hurdles.

We would suggest cropping, viewing and communicating 3D echo in anatomic planes, instead of from where the images are obtained (as in 2D echo). These anatomic planes, i.e., transverse, sagittal and coronal, are more readily understandable and akin to that obtainable in a computed tomography (CT) scan or CMR. Additional, helpful, views are those from anatomical structures: e.g, view of the mitral valve from the left atrium or the aortic valve from the aorta. These views are more easily understood by cardiac surgeons and interventionists.

2D or 3D Echo

Proponents of 3D echo would suggest that the full echocardiographic examination should be performed in 3D as numerous studies have demonstrated superiority of 3D over 2D echo in the assessment of cardiac structures and function. With the current day 3D transthoracic echo transducers with small footprints, a full 3D examination is feasible with appropriate scanning protocols and modification of workflow [1]. The image quality obtainable with the state-of-the-art 3D transthoracic transducers is comparable to that from dedicated 2D probes. A complete 3D examination should entail multiple acquisitions from all standard echocardiographic windows. The American Society of Echocardiography and the European Association of Echocardiography have issued recommendations for the views and the protocol for a full 3D echo examination [1]. The resulting 3D echo dataset can be cropped either online or offline to display the cardiac structures in question.

Opponents of 3D echo may claim that 3D echo is just about pretty pictures, without many practical additional uses and without incremental clinical benefits. For the most part, they may feel 2D echo is sufficient for their use in clinical practice. This may arise from the fact that performing and interpreting 3D echo requires further training. The views obtained are very different from the familiar, standard 2D echo views. Furthermore, at least initially, image cropping, manipulation and display take extra time.

We would advocate a focussed 3D examination. After a complete 2D echo examination, a gated 3D echo data set

should be obtained from the apical window to allow quantification of left ventricular volumes and ejection fraction. Further focussed 3D examination may be performed depending on the pathologies identified on 2D echo or the areas of interests.

Left Ventricular Volumetric and Functional Assessment

Quantification of LV volumes and function is the area where 3D echo has been consistently shown to be superior to 2D echo. We recommend a focussed 3D examination of the left ventricle in the apical window in all cases. There are three different approaches used for LV volume quantification: 3D guided bi-plane analysis, real-time tri-plane quantification and direct 3D volumetric analysis. Three-dimensional guided bi-plane analysis is performed by obtaining anatomically correct, non-foreshortened apical two- and four-chamber views from a 3D echo dataset. Left ventricular volumes are then measured with Simpson's biplane method. Real-time tri-plane technique simultaneously acquires the three standard LV apical views within a single cardiac cycle, and is particularly suited for rapid acquisition and analysis or in patients with an irregular heart rhythm. Direct 3D volumetric analysis is based on semi-automated detection of endocardial borders using a deformable shell model [2–4]. Left ventricular volumes can be measured throughout the entire cardiac cycle and displayed as a time varying curve with the electrocardiogram (Figure 1A and B).

Left ventricular volumes and ejection fraction obtained by 3D echo have been consistently shown to show lower intra- and inter-observer, as well as lower test-retest, variability. Furthermore, 3D echo derived LV volumes have been demonstrated to have better correlation with that obtained with CMR [5–10]. In a meta-analysis which included 28 studies and 1,198 patients comparing 3D and 2D echo with CMR, 2D echo underestimated LV end diastolic volumes by 33 ± 10 mL and end systolic volume by 16 ± 5 mL. Underestimation by 3D echo was consistently less: end diastolic volume by 14 ± 5 mL and end systolic volume by 7 ± 3 mL. Of note, despite the underestimation of LV volumes by 3D echo, there was excellent agreement for 3D echo-derived LV ejection fraction with CMR-derived values [11]. In a meta-analysis of 12 studies comparing 2D and 3D echo in measuring LV volumes and ejection fraction, both the underestimation of LV volumes and the variabilities were lower with 3D echo [8]. Due to its lower test-retest variability, 3D echo derived LV volumes and ejection fraction are ideally suited for serial monitoring of LV function. Changes in LV volumes assessed by serial 3D echo showed better correlations than that obtained with CMR [12].

The underestimation of LV volumes by 3D echo compared with CMR may be related to the superior image quality of CMR, with better endocardial border definition as well as the different tracing methods of 3D echo and CMR. This underestimation may not be due to inherent inaccuracies of the 3D

echo methods. In CMR, LV volumes are obtained with the endocardial border traced inside the trabeculations whereas in 3D echo it is often traced where the trabeculations meet the LV cavity. The inclusion of basal LV slices may also play a part in the larger LV volumes obtained with CMR [4].

Full-volume multi-beat acquisitions are traditionally recommended for LV volume and function assessment as they offer the best available 3D resolution and wider sector width. The wider section width is potentially important in encompassing the whole left ventricle especially in patients whose left ventricles are dilated. However, breath-holding and ECG gating are required. Inability to breath hold or irregular heart rhythm may result in stitching artifacts. Single-beat acquisitions are feasible and have been shown to provide values similar to those obtained using multi-beat acquisition [13–15]

A semi-automated algorithm for endocardial border detection is now available in commercially available echo machines provided by major vendors (Figure 1A and IB). This has been showed to be feasible, time-efficient and reproducible in LV volumes and ejection measurements [16,17]. A recent study showed inter-vendor consistency of measurement of LV volumes and ejection fraction as compared with CMR. However, the use of automated endocardial border detection algorithms significantly underestimated LV volumes, and the degree of underestimation was higher with larger LV volumes [10].

In patients with suboptimal image quality, intravenous administration of echo contrast during 3D echo results in improved determination of LV volumes with reduced inter-reader variability and can thus be proposed as an acceptable alternative when MRI cannot be performed [9,18,19].

Assessment of Mitral Valve Pathologies

Assessment of mitral valve pathologies is another area of cardiac imaging where 3D echo should form part of routine clinical practice. Both transthoracic and transoesophageal 3D echo allow comprehensive assessment of mitral valve pathologies. In particular, the ability to display *en face* views and views from both the left atrial as well as LV aspects of the mitral valve apparatus are distinct advantages of 3D echo. In particular, *en face* views of the mitral valve from the left atrium showing its relationships with neighbouring structures are particularly important for cardiothoracic surgeons as this is the view of the mitral valve they are very familiar with. Having these anatomical views are especially helpful in surgical planning.

Mitral Stenosis

The utilities of 3D echo for the assessment of mitral stenosis have been established [20–23]. Compared with 2D echo and Doppler pressure half time methods, mitral valve areas by direct planimetry of 3D echo images had better agreement with that obtained with the Gorlin equation during cardiac catheterisation [20,21]. Three-dimensional echo were also

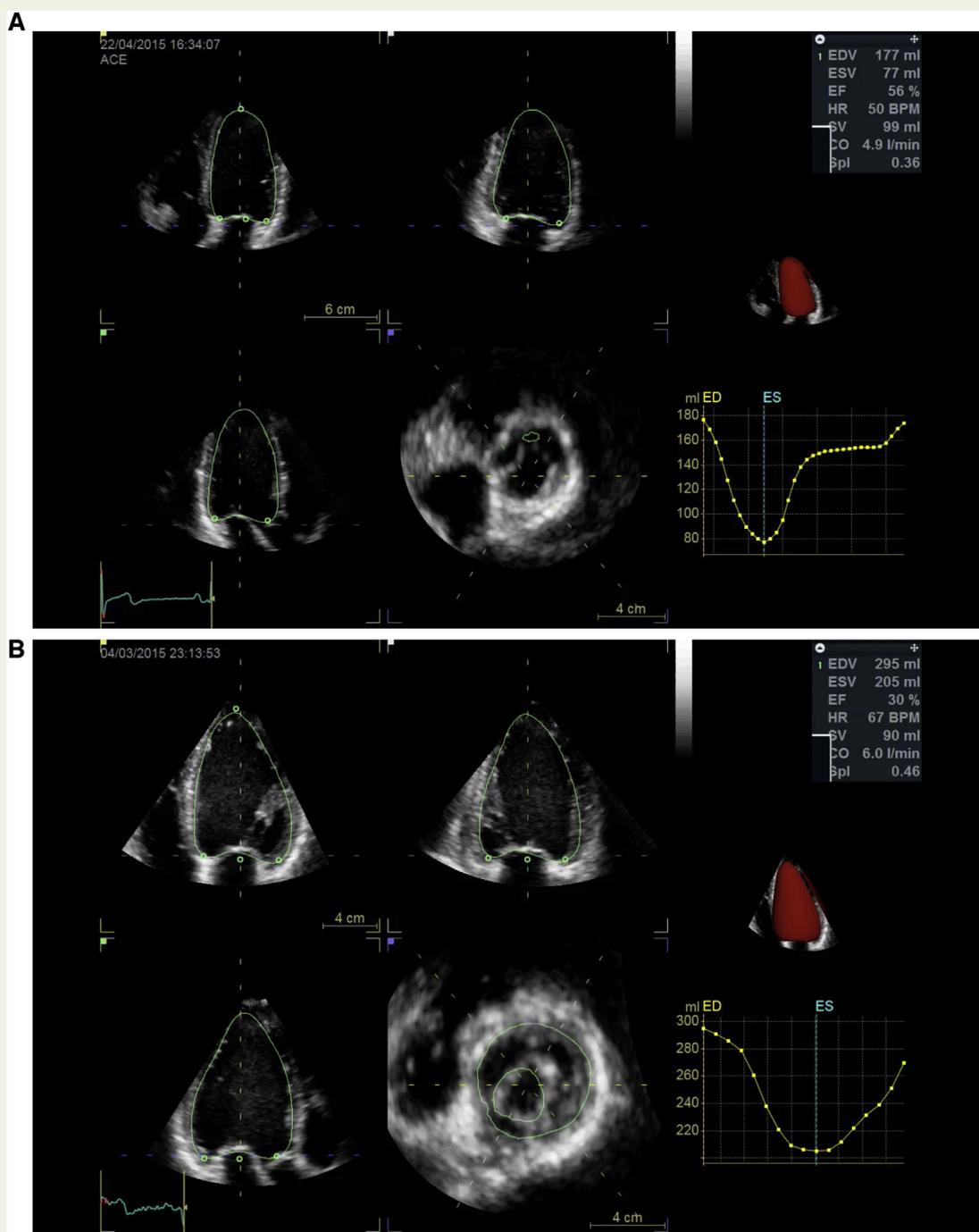


Figure 1 (A) Measurement of left ventricular (LV) volumes and ejection fraction by a semi automated algorithm for endocardial border detection with three-dimensional (3D) echo from the apical window. In this case, the LV end diastolic volume (EDV) is 177 mL and end systolic volume (ESV) is 77 mL, corresponding to an ejection fraction of 56%. The stroke volume (SV) and cardiac output (CO) are instantly displayed together with a time varying volume curve shown at the right lower corner. (B) Measurement of left ventricular (LV) volumes and ejection fraction by a semi automated algorithm for endocardial border detection with three-dimensional (3D) echo from the apical window in a patient with previous anterior myocardial infarction. In this case, the LV end diastolic volume (EDV) is 295 mL and end systolic volume (ESV) is 205 mL, corresponding to an ejection fraction of 30%. The stroke volume (SV) and cardiac output (CO) are instantly displayed together with a time varying volume curve shown at the right lower corner. Furthermore, it can easily be appreciated that the normal early diastolic filling, diastasis and late diastolic filling are abolished compared with the example in Figure 1A.

associated with lower intra-observer and inter-observer variability [20,21]. As 3D echo allows direct, perpendicular, *en face* views of the mitral valve from both the left atrial and the LV aspects, the cut-planes with the smallest valve area can be obtained (Figure 2). Furthermore, 3D echo provides detailed anatomical information on the commissures and the subvalvular apparatus, important in planning an interventional approach by percutaneous transseptal mitral valvuloplasty.

Mitral Regurgitation

Assessment of mitral valve morphology in patients with mitral regurgitation, especially in those with excessive leaflet motion, is the area where 3D echo, especially 3D TOE, is particularly helpful. While most echocardiographers may do their 3D reconstruction in their heads, having the mitral valve morphologies displayed in anatomically understandable views is important for surgeons for their surgical planning. The exact location of prolapse, and ruptured chordae tendinae if present, can be easily visualised (Figure 3).

Specialised software is available for delineating mitral valve anatomy in real time for 3D echo. The mitral annulus and the leaflets can be traced and the resultant 3D model shows the saddle-shaped mitral annulus and can display information like mitral leaflet area, annulus height and dimensions, tenting height and area. While the 3D model and the measurements may be useful for surgical planning, at this stage we do not feel these software add clinically significant incremental benefits.

Quantification of severity of mitral regurgitation is where 3D echo is potentially more accurate than 2D echo. Unlike 2D echo, direct visualisation and measurement of the regurgitant orifice area and *en face* views of the vena contracta are possible with 3D echo with colour Doppler. Different aetiologies of mitral regurgitation are associated with different shaped vena contractae [24,25]. While a non-hemispherical shape is observed in the majority of the patients (in contrast to what was assumed with the proximal isovelocity surface area methods with 2D echo), a more elongated semilunar-shaped vena contracta along the line of incomplete leaflet coaptation is seen with functional mitral regurgitation [25]. As 3D echo colour Doppler flow does not involve any geometric assumptions, it may be more accurate than 2D echo for quantification of severity of mitral regurgitation. It has been shown to be associated with less underestimation of regurgitant volume for different aetiologies and severity of mitral regurgitation than 2D flow proximal isovelocity surface area methods in vitro [26,27], as well as in humans [24,26]. With 3D echo colour Doppler imaging, it is also possible to measure regurgitant jet volumes. While this application of 3D echo with colour Doppler is promising, we often find the frame rate with real time 3D echo colour Doppler too low for diagnostic purposes. Although a full volume 3D dataset with colour Doppler flow is possible with ECG gating and breath hold, it is often hampered by an irregular heart rhythm and breathless patients, which is commonly seen in patients with significant mitral regurgitation.

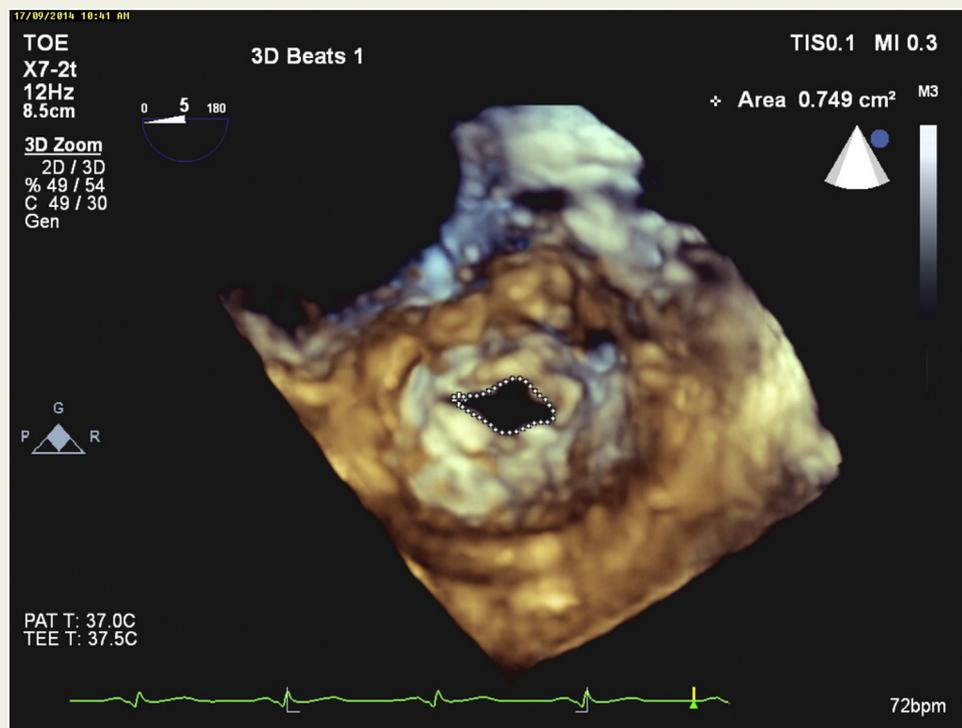


Figure 2 Three-dimensional transoesophageal echo in a patient with mitral stenosis. A direct, perpendicular, *en face* view of the mitral valve with the cut-plane at the smallest valve area can be obtained. By planimetry, the mitral valve area is 0.75 cm^2 .

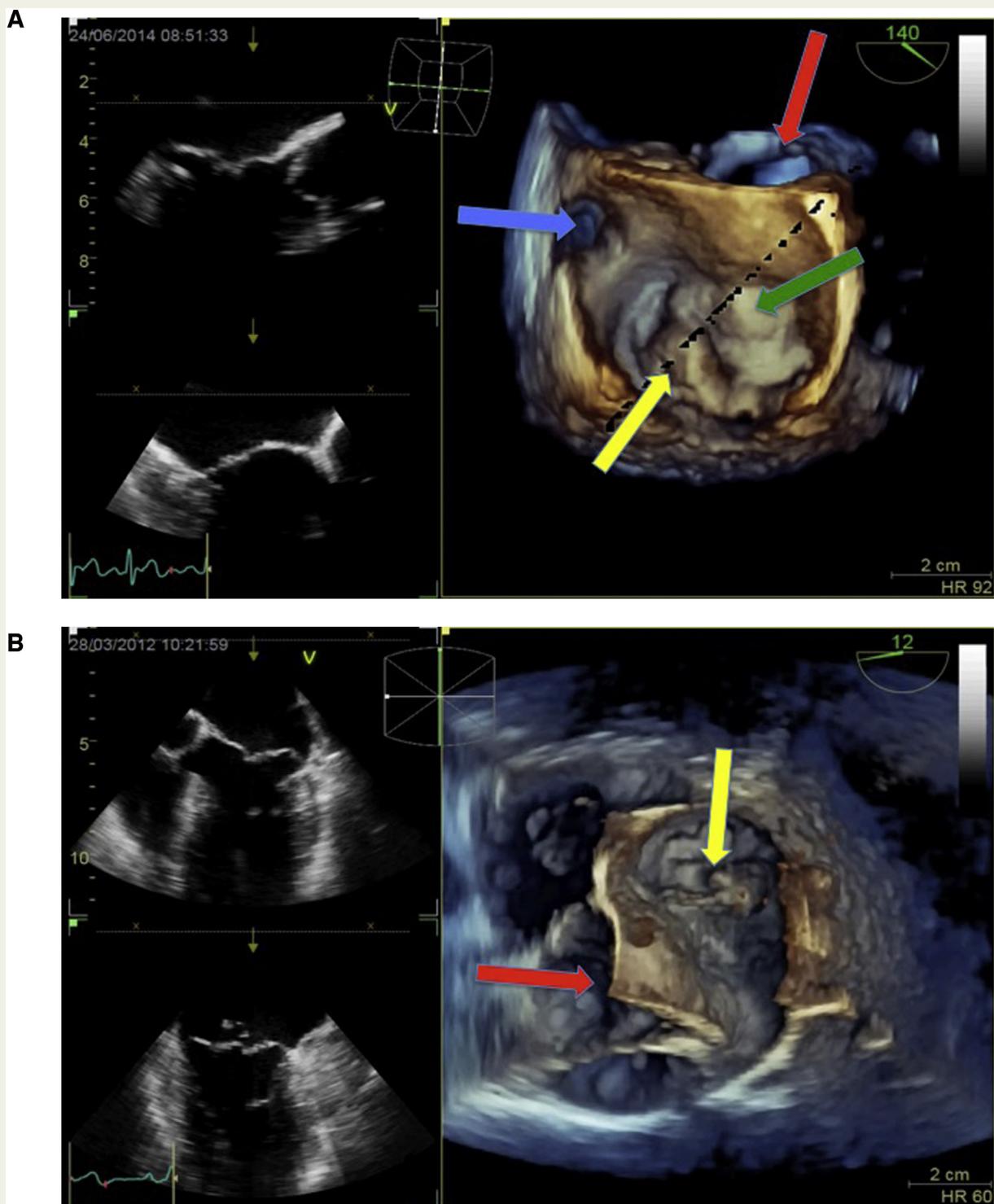


Figure 3 (A) Real time live three-dimensional (3D) transoesophageal echo with the zoomed 3D view of the mitral valve from the left atrium. The aortic valve (red arrow) is continuous with the anterior mitral leaflet showing prolapse of the A2 scallop (green arrow). There is prolapse of the corresponding P2 scallop (yellow arrow). The anterolateral commissure of the mitral valve can be identified with its proximity to the left atrial appendage (blue arrow). (B) Real time live three-dimensional (3D) transoesophageal echo with the zoomed 3D view of the mitral valve from the left atrium. In this case, there is prolapse and flail of the P2 scallop of the mitral valve with ruptured chordae (yellow arrow). The aortic valve (red arrow) is on the opposite side of the leaflet identifying the flail segment being part of the posterior leaflet.

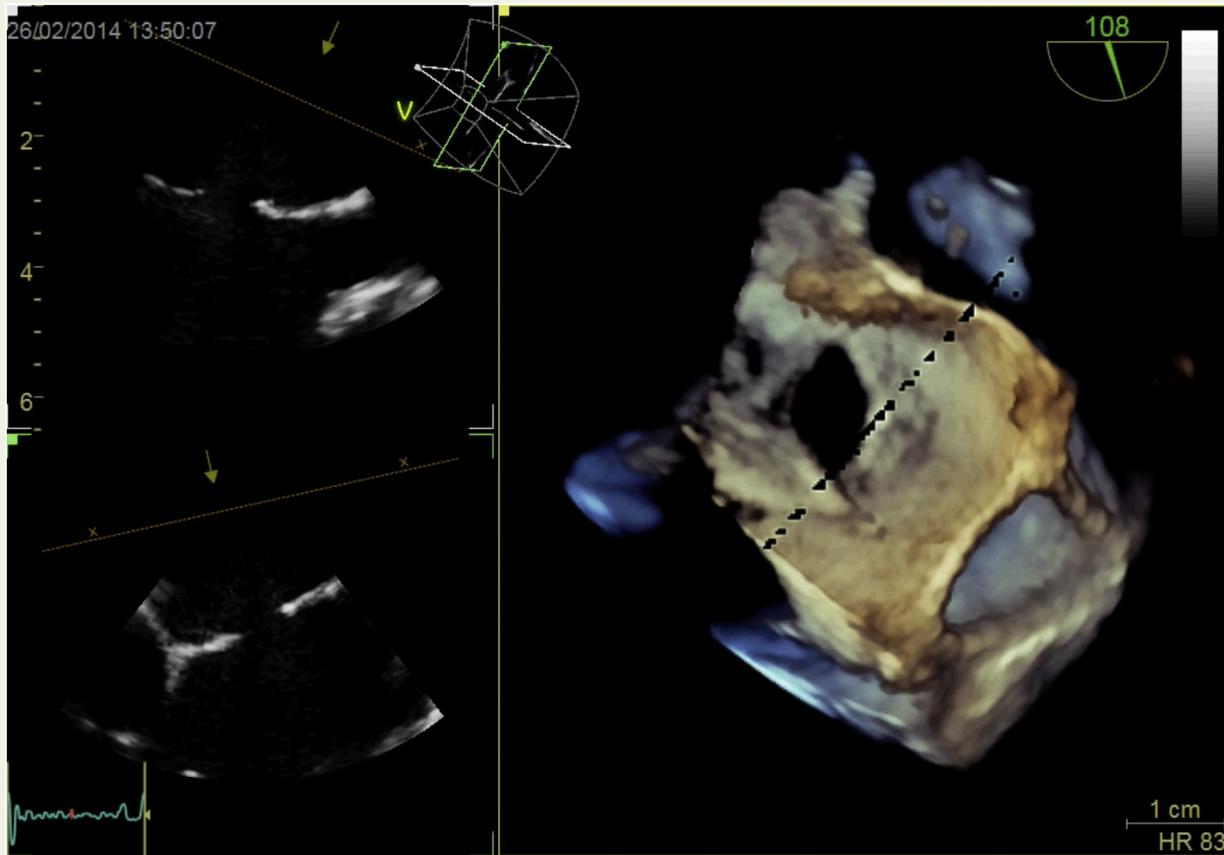


Figure 4 Direct *en face* view of an ostium secundum atrial septal defect from the left atrial side (as indicated by the small arrows from the left atrium on the two-dimensional (2D) images). It can be immediately appreciated that the defect is not circular but oval in shape.

Congenital Heart Disease

Due to its ability to display complex anatomy in 3D, 3D echo is theoretically ideally suited for complex congenital heart disease. However, as a result of limitations of image quality, especially in adults, the spatial resolution obtained with 3D echo is inferior to that obtained with cardiac CT and CMR. One area of assessment of congenital heart disease where 3D echo, in particular, 3D TOE, is of value is the assessment of ostium secundum atrial septal defects (ASD).

Most secundum ASD can be closed percutaneously with an Amplatzer occluder device. Accurately sizing the defect is essential for choosing the appropriate occluder to be used. As most ASDs are oval in shape, the diameter of the ASD may be underestimated and hence 2D echo may lead to undersizing of the device. As direct perpendicular *en face* views of ASD can be obtained with 3D echo, more accurate sizing of the defect is possible [28] (Figure 4).

Guidance of Interventional Procedures

Transoesophageal echocardiography is a valuable tool to guide cardiac interventions. Three-dimensional TOE allows

the display of the complex spatial relationships between cardiac structures more readily than 2D TOE. Real time 3D TOE is a particularly useful technique during cardiac interventions. Although 2D TOE is often sufficient in guiding cardiac interventions, the addition of real time 3D TOE does make the appreciation of complex 3D anatomy quicker and easier to comprehend for the interventionist.

Percutaneous transeptal mitral balloon valvuloplasty is an accepted technique in the treatment of rheumatic mitral stenosis. Three-dimensional TOE guidance is helpful in transeptal puncture and in aiding balloon crossing of the stenotic mitral valve (Figure 5). Three-dimensional TOE is also helpful in guiding percutaneous mitral valve repair with the MitraClip, which has been shown to be effective in selected patients with suitable anatomy.

Three-dimensional TOE is not only useful in assessing the shape and size of ASD as discussed earlier, it is helpful in guiding their percutaneous closure. The correct sizing, positioning and apposition of the occluder device during the procedure can be guided by real time 3D echo (Figure 6).

Three-dimensional TOE provides helpful information before, during and after percutaneous transcatheter aortic valve implantation. Selection of the appropriate prosthesis size is important, as under-sizing increases the risks of para-valvular aortic regurgitation and over-sizing may increase

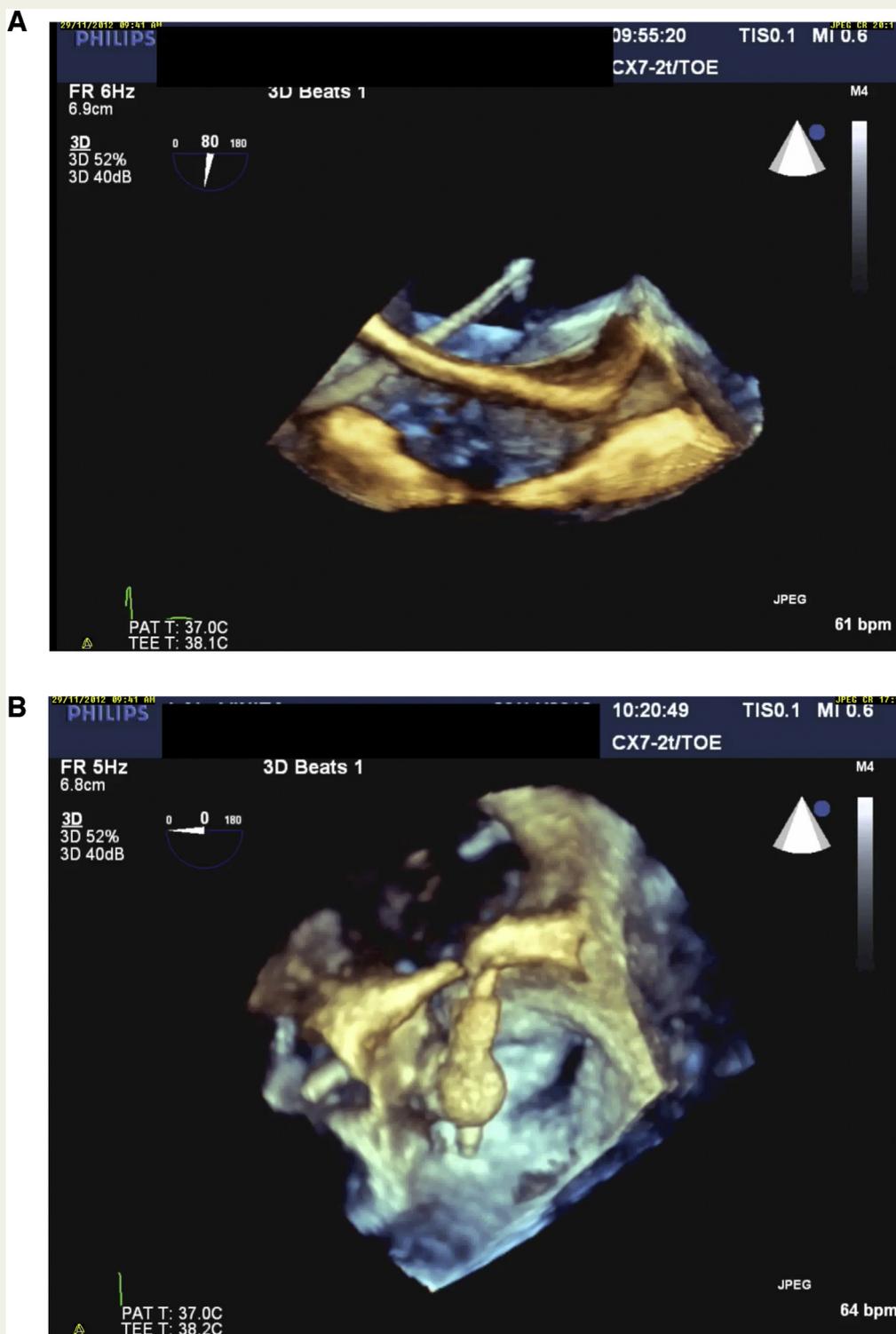


Figure 5 (A) Guiding transseptal puncture with live three-dimensional (3D) transoesophageal echo. (B) Guiding crossing of a stenotic mitral valve with live three-dimensional (3D) transoesophageal echo with the Inoue balloon. View from the left atrium.

the risks of aortic rupture and conduction block. Three-dimensional TOE allows exact characterisation of the aortic annular geometry and sizes, as it is well documented that the aortic annulus is oval-shaped rather than circular. Two-

dimensional echo or TOE may not allow accurate assessment of the exact shape and size of the aortic annulus [29]. In addition, procedural complications such as valvular or paravalvular regurgitation, aortic injury, myocardial infarction or

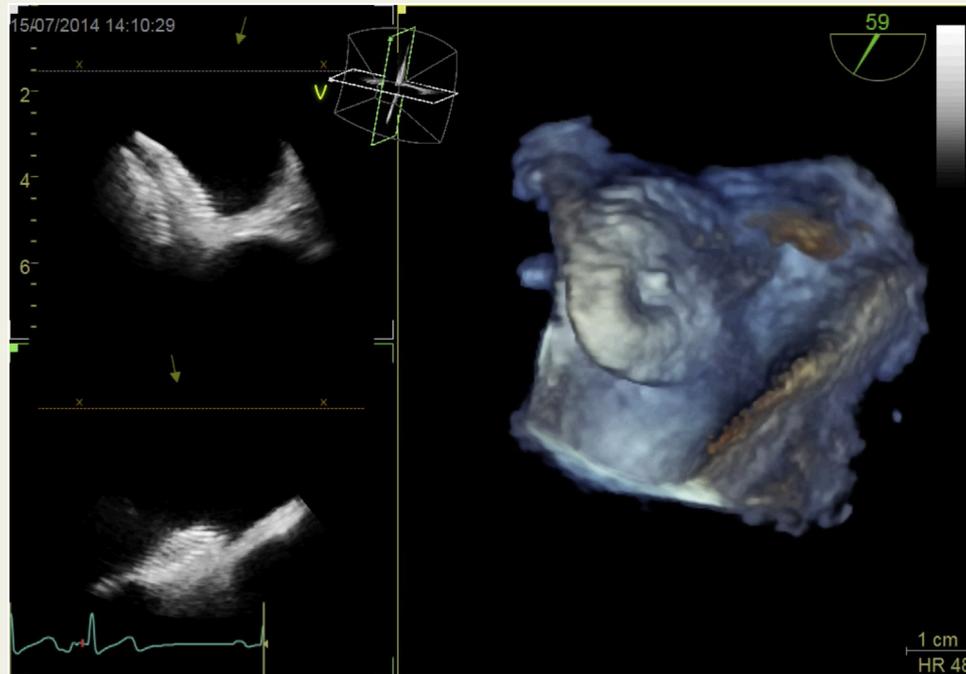


Figure 6 Guiding percutaneous closure of atrial septal defect with real time three-dimensional (3D) transoesophageal echo. The Amplatzer device (St Jude Medical, Uppsala, Sweden) is viewed from the left atrium before release. The left atrial disc is well opposed. The device is still seen attached to the delivery mechanism.

pericardial tamponade can be evaluated immediately during the procedure. Although cardiac CT also allows accurate assessment of aortic annular size, and the presence of paravalvular regurgitation post-procedure can be assessed with contrast aortogram, the use of 3D TOE does allow assessment by one imaging technique in real time.

Other procedures where guidance with 3D TOE may be of benefit include percutaneous closure of peri-prosthetic mitral regurgitation and left atrial appendage closure.

Left Ventricular Strain

Left ventricular global longitudinal strain (GLS) has gained wide clinical acceptance and is a useful clinical tool. It is a sensitive parameter for LV dysfunction and allows early detection of dysfunction when LV ejection fraction is still within the normal range [30]. Furthermore, LV GLS provided incremental prognostic value independent of LV ejection fraction in a wide range of conditions [31]. Traditionally, LV GLS is obtained from the three apical views of the left ventricle. One limitation inherent in this approach is that the three apical views are necessarily from three different heart beats and the global values are not actually obtained from the same heart beat. This is particularly important in patients with irregular heart rhythm. Another pitfall is that foreshortening of the left ventricle may lead to inaccurate assessment of longitudinal strain. Three-dimensional echo with a full volume acquisition in the apical windows allows assessment of true LV GLS in the same heart beat and avoids foreshortening. Semi-automated

software with automatic border detection allows assessment of both 3D LV GLS and circumferential and radial strain without foreshortening (Figure 7).

Right Ventricular Assessment

Echo assessment of right ventricular (RV) volumes and function remains challenging in clinical practice because of its complex geometry and its unique crescent shape. Its anterior position in the chest poses additional difficulties because of suboptimal image quality in many patients. Conventional echo parameters such as fractional area change, tricuspid annular plane excursion and tissue Doppler S' are recommended measures to assess RV systolic function. However, they have major limitations of being angle-dependent, load-dependent and not fully representing RV global function.

Three-dimensional echo has gained increasing acceptance for evaluation of RV volumes and function. Several studies have shown that it correlated well with CMR-derived volumes in different patient groups [32–35].

Similar to the situation with LV volumes, RV volumes were underestimated by 3D echo, particularly in patients with larger RV volumes and ejection fraction [36]. A volumetric semi-automated border detection software is available for RV volume assessment. While 3D echo assessment of RV volumes and function has shown promise, its incorporation into routine clinical practice is still hampered by the need for excellent image quality and, in our opinion, cumbersome software packages.

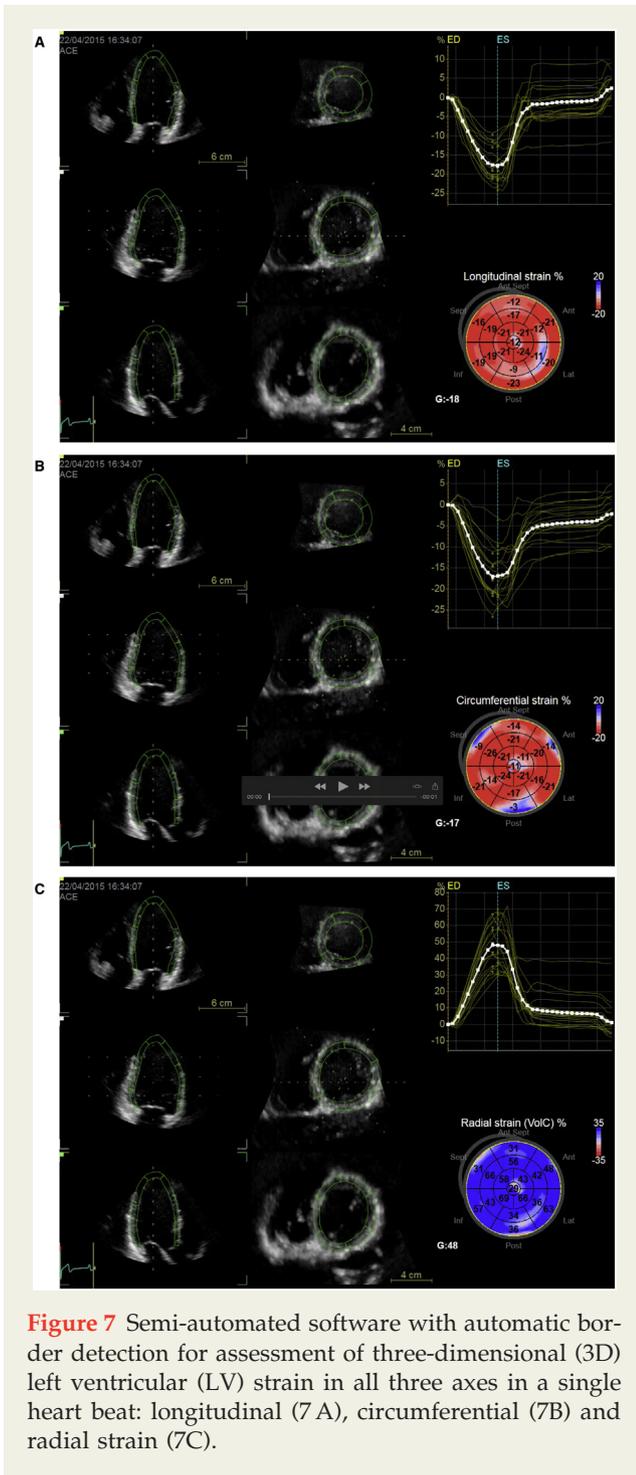


Figure 7 Semi-automated software with automatic border detection for assessment of three-dimensional (3D) left ventricular (LV) strain in all three axes in a single heart beat: longitudinal (7A), circumferential (7B) and radial strain (7C).

Other Assessments

Although 3D echo has been used in assessment of tricuspid valve, left and right atrial volume and LV dyssynchrony, we feel that their incorporation into routine clinical practice cannot be recommended in 2019. In particular, the main problem with 3D echo assessment of LV dyssynchrony is the limited frame rate, thereby limiting the temporal resolution in the assessment leading to significant under-sampling and uncertainties.

Conclusions

Three-dimensional echo has come a long way since its first inception. With current technologies, a full 3D examination in routine clinical practice is feasible. The main advantages of 3D echo are the infinite cut planes possible allowing direct *en face*, and anatomical views of cardiac structures, thereby avoiding foreshortened views of cardiac structures. Three-dimensional echo can circumvent any geometric assumptions of the cardiac chambers inherent in any 2D echo techniques. While 3D echo has been shown to be helpful in assessing most cardiac structures, it is still affected by image quality, subjected to artifacts seen with 2D echo and the compromise between spatial and temporal resolution. This compromise is imposed by the physics of ultrasound which any future technical advances are unlikely to resolve. In routine clinical practice in 2019, we recommend a focussed 3D echo examination after a full 2D echo study. The area where 3D echo has been consistently shown in multiple studies to have superior accuracy and reproducibility over 2D echo is in the assessment of LV volumes and ejection fraction. We recommend obtaining a full volume 3D echo data set from the apical window for measurement of LV volumes and GLS. Further 3D examination can be performed depending on the pathologies identified on 2D examination. Assessment of mitral valve pathologies and ASD with 3D echo should be used in routine clinical practice. Furthermore, real time 3D TOE is a very useful technique in guiding structural cardiac intervention, both before, during and after the procedure. While 3D echo is not the holy grail of echocardiography, it does represent a useful technique in selected areas of cardiac imaging.

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