Review Article
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Use of Three-Dimensional Echo in Clinical Practice

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ABSTRACT

Three-dimensional echocardiography (3DE) is an imaging modality that is rapidly gaining clinical application. Since its introduction in 1973, it has emerged from an unwieldy research modality to a practical and readily available clinical tool in the last decade.

The four major focus areas with an established role for 3DE include the analysis of cardiac volumes and left ventricular (LV) mass, ischemic heart disease, congenital heart disease and valvular pathology. The real time display of the deeper cardiac structures in a three dimensional plane improves the diagnostic capabilities and discards any geometric assumptions included in the two-dimensional data set. The reduced foot print of the current generation of 3DE imaging transducer allows a larger real time data pyramid. This is particularly useful when precise measurements of chamber volumes may be important for decision making, for example in the assessment of patients with reduced LV function when considering implantable defibrillators or cardiac resynchronisation therapy. Another important application of 3DE is in the guidance of interventional cardiac procedures, namely, mitral valve balloon valvuloplasty, percutaneous atrial and ventricular septal defect closure and in percutaneous closure of para-prosthetic mitral and aortic regurgitation.

The ability of 3DE to simulate surgical views helps to facilitate vital surgical decisions and planning for mitral and aortic valve repair. It is instrumental in the selection and performance of percutaneous aortic valve implantation and mitraclip repair for mitral regurgitation. Finally it may help in making more accurate qualitative diagnosis and classification of congenital heart disease. (J Clin Prev Cardiol 2012;1:11-9).

Key Words: 3D echo; clinical practice; review.

The rationale for the use of three-dimensional echocardiography (3DE) in a clinical setting is growing. The four main areas that have investigated the value of 3DE include the analysis of cardiac volumes and left ventricular (LV) mass, ischemic heart disease, congenital heart disease, and valvular pathology. Although various versions of 3DE have now been in use since the early 1970s (1), "live" 3DE has only been in use since the early 2000s.

3DE can display, in real time, the views and motions of deeper cardiac structures, which are unavailable by two-dimensional echocardiography (2DE) and is therefore capable of providing superior diagnostic information. This is particularly advantageous given the complex spatial relations of cardiac structures especially in the fields of acquired valvular disease (2), atrial and ventricular septal defects (3), and LV remodeling (4). It can also display exact assessments of left atrial volume (5,6), LV volumes and function, and volumetric measurements of irregularly shaped geometric chambers such as right ventricle. The ability of 3DE to simulate surgical views helps to facilitate vital surgical decisions such as the accurate assessments of the effect of percutaneous balloon valvuloplasty and the function of prosthetic valves and septal occluders. Finally it may help in making more accurate qualitative diagnosis and classification of congenital heart disease (7).

Both qualitative and quantitative limitations of the two-dimensional (2D) imaging have led to the emergence of the 3DE technique. Until recently, the 3DE technology has been slow due to image quality and longer processing and acquisition times compared with 2DE. The most recent of the 3DE technologies is the "live" or "real-time" three-dimensional (RT3D) technique; however, there have been a number of systems and methods that led up to this recent advancement.

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Evolution of Three-Dimensional Echocardiography

The first step in the development of "real-time" 3DE was the development of external tracking or freehand scanning. In 1973, Dekker et al. (8) were the first to demonstrate hardware capable of collecting three-dimensional (3D) cardiac ultrasound. This consisted of four-dimensional data collection and display subsystems. It used a large mechanical arm that measured the probe displacement during 2D image acquisitions. Even though this was a new and exciting technique and even a nonskilled worker could use the machine, it was time-consuming and very impractical (8). The next group to expand on the 3D tracking method was Brinkley et al. in 1978 (9). This group developed an acoustic locator or "spark gap" where regular audio pulses are sent attached to the ultrasound probe and detected by a fixed antenna.

Following this, a "freehand" scanning device was developed which was attached to the ultrasound probe allowing continuous scanning of the heart in space. Freehand scanning was developed in 1979 and is still used in some clinical laboratories today. This device uses a magnetic field system, which orients sequentially acquired 2DE images by tracking the movement of the ultrasound probe used by the sonographer. However, this system is time-consuming and relatively immobile because of the associated receiving computer where the image is reconstructed. Gated sequential imaging was another method for 3DE. This modality worked under the assumption that both the patient and the ultrasound probe remain in a fixed position. Using three transducer methods (rotational, fan-like, and linear scanning), aligned cuts of the heart are obtained and reconstructed (10). This method, however, fundamentally relies on maintaining adequate 2DE image quality over a long acquisition time and, therefore, is subject to heart rate variability, lung artifact, and respiratory rate.

In the early 1990s, the "real-time" volumetric 3DE was developed by Duke University using a sparse matrix array transducer. This technique is based on the concept that the heart would fit into a pyramidal dataset and does not rely on the transducer movement or sequential capturing. Although the output is known as "real-time," the output actually consists of multiple 2D images displayed simultaneously (11).

This technique formed the basis of the newest three-dimensional technique – "real-time" or "live" 3DE. RT3D uses a 3.5 MHz transducer with 256 firing elements in the form of a 2D grid. The elements are arranged in a grid instead of a line that enables acquisition of an on-line three-dimensional volume of ultrasound data.

The previous three-dimensional transducers used a modified two-dimensional probe that had elements arranged in a single line. The advantage with RT3D is that the transducer does not move to obtain data, unlike previous models where multiple windows and planes were needed to reconstruct an image.

RT3D uses linked images from four cardiac cycles gated from an electrocardiograph (ECG). However, image quality remains limited because of the number of transducer elements, transducer frequency, image depth, and processing power. This leads to lower spatial and temporal resolution compared with other techniques. The matrix array transducer includes up to 3000 individual elements and a faster processing speed, which also allows for "live" 3D imaging. This is a useful tool, not only for 3D viewing but also for biplane 2DE where two simultaneous perpendicular images can be viewed side by side.

The development of the 3D transesphageal imaging probe is similar to the trans-thoracic probe, allowing imaging in three different modes. Firstly, there is a narrow sector acquisition, which is a $50^{o} \times 30^{o}$ pyramid. Secondly, there is a 3D zoom, which shows a smaller but magnified $85^{o} \times 85^{o}$ pyramid. Lastly the full pyramid sector which is similar to the trans-thoracic echo (TTE) probe in which four consecutive beats make up a $90^{o} \times 90^{o}$ pyramid.

Assessment of Left Ventricular Function

The quantification of LV volumes and ejection fraction (EF) is an important aspect of cardiac evaluation in all cardiac disorders. Indeed assessment of LV function is perhaps the most common of all indications to request an echocardiogram. The serial assessment of LV function is frequently used to guide therapy. However, repeated measurements are prone to variation due to poor image quality, geometric issues related to volume and mass calculations, the performance of measurements from off-axis cuts, and variations in ventricular loading (12). EF is a simple numerical value that reflects LV function. However, trans-thoracic 2DE has limited test–retest reliability (13). Studies have shown that Simpson's biplane calculation of EF can vary up to 4.1% between readers (14,15). This variability is due to the complex

geometric assumptions and potential problems with image foreshortening that 2DE calculation of EF encounters.

Consequently, cardiac magnetic resonance imaging (MRI) has been proposed as a more desirable alternative for LV assessment, especially in clinical trials (16) because of its good image quality and high spatial resolution. Given this, cardiac MRI has become the "gold standard" for LV volumes, EF, and LV mass. However, expense, patient intolerance (e.g., claustrophobia, noise), a relative contraindication in patients with cardiac devices, and lack of portability have limited the use of this modality in routine clinical practice.

To overcome many of the geometric assumptions and to counteract the issues related to LV axial alignment, in the last three decades, 3DE has developed into clinical tool for measuring volumes, EF, and LV mass. Many studies have shown that 3DE is more closely correlated to MRI with less variability than 2DE for cardiac measurements (Fig. 1). The advancement of 3DE from a cumbersome offline tool to a "real-time" online process has taken it out of the research arena and into the clinical laboratory.

3DE has the advantage of accurate delineation of the true long axis length of the ventricle, thereby increasing the accuracy of Simpson's guided biplane measurements. For 2DE, the accuracy of LV volumes by Simpson's method is dependent on the apical four- and two-chamber lengths being nearly equal. Since the geometric assumptions of the 2DE calculations depend on the accuracy of ventricular lengths, foreshortening will result in underestimation of the cross-sectional area and thereby volumes. Recent advancements in 3DE technology have allowed for faster assessment in full LV volume measurements due to the semi-automated endocardial edge detection. Online measurement of 3D LV volumes is feasible and more accurate than with 2DE (17).

The calculation of LV volumes and function underpin important clinical decisions in patient management. This increasing application and monitoring of devices in heart failure, for example implantable defibrillators (AICD), cardiac resynchronization therapy (CRT), LV remodeling surgery, and in future stem cell therapy, require more accurate assessment of LV remodeling. The current American College of Cardiology and American Heart Association guidelines for the management of heart failure recommend the use of LV dimensions and 2DE EF for this purpose (18). A number of studies have shown that 3DE has overcome many of the limitations of 2DE with less test–retest variation, better reproducibility, and accuracy in LV volume estimations. A recent study by Hare et al. (19) has shown differences in the classification of patients into EF thresholds with 3DE compared to 2DE, which may impact treatment decisions, especially regarding device therapy. Moreover, 3DE appears to be superior to 2DE for evaluating LV size in long-term follow-up. Recently, there has been an attempt to validate a standardized 3DE protocol for measuring LV volumes and EF. The first multicenter study to validate and provide information of the sources of error between MRI and 3DE found that the major source of error of 3DE is the definition of endocardial

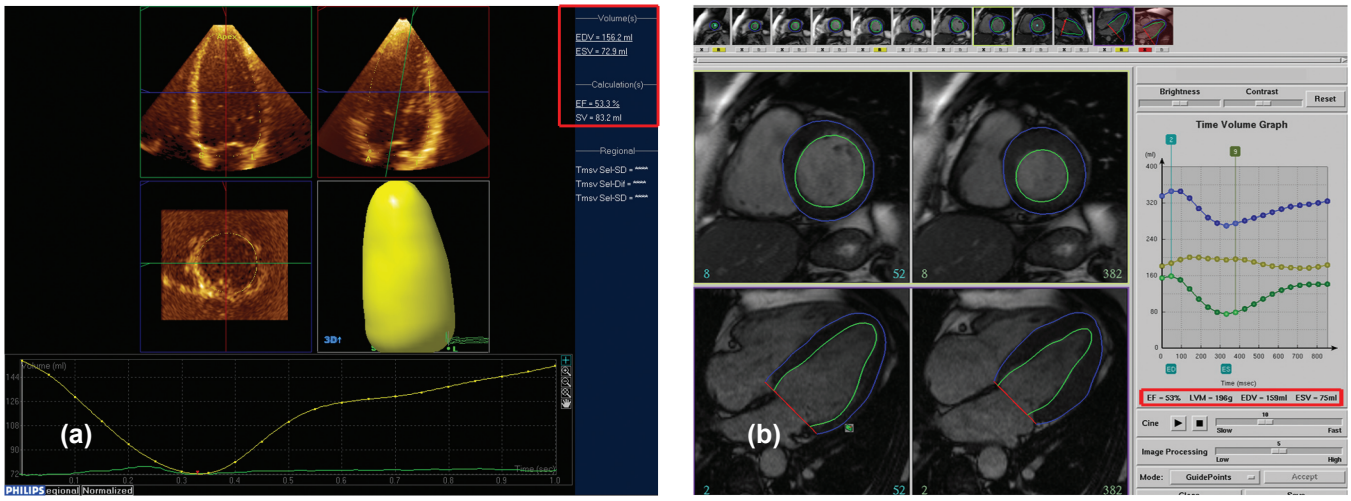


Figure 1. Comparison of 3DE and MRI LV volume and EF measures. **(a)** 3DE global time volume curve (QLab, Philips, Andover). **(b)** MRI global time volume curve (CIM, Auckland University).

borders. In 3DE, the trabeculae are blended in with the myocardium rather than being included in the LV cavity, as is the case with MRI. Another critical difference is that MRI uses short-axis slices whereas 3DE uses long-axis slices and both use separate software for analysis. This was investigated with the use of a phantom which found very small differences between the techniques for measured volumes (20). 3DE is now the gold standard echocardiographic measurement of choice for the accurate calculation of LV volumes and EF. As demand for more reproducible measurements is sought to guide management decisions, the demand for 3DE will grow accordingly and is likely to be soon incorporated into mainstream cardiac guidelines.

Quantification of global LV function is important; however, in patients with heart failure there is potential for LV dyssynchrony and regional analysis. Previous techniques for assessment of intra-ventricular dyssynchrony including tissue Doppler and M-mode analysis have been used to assess the LV on a per segment basis. These methods used to evaluate LV mechanical dyssynchrony are technically difficult and do not assess the whole LV simultaneously. RT3D can quantify global mechanical dyssynchrony. LV mechanical synchrony has emerged as a therapeutic target using cardiac resynchronization therapy in selected patients with chronic heart failure. RT3D represents a new technique to identify chronic heart failure patients, previously not considered suitable for resynchronization therapy, who might benefit from such therapy (Fig. 2). The first of the dyssynchrony studies using 3D was published in 2005 and found a systolic dyssynchrony index for both normal EF and abnormal EF populations (4). It has also been found to have high sensitivity and specificity (21) and good reproducibility at centers (22).

Assessment of Valvular and Congenital Abnormalities

Three-dimensional echocardiography and in particular 3D trans-esophageal echocardiography (3D-TEE) has become a critical diagnostic tool for patients with valvular abnormalities. In mitral valve assessment, 3D-TEE has allowed visual analysis of the leaflets scallops, chordate, and shape of the annulus (23,24). It allows easy visualization of the valve from a surgical view and accurate diagnosis of pathology such as stenosis (25), prolapsed segments (23) (Fig. 3), and regurgitation (26).

In patients with mitral stenosis, a 3DE dataset can be manipulated to show the true orifice area (Fig. 4). Studies have shown that 3DE has a better correlation than 2DE to invasive methods when assessing mitral valve areas (2,25). 3DE has also shown to play an important role in pre- and post-percutaneous balloon mitral valvuloplasty (27).

3DE allows superior visualization of all mitral valve apparatus and leaflets scallops than 2DE and is particularly useful in conditions such as Barlow's disease (28). 3DE can accurately show each prolapsing segments and aid in the decision to proceed to either mitral valve repair or replacement. In mitral regurgitation cases, 3DE has been shown to provide information of jet origin and orientation, improve calculation of flow

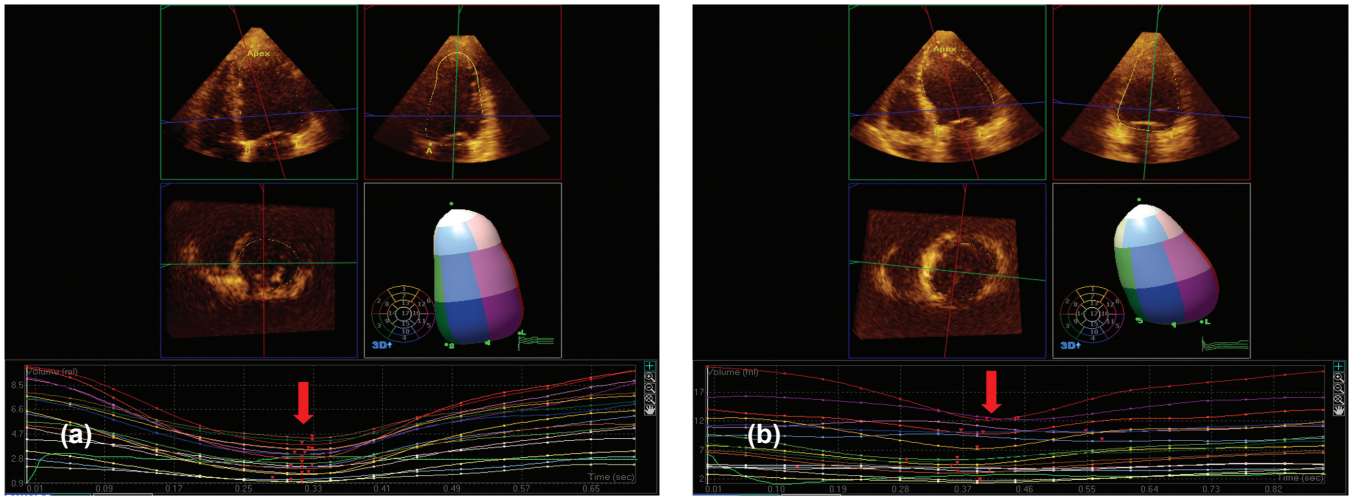


Figure 2. 3DE regional time volume curve of the 16 segment LV (QLab, Philips, Andover). **(a)** Synchronous LV, red arrow showing that all regions are at end-systole at the same time. **(b)** Dyssynchronous LV, red arrow showing that all regions are not at end-systole at the same time.

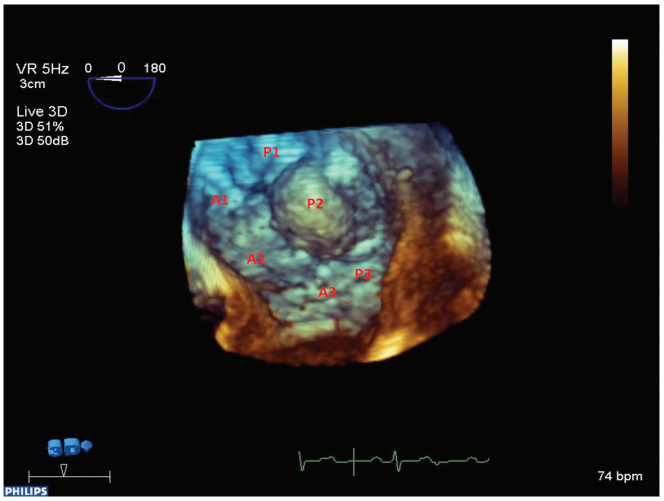
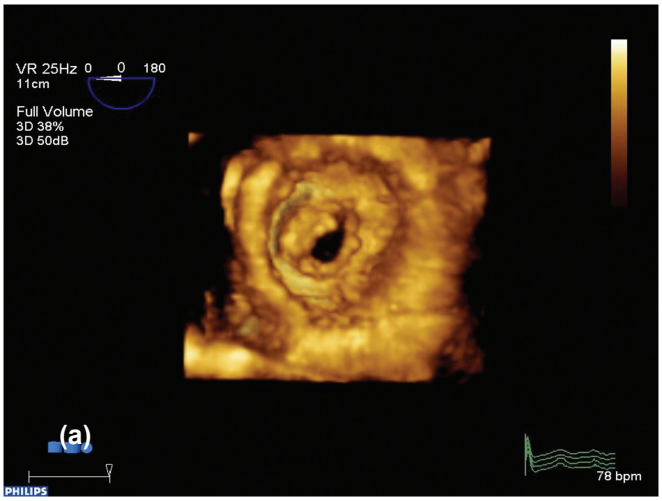


Figure 3. Mitral valve prolapse shown using TEE. View from LA into the LV and a prominent P2 prolapse (Philips, Andover).

convergence areas, and effective regurgitant orifice areas (26,29). In functional mitral regurgitation, the vena contracta width and area can vary significantly depending on image orientation. 3DE derived vena contracta area has been shown to correlate better with severity of mitral regurgitation, and well emerge as a new quantification tool (26). Paravalvular leaks are a post-surgical complication of valvular replacement or repair. 3D-TEE is superior to 2D-TEE in determining the number, locations, and shape of the leak (30) (Fig. 5). 3D-TEE is now the method of choice for guiding repair of paravalvular leaks, in positioning prosthetic devices into the defect, and assessing any residual leaks or interference to the valve leaflets (31).

In patients with congenital heart disease (especially atrial septal, or ventricular septal defects, ASD or VSD), 3D can show the location, size, configuration, type, and motion of the defect (Figs. 6–8). 3D also shows the spatial relations of the defect with the neighboring structures and the image can be rotated to view the defect from either the left or the right side of the septum. Studies have shown that 3D is a technology that allows instant visualization of cardiac anatomic details that could not be well-delineated by 2D imaging (32). It is also now feasible to guide percutaneous ASD and VSD closures with the use of 3D-TEE (33–35). 3D-TEE has the advantage over 2D by accurately measuring rim lengths, distance between multiple defects, and localization of the defect in relation to other structures such as the aortic or mitral valvular apparatus, aortic root, pulmonary veins,



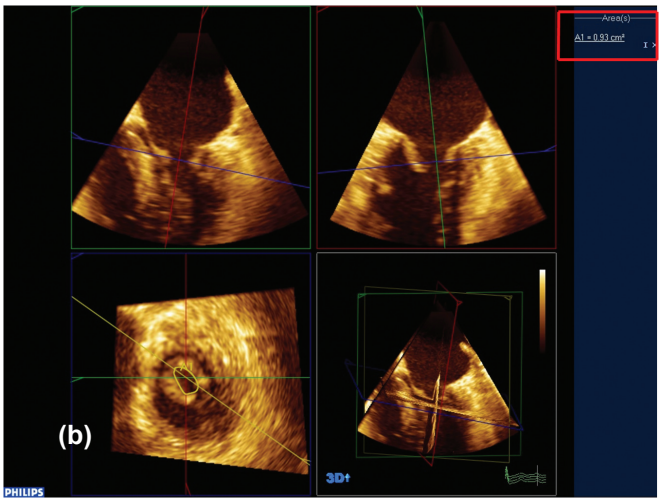


Figure 4. Mitral stenosis shown using TEE. **(a)** View from LV into the LA showing thickened MV leaflets and small opening during diastole (Philips, Andover). **(b)** Measurement of MVA, by manipulating the dataset it can show a truepeak opening (QLab, Philips, Andover).

and the vena cava. Not only has TEE been shown to aid in the evaluation of complex congenital defects (36) but also in detection of intracardiac masses, tumors (37) and thrombus, and the evaluation of structure such as the left atrial appendage (LAA) (38). 3D-TEE has become the imaging modality of choice to size the device for LAA occlusion and to guide the procedure safely (39).

Key Uses of Three Dimensional Echocardiography

1. Volume and EF analysis
    a. For use in serial follow-up on patients who need intracardiac devices, valvular abnormalities, and chemotherapy.

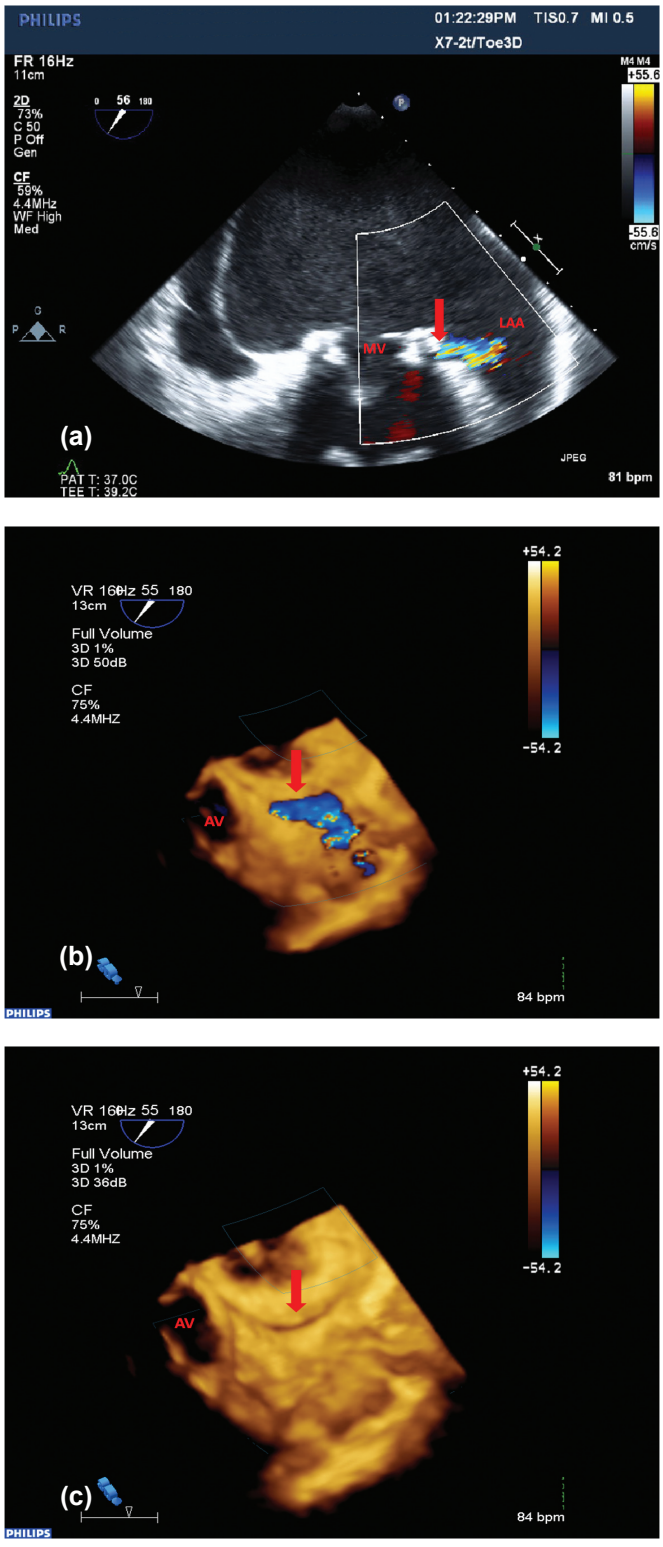


Figure 5. Example of mitral valve paravalvular leak (Philips, Andover). **(a)** 2DE image showing MR leak into LAA **(b)** 3D-TEE image showing extent of leak with color flow. **(c)** 3D-TEE image showing shape and extent of regurgitant orifice area.

2. Dyssynchrony and regional analysis
    a. For patients with heart failure and the need for resynchronization therapy.
3. Valvular abnormalities
    a. Assessment of leaflets scallops, chordae, and shape of the annulus.
    b. Surgical view of pathology such as origin of regurgitant jets, prolapsing segments and calculation of valve areas.
4. Congenital abnormities
    a. Septal defect evaluation and percutaneous device repairs.
    b. Detection of intracardiac masses, tumors, and thrombus.

Conclusions

Although 3DE is emerging as the echocardiographic method of choice for LV volume, valvular and congenital abnormality assessment, however, practice guidelines do not yet take cognizance of this evidence. The uptake of this technique into the clinical laboratory has been slow and may be limited by inexperience. An interactive teaching course with rehearsal and direct mentoring appears to overcome this limitation and may improve the uptake of this technique (40).

Both 3D-TEE and TTE are no longer just a research tool but a feasible clinical tool for the diagnosis and measurement of volumes, valvular abnormalities, and structural defects.

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Conflict of Interest

None

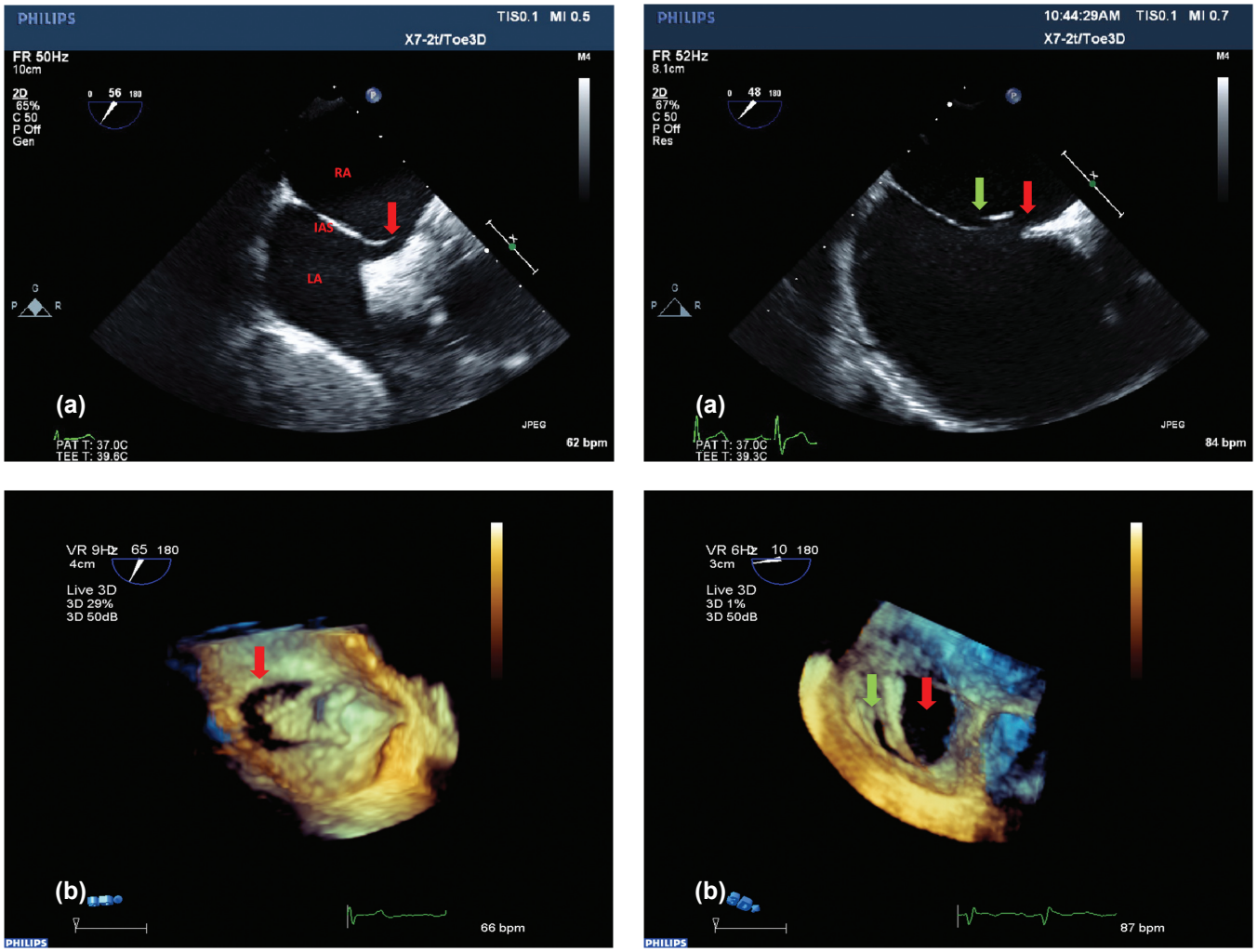

Figure 6. Example of patent foramen ovale (PFO) (Philips, Andover). **(a)** 2DE image of PFO (red arrow). **(b)** 3DE image showing shape and extent of PFO; fenestrations across hole.

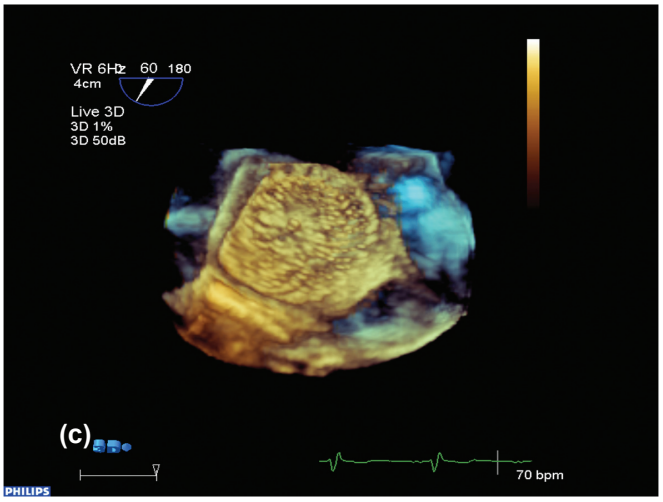

Figure 7. Example of patient with patent foramen ovale (PFO) and ASD (Philips, Andover).**(a)** 2DE image of PFO (green arrow) and ASD (red arrow). **(b)** 3DE image showing shape and extent of PFO (green arrow) and ASD (red arrow). (c) 3D-TEE image of amplatzer device.

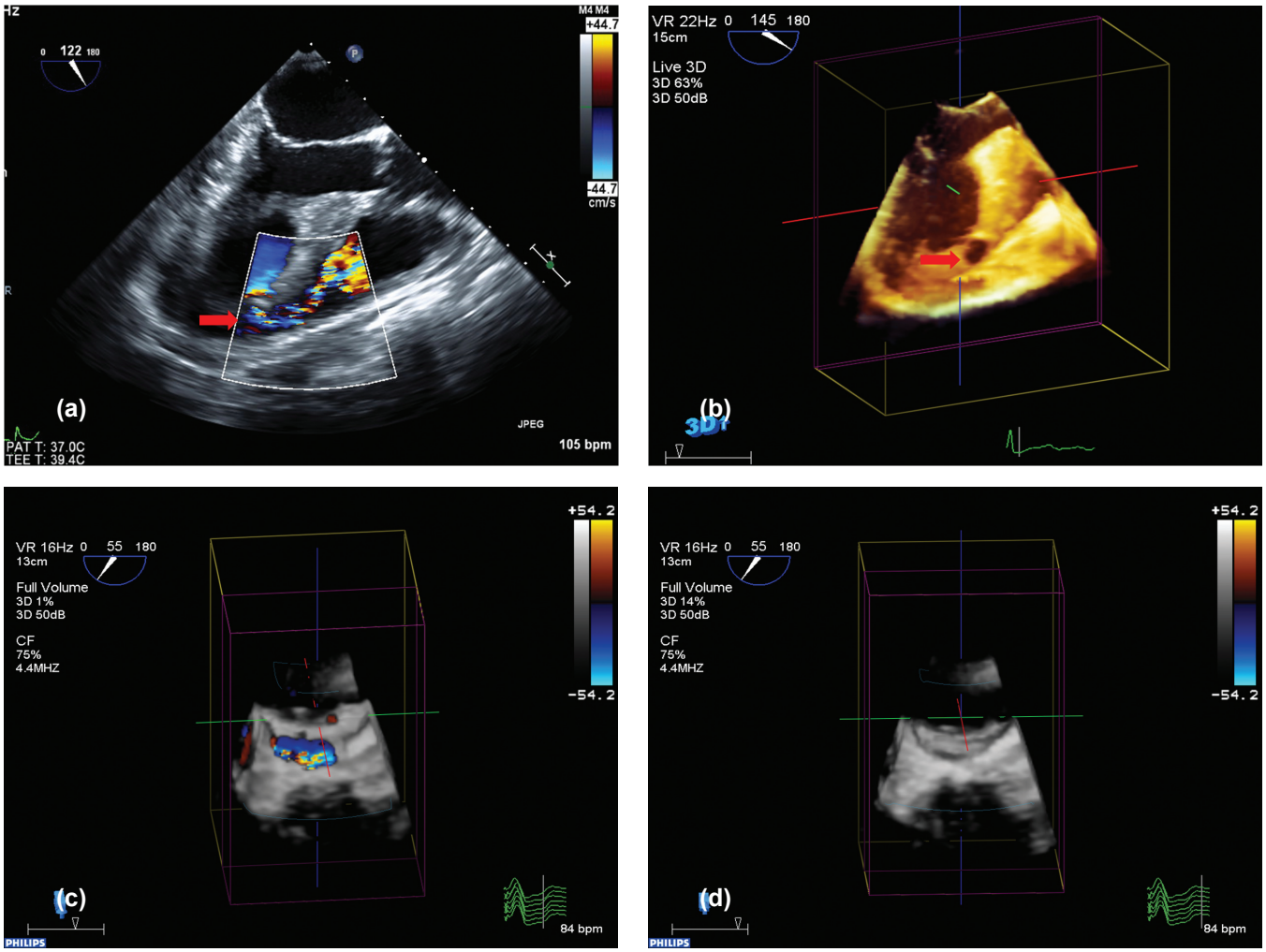

Figure 8. 3DE images of post-infarct VSD. **(a)** 2D-TEE image showing VSD with color flow (red arrow). **(b)** 3DE image showing size of VSD (red arrow). **(c)** 3DE image short axis showing color convergence through VSD. **(d)** 3DE image short axis showing size of VSD.

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