OPINION ARTICLE

Impact of Three-Dimensional Echocardiography

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BACKGROUND

The development of real-time three-dimensional echocardiography (3DE) in the past decade has been a truly remarkable advancement in cardiac imaging. 3D imaging enhances the visualization of heart valves and improves the quantification of cardiac chamber volumes, ejection fraction and ventricular mass. These measurements are more accurate than conventional 2D measurements, because 3DE eliminates the errors associated with foreshortening and geometric modeling. It also helps with the guidance of interventional procedures including closure of septal defects and paravalvular leaks as well as the percutaneous implantation of aortic and mitral valve devices.

The first 3D reconstructed images were obtained offline in the 1980's using sequential 2D acquisitions gated to respiration and electrocardiogram (ECG). This was a tedious, time-consuming approach prone to motion artifacts. In the 1990's, real-time volumetric imaging using transducers with piezoelectric crystal arrays capable of capturing pyramidal volumes instead of single-plane, fan-shaped sectors, were introduced (Figure 1 online version). However, the computational power required to analyze real-time 3D data was beyond what was available at the time resulting in suboptimal 3D image quality limiting the technique to research laboratories. Later, in the 2000's, fully sampled matrix-array transducers with larger numbers of piezoelectric elements and parallel processing were developed, resulting in real-time volumetric images of better quality. (1). In parallel, these transducers evolved to the point of being housed within the tip of a TEE probe.

3D TRANSTHORACIC AND TRANSESOPHAGEAL ECHOCARDIOGRAPHY

3DE transthoracic imaging is particularly useful to quantitate right and left ventricular volumes. 3D TEE is best used to image valves and guide procedures because it provides higher spatial resolution allowing detailed visualization of the mitral and aortic valve, interatrial septum and left atrial appendage. It also provides excellent views of bioprosthetic and mechanical valves including leaflets, rings and struts.

CARDIAC CHAMBERS

Volume and ejection fraction data is best assessed using full-volume datasets. To accomplish this, a full-volume pyramidal dataset of the structure of interest is typically obtained in which several sub-volumes acquired during consecutive cardiac cycles are 'stitched' together to create a representative cardiac cycle dataset (Figure 2).

Left ventricle

Using 3DE it is possible to obtain accurate information on left ventricular (LV) volumes and ejection fraction, as well as LV shape and regional and global strain. Quantification of LV volumes and function is essential for optimizing timing of surgery in patients with valvular heart disease. This information is also useful for decision-making with regard to defibrillator implantation and cardiac resynchronization therapy.

Left ventricular volume: Multiple studies have demonstrated that LV volumes derived from 3D TTE are more accurate than 2D values when compared to cardiac magnetic resonance (CMR), since they avoid geometric assumptions and minimize LV foreshortening. In addition, 3DE-derived LV volumes and ejection fraction are more reproducible than 2D measurements. There are three approaches to quantify LV volume and function from 3DE datasets (Figure 3):

1. ***3D-guided biplane technique:*** This approach is based on the selection of anatomically correct non-foreshortened 2D apical 4- and 2- chamber views from a pyramidal dataset using multi-planar reconstruction. The method of discs is then used to calculate LV volumes. (2). This methodology, however, still relies on geometric assumptions to calculate volumes and is likely to be inaccurate in ventricles with regional wall motion abnormalities.
2. ***Direct volume quantification:*** This approach is based on semi-automated detection of the LV endocardial surface, followed by calculation of the volume contained within this surface. This approach does not rely on geometric modeling and was found to be more accurate in the presence of distorted ventricular shapes.
3. ***Anatomic Intelligence:*** Based on automated

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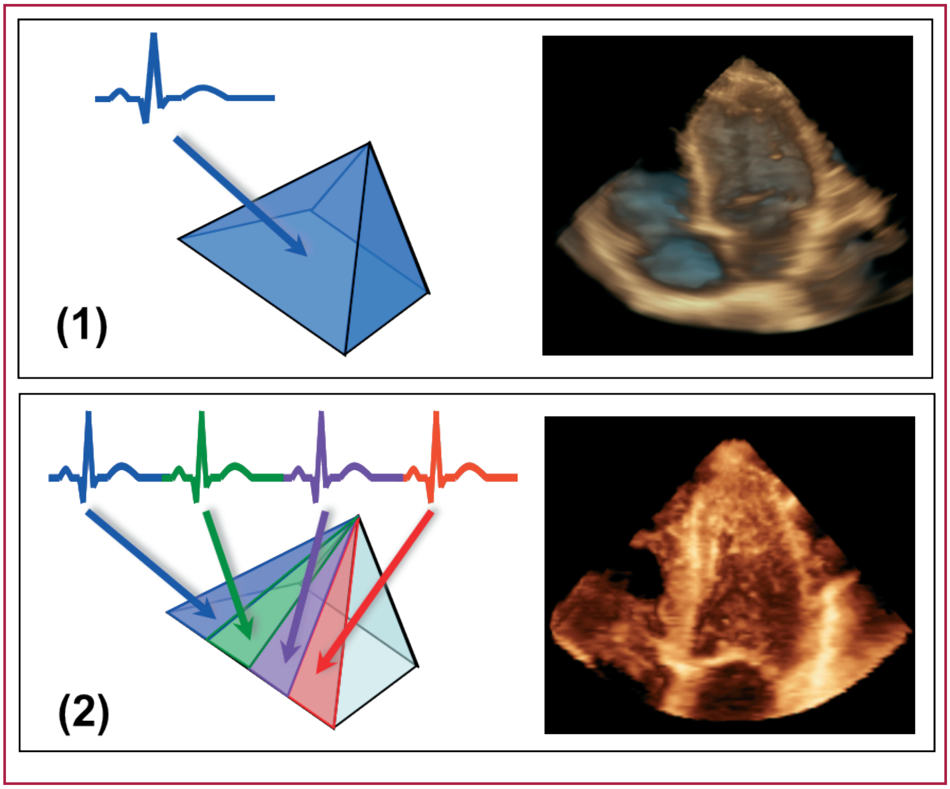

Fig. 2. Two currently available approaches to create a dynamic 3D image of the beating heart: (A) by "stitching" dynamic sub-volumes scanned during consecutive cardiac cycles, and (B) decreasing the number of cardiac phases to allow imaging of the entire heart in a single cardiac cycle. Approach (A) allows imaging at higher frame rates (higher temporal resolution), with the potential disadvantage of having "stitch artifacts" as a result of changes in the position of the heart relative to the transducer. Approach (B) avoids motion artifacts but suffers from intrinsically lower frame rates (lower temporal resolution). (Reproduced with permission from Mor-Avi V, Lang RM. Transthoracic Three-Dimensional Echocardiography.In Advanced Approaches in Echocardiography. Eds. L.D. Gillam and C.M. Otto, Elsevier, Philadelphia, 2012)

chamber identification and model determination. This method has the advantage of being completely automated while providing volume information of all cardiac chambers simultaneously

Studies have shown that LV volumes measured using these approaches are underestimated compared to CMR. This is because the spatial resolution of 3DE is not sufficiently high to enable differentiation between myocardial tissue and endocardial trabeculae. (3). Also, true end-systole may not be accurately captured because of low frame rates, leading to inaccurate end-systolic volume and ejection fraction measurements.

Left ventricular mass: LV mass is an important predictor of morbidity and mortality, particularly in patients with systemic hypertension. LV mass measurements rely not only on endocardial but also on epicardial visualization, which is even more challenging (Figure 4 online version). LV mass can be measured using either one of the approaches used to measure LV volumes from 3DE datasets: the 3D-guided biplane technique (4), volumetric analysis. (5) and anatomic intelligence. To obtain accurate LV mass measurements from 3DE datasets, the same guidelines for endocardial tracing as for LV volume measurements should be strictly followed to avoid underestimation of LV mass. Epicardial boundaries should be carefully initialized in multiple views. Recently, using semi-automated volumetric detection of endocardial and epicardial surfaces, LV mass was validated using CMR as the gold-standard. (6). Importantly, 3DE-derived LV mass measurements were more accurate, when compared with CMR, and more reproducible than conventional biplane 2D techniques.

Myocardial deformation: More recent developments include 3D strain measurements, which can be performed using 3D speckle tracking (7). Speckle tracking echocardiography is an off-line technique that tracks myocardial motion from frame to frame. It has been previously mostly applied to 2D echocardiographic images allowing quantitative evaluation of LV deformation. The main advantage of deformation indices over traditional wall motion assessment is that they are less affected by cardiac translation and are independent of the Doppler angle of incidence. Today, speckle tracking can be applied to 3DE datasets, which allows measurements of deformation parameters in 3D space. It has been recently shown that unlike 2D speckle tracking, which requires high frame rate acquisitions (>60 fps) in order to avoid loss of speckles due to speckle motion out of the imaging plane, 3D speckle tracking is less demanding in this regard (>18 fps). (8). This is because with 3DE, speckles remain within the scan volume irrespective of their direction throughout the cardiac cycle.

Right Ventricle

Right ventricular (RV) volumes and ejection fraction measurements are of prognostic importance in a variety of disease states, including right-sided congenital heart disease, pulmonary hypertension and heart failure. Estimation of RV volumes using geometric modeling from 2D images has been challenging due to the complex crescent shape of this chamber. There are two distinct approaches to quantify RV volume and

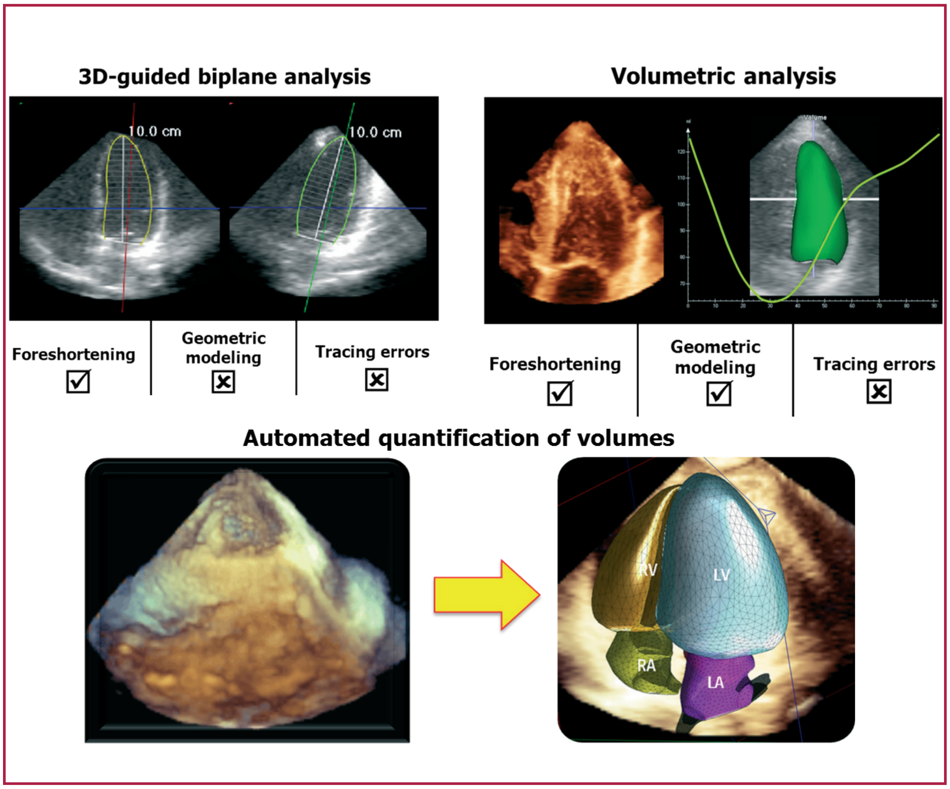

Fig. 3. Three approaches exist to quantify left ventricular volume from 3D datasets. The first uses 3D guided biplane analysis and can be done using Simpson's rule in two orthogonal planes (usually the 4- and 2-chamber images). The second uses semi-automated endocardial border detection and constructs a volume over time curve (green curve). The third uses a fully automated algorithm to quantify left atrial and ventricular volumes and ejection fractions. This software is currently in the testing and validating stages. The right heart has not been included in the algorithm yet. (Reproduced with permission from Mor-Avi V, Lang RM. Transthoracic Three-Dimensional Echocardiography. In Advanced Approaches in Echocardiography. Eds. L.D. Gillam and C.M. Otto, Elsevier, Philadelphia, 2012)Key: ☑ - resolved; ☒– remains unresolved.

function from 3DE datasets (Figure 5):

1. ***Disk summation or method of disks:*** With this approach, the operator traces the contour of the RV endocardial border in a stack of short axis views spanning the RV from base to apex, at end-systole and end-diastole. The software then computes end-systolic and end-diastolic volumes by summating the different slices.
2. ***Direct volume quantification:***This approach is based on semi-automated detection of the RV endocardial surface, followed by calculation of the volume contained within this surface. The operator works offline with end-diastolic and end-sys tolic frames in the sagital, four-chamber, and coronal views obtained from a full-volume 3DE dataset. This method has been validated using in-vitro models as well as in-vivo using CMR as the gold standard. (9). Routine clinical use of 3DE for this application is limited by the need for excellent quality transthoracic datasets.

Left atrium

Left atrial (LA) enlargement is a marker of long-term LA pressure elevation. It is associated with increased incidence of atrial fibrillation, ischemic stroke and poor cardiovascular outcomes, including increased risk of overall mortality in patients post MI and increased cardiac event rate in patients with severe LV dysfunction.

LA volume is incompletely characterized by 2D approaches, which are based on geometric assumptions. Acquisition of LA datasets for volume and function measurements can be made from the TTE apical four-chamber or TEE transgastric views. Similar to the left ventricle, LA boundaries can be identified in 3D space and LA endocardial surfaces reconstructed. Recently, LA volume measurements using 3DE have been validated against CMR, the current reference standard, and 3DE evaluation of LA volumes has been demonstrated to be superior to 2D measurements (Figure 6). (10). Volume measurements are preferred over linear dimensions because they allow accurate assessment of the asymmetric remodeling of the left atrium. Both the area-length and the biplane method of disks are dependent on the selection of the location and direction of the LA minor axis, and the ability to clearly visualize LA boundaries. With its independence of geometrical assumptions, 3DE imaging is ideally suited for LA volume measurements. Although there is clear evidence of the prognostic value of LA enlargement as assessed by 2D echocardiography, currently no such data exists for 3DE derived LA volumes.

The rapid development of cardiac electrophysiology has triggered renewed interest in the anatomy of atrial cavities and their target structures. Although fluoroscopy is routinely used to localize atrial anatomic landmarks during electrophysiology procedures, this technique is limited by its 2D projection of complex 3D structures. While multi-detector computed tomography is increasingly used to address this issue, it is associated with ionizing radiation. This area may therefore be one in which we may see more

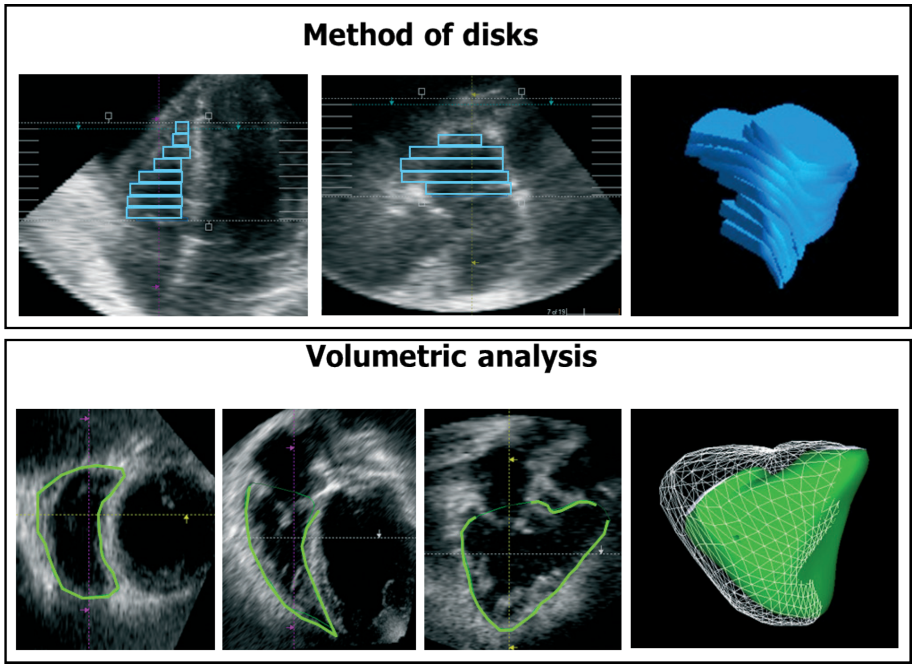

Fig. 5. Two approaches exist to quantify right ventricular volume from 3D datasets. The first uses the method of disks to stack multiple tracings of the RV boundaries in multiple short-axis views spanning the ventricle from base to apex (top). This is done for end-systolic and end-diastolic images to allow the calculation of RV ejection fraction. The second uses semi-automated RV endocardial surface detection (from RV boundaries manually initialized in 3 orthogonal views) and calculates RV volume confined within the detected surface (bottom). The surface is automatically tracked throughout the cardiac cycle, allowing the extraction of end-systolic and end-diastolic volumes for the calculation of ejection fraction.

applications for 3DE in the future.

CARDIAC VALVES

3DE has enabled real-time visualization of the pathomorphology of valvular and subvalvular anatomy from a single volumetric dataset, without the need for off-line reconstruction, resulting in an incremental role in evaluating valvular anatomy, pre-surgical planning, intra-procedural guidance, and post-procedural assessment of valvular heart disease. This is especially true in the case of 3D TEE imaging. The zoom mode is preferred for the assessment of valves, since it provides the highest temporal and spatial resolution, especially when performed over 4 beats. Figure 7 (online version) shows how 3DE datasets can be cropped to obtain optimal views of the four cardiac valves. Note that the tricuspid valve is best visualized from the transthoracic approach while all other valves are best visualized on TEE.

Mitral valve

The mitral valve (MV) can be imaged using a 3D TTE or 3D TEE approach. 3DE enhances measurement and assessment of a number of MV parameters, including shape and dynamics of the annulus (11-14), leaflets, coaptation line, as well as subvalvular geometry and inter-valvular relationships. 3DE is capable of volumetric characterization of the MV apparatus, and evaluation of the spatial relationships between its anatomic components, which has provided valuable insight into the pathophysiological mechanisms related to ischemic and degenerative disease. (15-17).

With improvements in image quality, commercial software has been developed to provide a method for objective quantification of MV changes. Using 3DE datasets, the mitral annulus and leaflets can be traced to create a 3D model of the MV (Figure 8, left). From these models, volumetric measurements of a variety of geometrical parameters of the mitral annulus and leaflets can be performed (Figure 8, middle and right). These dimensions have provided insight into the effects of various MV pathologies and may be useful for guiding repair procedures. (18-21).

Degenerative mitral valve disease: 3DE visualization of the mitral apparatus from the transgastric 2-chamber view enables visualization of papillary muscle pathology, including fibrosis, necrosis or chordal rupture. TEE is especially useful in the diagnosis of degenerative MV disease. Diagnostic accuracy of 3D TEE was compared to 2D TEE in a large number of patients undergoing repair for MV prolapse, in whom echocardiographic findings were compared to surgical findings. 3D TEE correctly identified prolapse in 92% of patients versus 78% using 2D TEE. (22-25). Billowing height and volume as measured by 3DE were the strongest predictors for the presence of degenerative mitral valve disease. (22). Mitral annular dimensions made with 3DE guidance have been shown to be accurate and reproducible compared with direct intraoperative measurements. (26). Although sizing of mitral annuloplasty rings is controversial, accurate sizing by 3DE can potentially help prevent post-operative systolic anterior motion (SAM). (27, 28). The propensity for developing post-mitral valve repair SAM is dependent, in part, on the degree of mitro-aortic and septo-aortic angles, presence of excess tissue, and displacement of the mitral coaptation line towards the posterior leaflet, all of which can be

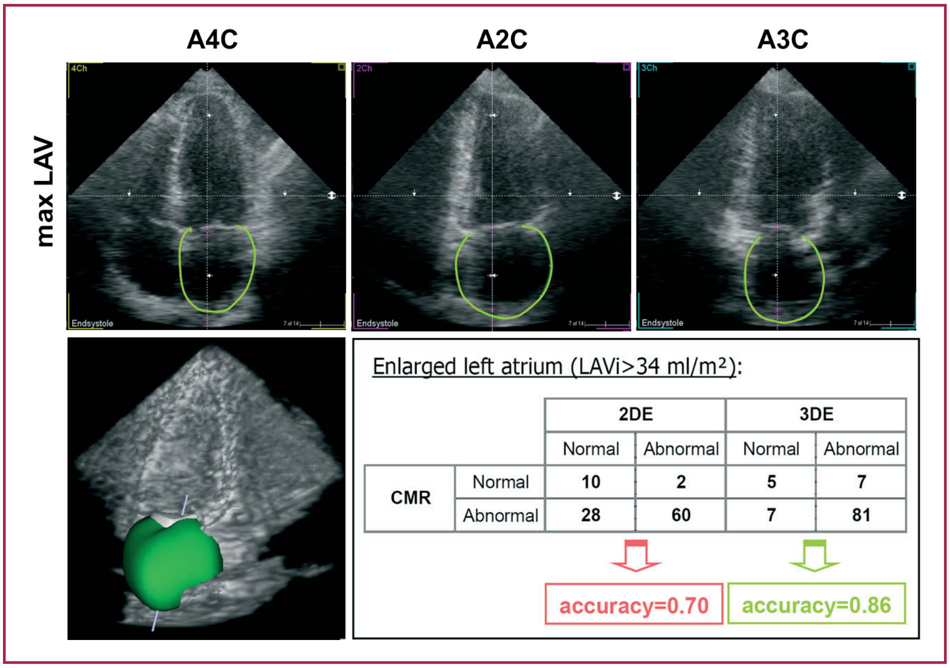

Fig. 6. After the left atrial cavity is manually traced at end-systole and end-diastole in 3 apical views extracted from the 3DE dataset (top), LA endocardial surface is reconstructed in three dimensions, allowing direct measurement of LA volume (bottom left). The measured volume is more concordant with volumes obtained by CMR, resulting in improved diagnosis of LA enlargement compared to 2DE (bottom right). (Modified with permission fromMor-Avi V, et al., J Am Coll Cardiol Imaging 2012; 5:769-77).

well characterized by 3DE. (27-30). By quantifying the extent of anterior and posterior leaflet length, surface area, and billowing volume before and after surgery, 3DE analysis helps identify patients who are most at risk for developing SAM.

Mitral regurgitation: Three-dimensional imaging techniques have shown that the regurgitant orifice is not circular (31) and that the shape varies among MV disorders. Functional mitral regurgitation, for instance, has been shown to have a more crescent shaped regurgitant orifice while degenerative MV disorders tend to have a more elliptical or circular shape. (32, 33). 3D assessment of mitral regurgitation(MR) allows more complete description of the effective regurgitant orifice area (EROA) by vena contract a area, proximal isovelocity surface area (PISA), and anatomical regurgitant surface area (AROA).

2D methods for EROA quantification require two assumptions: 1) the convergence zone is hemispherical, and 2) the regurgitant orifice is circular and centrally located (Figure 9). 3DE-based measurements have demonstrated that these assumptions are often inaccurate, and as a result, 2D EROA is often underestimated, especially in the case of eccentric jets. Today, direct tracing of radial planes of the PISA zone and reconstruction of the total surface area from 3DE datasets is possible, avoiding the need for geometric assumptions. 3DE derived vena contracta area was shown to correlate more closely with Doppler-derived EROA than with the 2D vena contracta diameter. Multiple studies have compared vena contracta area measurements by 3DE to various 2D quantitative parameters consistently finding superior accuracy and reproducibility with 3DE measurements. (34-36). Currently available software allows the direct tracing of the PISA convergence zone in multiple radial imaging planes with reconstructions of the total surface area, obviating the need for geometric assumptions. (37, 38)

An emerging method for MR quantification by 3DE is delineation of the AROA by volumetric "en-face" visualization of the MV orifice. The potential advantage of the AROA is that it directly measures the true anatomic orifice in three dimensions, taking into account the complex non-planar geometry of this orifice. (39, 40).AROA measurements demonstrated good correlation with 2D PISA-derived EROA in patients with central jets and single regurgitant orifices. However, in patients with multiple orifices or eccentric jets, the AROA was noted to be considerably larger, emphasizing the need for 3D AROA measurements. (39).

Current drawbacks of 3DE color flow include: (1) limited availability and the fact that this new technology requires specific skills not yet widely available; (2) full-volume color Doppler acquisition requires multiple cardiac cycles, which can be problematic in patients with arrhythmias; (3) currently, online quantification of the flow convergence zone, vena contracta or AROA must be done manually. Semi-automated methods of assessment are required for data analysis to be more efficient, user-friendly and less subjective; (4) the lower temporal resolution of 3D color Doppler might affect the adequate selection of the largest flow convergence region; (5) at the present time, there are no guidelines to assist in the 3D quantification of MR, nor is there a validated reference standard for comparison of 2D and 3D findings. Despite these obstacles, 3DE may in the future become a valuable tool for the assessment of MR.

Mitral stenosis: The spectrum of lesions in mitral stenosis (MS) include commissural fusion, leaflet thickening, chordal fusion, which lead to leaflet re-

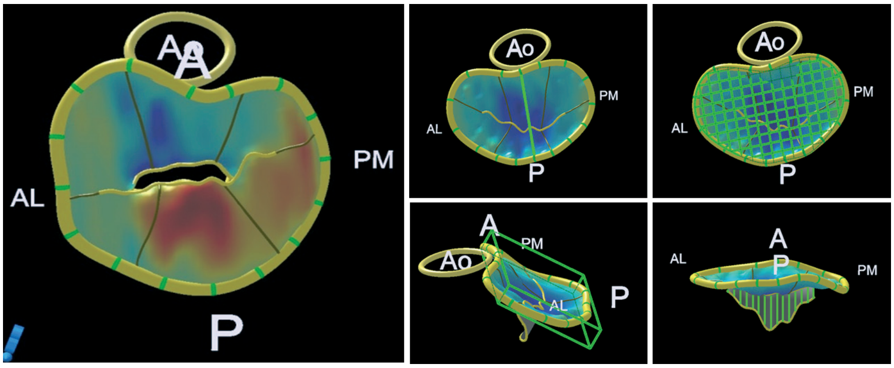

Fig. 8. Color-coded topographic map of mitral valve with prolapsing P2 scallop and billowing P3 scallop (left). Defect in coaptation line occurs at end-systole and corresponds to the anatomic regurgitant orifice area in this patient. A variety of geometrical parameters of the mitral valve can be measured, including: anterior-posterior diameter (top middle), annular height (bottom middle), surface area (top right), height of the coaptation line (bottom right), and others. Abbreviations: Ao – aorta, AL – anterolateral, PM – posteromedial, P – posterior.

striction, especially in systole. 3DE has many advantages over 2DE in examining mitral valve anatomy in MS. (41). With 3DE and its ability to visualize the MV from both the left atrial and ventricular perspective, the morphologic assessment of the MV is potentially more accurate.

To define the best therapeutic strategy, accurate measurements of the MV orifice area are required. Currently used methods to measure MV orifice area, such as 2D planimetry, pressure-half time and flow convergence are heavily influenced by hemodynamic variables, LV hypertrophy and associated valvular heart disease. Direct measurements of MV orifice area are believed to be more accurate. To date, this has been performed using 2D planimetry of the MV orifice area. This methodology is limited by the orientation of the measurement plane. 3DE allows visualization of the MV anatomy in any desired plane and orientation, improving the operator's ability to perform an accurate MV area 'en-face" planimetry (Figure 10 online version). These 3DE measurements are known to correlate strongly with measurements derived invasively using the Gorlin formula. (42-44).

Aortic valve

The aortic root is composed of the aortic valve with its three semilunar cusps, which form part of the sinuses of Valsalva, and the fibrous inter-leaflet triangles. About two thirds of the circumference of the lower part of the aortic root is connected to the septum,while the rest is connected to the mitral valve via a fibrous continuity, also known as the aorto-mitral curtain. The surgical definition of aortic annulus refers to the crown-like structure demarcated by the hinges of the aortic valve leaflets, while the imaging definition refers to the virtual or projected ring that connects the three most basal insertion points of the leaflets. It is now recognized that the aortic annulus is not circular, but rather elliptical in shape. (45). Normal reported adult aortic annular area using planimetry by 3DE is 4.0 ± 0.8 cm^2 (46).

On both TTE and TEE, a full-volume pyramidal dataset of the aortic root from the long axis view can be used to obtain an image of the aortic valve from which planimetry can be performed. This cut plane can be shifted to the LV outflow tract (LVOT), the sinus of Valsalva or the sinotubular junction to obtain cross-sectional areas. The cropping planes can also be placed perpendicular as well as parallel to the aortic annulus to assess supravalvular and subvalvular anatomy for serial stenosis (Figure 11 online version). Measurements of the aortic root obtained on 3DE show good correlation with measurements obtained using CT and MRI. (45-53). Also, compared to 2DE measurements, the 3DE measurements have been shown to be more reproducible. (54).

When compared to 2DE, the use of 3DE has been shown to accurately identify abnormal aortic leaflet morphology, especially bicuspid and quadricuspid aortic valves. (55-59).Also, 3DE has been proven useful for the assessment of leaflet masses such as Lambl's excrescences and aortic valve papillary fibroelastomas. (60-62). 3DE also provides information on the spatial relationship with surrounding structures such as the LVOT and mitral annulus (Figure 12 online version).

Aortic stenosis: The aortic valve orifice shape during systole may be stellate, circular, triangular or an intermediate form of these three variants. 3DE has improved the accuracy and reproducibility of the aortic stenosis severity quantification through 1) accurate LVOT area measurements, 2) the use of direct volumetric measurement of stroke volume and 3) direct planimetry of the aortic valve area (AVA). (55, 56, 63-70).

One of the most commonly used methods for the non-invasive determination of AVA is the continuity equation, which assumes that the LVOT area is circular. Analysis of 3DE images, however, has demonstrated that the LVOT cross-section is often elliptical. By assuming a circular shape, AVA may be underes-

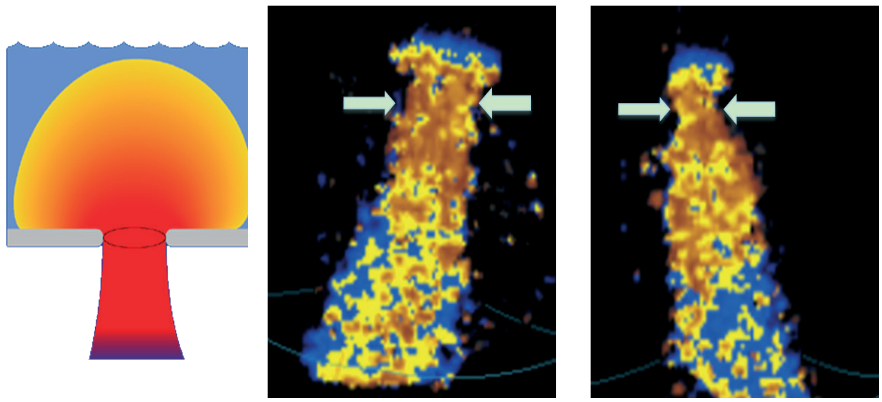

Fig. 9. Three approaches exist to quantify left ventricular volume from 3D datasets. The first uses 3D guided biplane analysis and can be done using Simpson's rule in two orthogonal planes (usually the 4- and 2-chamber images). The second uses semi-automated endocardial border detection and constructs a volume over time curve (green curve). The third uses a fully automated algorithm to quantify left atrial and ventricular volumes and ejection fractions. This software is currently in the testing and validating stages. The right heart has not been included in the algorithm yet. (Reproduced with permission from Mor-Avi V, Lang RM. Transthoracic Three-Dimensional Echocardiography. In Advanced Approaches in Echocardiography. Eds. L.D. Gillam and C.M. Otto, Elsevier, Philadelphia, 2012)Key: ☑ - resolved; ☒– remains unresolved.

timated. It has been shown that accuracy of the AVA calculated by the continuity equation is improved by substituting planimetered LVOT area measured from 3DE. (57-59, 71). Another approach to improve the assessment of aortic stenosis severity is based on direct volumetric measurements of stroke volume. (72-75). This method avoids the need to measure the LVOT, a major weakness of the continuity equation. 3DE was shown to have superior accuracy compared to the continuity equation and 2D methods in determining AVA. With this method, AVA is calculated by dividing 3D-derived stroke volume by the AV Doppler time-velocity integral. AVA determined by 3DE stroke volume was considerably more accurate compared to 2DE-derived areas. An alternative method for assessing AVA is direct planimetry from the 3DE datasets. (48-51). 3D TTE planimetered AVA has been reported to be feasible in 92% of patients, with measured values correlating well with 2D TEE planimetry, TTE-derived continuity values and invasively measured AVA. (49, 50, 61).

Aortic regurgitation: 3DE has been used to improve the quantification of aortic regurgitation. Similar to mitral regurgitation, the vena contracta is a surrogate for EROA, and thus is a good indicator of aortic regurgitation severity. Quantification of the vena contracta using 2D color Doppler images, however, is based on frequently incorrect geometric assumptions, since the shape of regurgitant orifices can vary. Three-dimensional methods, which reconstruct the vena contracta region allowing measurement of the cross-sectional area, have been shown to be more accurate. (53, 76, 77). Other 3DE methods for improving the assessment of aortic regurgitation have yet to be further validated (Table 1).

Tricuspid valve

The utility of 3DE in the evaluation of tricuspid valve (TV) disease is just beginning to be explored. Normal tricuspid annulus area is approximately 8-12 cm^2 and is about 20% larger than the corresponding mitral annulus area. Using 3DE, the tricuspid annulus has been shown to be non-planar, with an elliptical saddle-shaped pattern. (65-67). It is less non-planar than the mitral valve with a wider angle of 170°. (78). A recent study found that 3DE measurements of the tricuspid annulus are comparable to those obtained from CMR images. (79). This may have important implications in planning tricuspid valve surgery.

Acquisition of the TV is better performed on TTE than TEE because the TV is an anterior structure. 3D TTE of the TV is possible in 90- 95% of patients. (80, 81).Three-dimensional TTE acquisitions for visualization of the TV can be made from the apical four-chamber and the parasternal long-axis RV inflow views. Using the zoom mode in the apical or RV inflow view, the TV can be visualized from either the right atrial or the RV perspective (Figure 13 online version).

Tricuspid regurgitation: 3DE has enhanced the understanding of leaflet morphology and pathophysiologic mechanisms underlying tricuspid regurgitation. Quantification of tricuspid regurgitation using

3DE color Doppler is feasible, and 3D measurements of the vena contracta have demonstrated good correlation with 2D methods. (82-84). With 3DE, planes parallel to the tricuspid orifice can be obtained and the entire vena contracta appreciated. Similar to vena contracta studies in mitral regurgitation, this has led to the recognition that the vena contracta in tricuspid regurgitation is not circular but elliptical. (84).

3DE of the TV has been shown to provide mechanistic insights into tricuspid regurgitation in patients with pulmonary hypertension, congenital heart disease and implanted device-leads. (85, 86).In the case of Ebstein's anomaly, 3DE allows visualization of the tricuspid leaflet morphology as well as the level of leaflet attachment and coaptation, sub-chordal anatomy, and quantification of regurgitant jets, which is valuable for surgical planning. (56, 87-89). In secondary or functional TR, the use of 3DE has provided insights into the geometrical changes of the tricuspid annulus. As TR progresses, the annulus becomes more dilated, planar and circular. (65, 66). The resultant circular tricuspid annular shape stems from greater enlargement of the antero-posterior dimensions compared to the medio-lateral dimensions. The annulus also flattens, pulling its low points away from the papillary muscles, increasing tethering. 3DE has also improved our assessment of TR in the presence of pacemaker leads. The success rate of identifying the position of the leads as they traverse the TV was only 17% on 2D TTE versus 90-94% with 3D-TTE (85) (Figure 14). 3DE can also play an important role in traumatic TR. (90-92). Due to its anterior position immediately behind the sternum, the TV is the valve most commonly injured in blunt chest trauma.

Tricuspid stenosis: The main advantage of 3DE stems from its ability to image the three TV leaflets simultaneously from the right atrial or ventricular perspectives. Each leaflet can be assessed with regards to thickness, mobility, calcification and its relationship to other leaflets. The en-face view available on 3DE also allows accurate planimetry of the TV area, which correlates well with trans-tricuspidal pressure gradients. (93).

Pulmonary valve

The pulmonary valve (PV) lies within the pulmonary root, which is composed of the valvular leaflets, the sinuses of Valsalva, the inter-leaflet triangles and the free-standing distal right ventricular muscular infundibulum. (94). PV morphology was discernable in 60% of consecutive patients using 3D-TTE. (95).Currently there is insufficient evidence to support routine use of 3D TTE or TEE in the evaluation of pulmonary valves (Table 1).

Prosthetic valves

3DE imaging is suitable for the clinical evaluation of prosthetic mitral, aortic, tricuspid valves, and annular rings, and is, in many circumstances, superior to 2DE imaging. (96, 97). In most cases, 3DE is able to clearly delineate the multiple components of both mechanical and bioprosthetic valves and avoid the challenges of acoustic shadowing. This was shown in a study, in which 40 patients with normally functioning prosthetic valves or mitral valve repair were examined with 3DE to assess the imaging quality versus 2DE. (96) This study demonstrated that, in normal mitral mechanical and bioprosthetic valves, the rings, leaflets and struts could be clearly visualized using 3DE from both the left atrial and LV perspective (Figure 15 online version). In contrast, shadowing artifact from the prosthesis consistently prevented the ability of 2DE to visualize the valve from the left ventricle. For patients who have undergone mitral valve repair, the annuloplasty ring and the anterior leaflet can be visualized optimally in 100% and 60% of cases, respectively. (96, 98). The posterior leaflet was only optimally visualized in 40% of patients.

3DE is particularly helpful when there is a clinical suspicion of infective endocarditis in patients with prosthetic mitral valves. (97). With the ability to manipulate and crop images in multiple planes, 3DE provides a comprehensive anatomical assessment of the entire valve lessening the chance that small vegetations might be missed and allowing for superior differentiation between vegetation and suture material. The en-face view of the prosthetic valve is particularly useful in evaluating for endocarditis as it allows the identification of valve dehiscence and associated paravalvular leaks. It must be noted, however, that due to frame rate limitations on 3DE, 2DE remains superior for the identification of small mobile vegetations.

In prosthetic mitral valve dehiscence, 3DE provides incremental information regarding the size of the dehisced area and the relationship between the dehiscence, the paravalvular regurgitation jet, and the adjacent cardiac structures (99) (Figure 16 online version). With the help of 3DE, it has been observed that most types of mitral valve dehiscence are located posteriorly and/or laterally. (100). Proper suturing in this area might be lacking because of the location of the posterior annulus in the surgical far field and its relationship with the left circumflex artery.

Aortic mechanical and bioprosthetic valve leaflets are poorly visualized in general. However the prosthetic ring is usually well seen from both the LVOT and aortic perspectives. Similarly, tricuspid prosthetic valve leaflets are usually poorly visualized, but the ring is adequately seen.

Use of 3DE in the guidance of interventional procedures

Traditionally, guidance of catheter-based procedures is done using fluoroscopy. This type of imaging, however, has limited contrast resolution to allow differentiation between soft tissues and involves significant radiation exposure. 3DE significantly aides in the guidance of intracardiac interventions especially transcatheter closure of atrial septal defects (Figure

Table 1. Indications for 3D echocardiography

Characteristics	Recommended for Clinical Practice	Areas of Active Research	Unstudied
Left ventricle assessment			
Volume	x		
Shape		x	
Ejection fraction	x		
Dyssynchrony		x	
Mass		x	
Right ventricle assessment			
Volume		x	
Shape			x
Ejection fraction		x	
Left atrial assessment			
Volume		x	
Right atrial assessment			
Volume			x
Mitral valve assessment			
Anatomy	x		
Stenosis	x		
Regurgitation		x	
Tricuspid valve assessment			
Anatomy			x
Stenosis			x
Regurgitation			x
Pulmonary valve assessment			
Anatomy			x
Stenosis			x
Regurgitation			x
Aortic valve assessment			
Anatomy		x	
Stenosis		x	
Regurgitation			x
Infective endocarditis			x
Prosthetic valves		x	
Guidance of transcatheter procedures	x		

Modified from Lang RM, et al., J Am Soc Echocardiogr 2012; 25:3-46

17 online version), placement of the novel left atrial appendage occluder devices, percutaneous mitral balloon valvuloplasty, transcatheter aortic valve implantation (TAVI) as well as guidance and closure of paravalvular leaks.

Balloon mitral valvuloplasty: Percutaneous mitral valvuloplasty(PBMV) is commonly performed in patients with significant mitral stenosis and suitable anatomy. Traditionally, it is performed with fluoroscopic guidance alone; however, orientation using radiographic anatomic landmarks is often challenging, even for experienced interventional cardiologists. 3D imaging allows excellent visualization of the valve and catheters involved in balloon valvuloplasty. (101). Using 3DE, the inter-atrial septum is usually viewed from the right atrium with the superior vena cava and the inferior vena cava at the 12 and 6 o'clock positions. This view shows the catheter as it is advanced into the right atrium and thus aides with positioning the catheter at the site of the inter-atrial septal puncture. 3DE can then be used to optimize the position of the balloon between the mitral valve leaflet tips to ensure a controlled commissural tear. Post-procedure views from the left atrial and left ventricular perspectives allow close inspection of the commissures for successful splitting and for any resultant leaflet tears. In addition, 3DE provides an accurate quantification of any procedure-related MR.

Percutaneous aortic valve replacement: Percutaneous aortic valve replacement is quickly gaining popularity as a less invasive and effective option for valve replacement in selected patients. In addition to fluoroscopy, 2D and 3D TEE allow accurate and reproducible assessments of the LVOT and aortic annulus dimensions, which are important in prosthetic valve size selection. This is because an undersized device

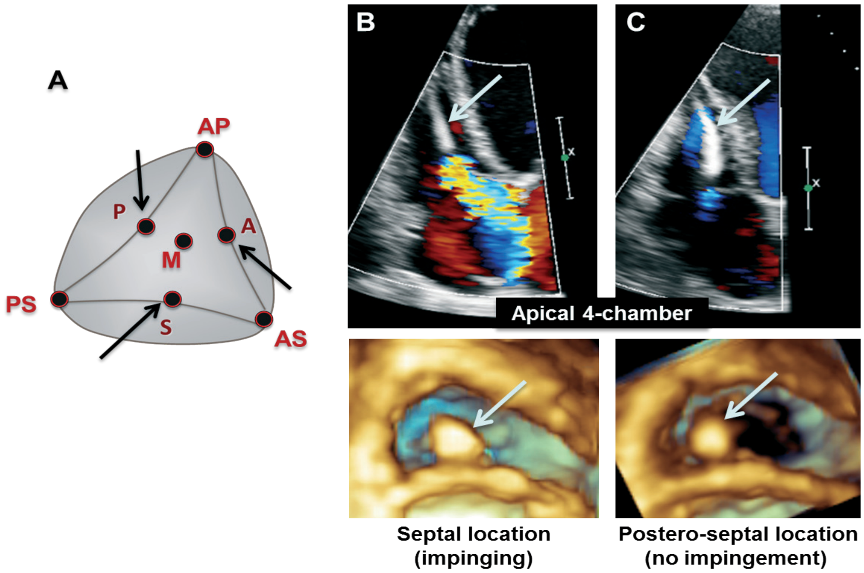

Fig. 14. A: Possible locations for device-leads as they cross the tricuspid valve leaflets. Device-leads positioned against a leaflet (arrows) impinge leaflet mobility while those positioned in a commissure (AP, antero-posterior commissure; AS, anteroseptal commissure; PS, postero-septal commissure) or in the center of the valve (middle or "M" position) are not associated with leaflet impingement. B: Top and bottom images illustrate a device-lead causing impingement of the septal leaflet (bottom, 3D image taken from the right ventricular perspective) with resultant severe tricuspid regurgitation (top). C: Top and bottom images illustrate a device-lead in the postero-septal commissure without leaflet impingement (bottom, 3D image taken from the right ventricular perspective) with resultant trace tricuspid regurgitation (top)

may result in a paravalvular leak or even detachment or embolization of the prosthesis, while an oversized device may result in damage or rupture of the aortic annulus. 3DE can also measure the distance between the annulus and leaflet tips to the coronary ostia which is crucial for optimal placement of prosthetic valves without interfering with the coronary circulation.

During the procedure, 3D TEE helps guide the catheter and the prosthetic valve into an optimal position. The exact spatial orientation of the device is crucial, as the valve and the catheter should be aligned coaxially in the LVOT. Advancing the device too far into the aorta may result in occlusion of the coronary ostia, while retraction toward the LVOT may interfere with the motion of the anterior mitral leaflet resulting in mitral regurgitation. (102). Post-procedure, 3D TEE is useful in evaluating the results and identifying potential complications including paravalvular and transvalvular regurgitation, new wall motion abnormalities, mitral regurgitation, damage to the aortic annulus, aortic dissection, pericardial effusion, and cardiac tamponade.

Paravalvular leaks: An estimated 10-15% of prosthetic aortic or mitral valves have some degree of paravalvular regurgitation. The role of 3D TEE in the detection and evaluation of aortic or mitral paravalvular regurgitation is in: 1) evaluating the size and location of the paravalvular regurgitation; 2) guidance during percutaneous closure procedures, and 3) post-interventional assessment. Diagnosis of paravavular regurgitation is primarily performed using echocardiography: the 3DE en-face view of the mitral/aortic valve improves identification of dehiscence sites, while simultaneously providing information on their location, shape, size, and number. (96, 103). Once these sites are identified, multi-planar imaging can be used to quantify the dimensions of the area of dehiscence (Figure 18 online version), while 3D color flow images confirm the presence of paravalvular blood flow. If the percutaneous method for repair is chosen, 3D TEE plays an important role in guidance and planning. The major advantage of 3DE imaging in this procedure is its ability to visualize the entire length of intracardiac catheters, as well as balloons or devices attached to the catheters and their position in relation to adjacent cardiac structures. (104, 105). 3DE imaging also allows continuous assessment of the prosthesis' function before, during and after the procedure. In addition, post-procedure, 3DE imaging can assess the location of the occluder device. Lastly, complications from the procedure, such as the creation of new paravalvular leakage sites caused by stretching of the suture line during device deployment, can be assessed.

SUMMARY

Over the past decade, three-dimensional echocardiography has gone through a tremendous technological evolution. The first major milestone was the development of matrix-array transthoracic transduc-

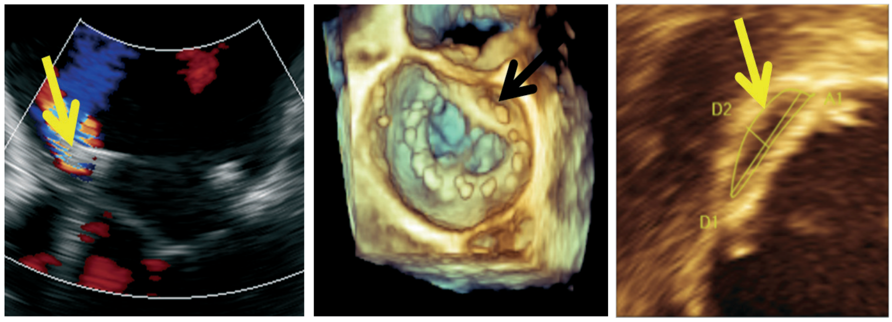

Fig. 18. This illustrates a patient with a paravalvular leak at the edge of a recently placed mitral annuloplasty ring: color Doppler image (top left), 2D TEE. On bottom left the hole is visible alongside the annuloplasty ring. Parametric offline analysis of the 3D dataset (right panels) allows measurement of the paravalvular leak dimensions. In this case the leak was very small and likely did not explain the patients' symptoms of congestive heart failure. Decision was made to repair the leak with percutaneous procedure as it was not likely to improve in the future.

ers, which replaced tedious and time-consuming 3D reconstruction from multiple consecutively acquired imaging planes, and resulted in near real-time volume datasets. Another, more recent major milestone was the development of a fully-sampled real-time 3D TEE probe, which over only the last five years has become widely used clinically. A major advantage of this technology includes consistent excellent image quality irrespective of patient's body habitus, ease of use, and the visually striking, easy-to-interpret images that provide new clinical information. In addition, the rapid emergence of percutaneous procedures for the treatment of structural heart disease, such as mitral valve repair and closure of perivalvular leaks, showed that the success of these procedures relies heavily on 3D TEE guidance. Table 1 illustrates areas of active research and areas which have not been explored yet.

We anticipate that in the future, further miniaturization of the 3D TEE probes could allow this methodology to be expanded to include young pediatric patients. This could have an impact on the outcome of complex intracardiac repairs in these patients. Furthermore, optimization of contrast-enhanced 3D imaging would make this technology useful in "technically" difficult patients and also for 3D stress testing. Development of 3D vascular probes with higher imaging frequencies would improve on the current diagnostic capabilities of atherosclerotic carotid disease, because it would allow easier evaluation of disease burden. All these future developments will strengthen the foundations of 3DE imaging and further enhance and expand its clinical utility into new territories.

Conflicts of interest

None declared.

REFERENCES

See web edition.