Assessment of aortic valve complex by three-dimensional echocardiography: a framework for its effective application in clinical practice

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Received 17 February 2012; revised 14 March 2012; accepted after revision 15 March 2012; online publish-ahead-of-print 19 April 2012

In the current era of expanding catheter-based and complex repair procedures to treat aortic valve (AV) diseases, growing consideration is being given to understanding the functional anatomy of the AV complex. Echocardiography is the primary imaging modality to assess and follow-up AV diseases, and the recent three-dimensional (3D) capabilities allow clinicians to appreciate the functional complexity of the aortic root in the beating heart. Despite being subject to several limitations, 3D echocardiography (3DE) holds promise as a more suitable imaging backup for aortic interventions of mounting complexity and for circumventing some of their current complications. In this review, we discuss the key principles of 3DE for assessing the AV pathology and the incremental clinical benefits in comparison with conventional 2DE and Doppler echocardiography, justifying its implementation in the diagnostic workup of aortic diseases. In view of an effective clinical use, a brief section is dedicated to the acquisition modalities, display, and interpretation of various abnormalities by 3DE.

Keywords
Aortic valve • Aorta • Three-dimensional echocardiography • Transthoracic • Transoesophageal • Aortic stenosis • Aortic regurgitation • Bicuspid • Tricuspid • Congenital • TAVI

Introduction
The anatomy and function of the aortic valve (AV) have triggered scientific curiosity early since the sixteenth century, when Leonardo da Vinci became fascinated by the three-cusped shape of the AV as the nature’s perfect example of optimal valve efficiency.1 Five centuries of scientific and technological progress allow us today to appreciate the complexity of the AV and aortic root in the beating heart. The role of non-invasive imaging and, in particular, of echocardiography has been pivotal in reaching these achievements. Nevertheless, in the current era of expanding catheter-based and complex repair procedures to treat AV disease, the expectations from advanced imaging modalities for a precise characterization of AV functional anatomy become progressively more challenging.

Two-dimensional echocardiography (2DE) and Doppler imaging have substantially improved our understanding of the AV interrelation with aortic root in the so-called AV complex. However, the inherent tomographic nature of 2DE and the impossibility to appreciate the 3D geometry of the AV complex as a whole make this technique insufficient at present for guiding the aortic root interventions of mounting complexity. The stereoscopic geometry of the AV complex and its real-time dynamics can be more easily assessed and interpreted using 3D echocardiography (3DE) (Figure 1; Supplementary data online, Video S1). Da Vinci himself utilized a 3D glass model to understand the mechanism of AV cusp closure by the vortices-forming blood in the Valsalva sinuses.1 Dynamic 3D imaging is mandatory for the assessment and quantitation of the spatial and functional relationship among the components of the AV complex. With the advent of transoesophageal 3DE (3D TEE), we are finally able to obtain 3D images of the AV in motion of unprecedented quality. Unlimited perspectives of the AV with no more erroneous geometric assumptions will definitely improve the diagnostic workup of AV pathology by ultrasound.2 Moreover, a better understanding of the interindividual anatomic variants of the AV complex could lead to additional refinements in the current designs of aortic prostheses.

This review describes the additional diagnostic value of 3DE in comparison with conventional 2DE and Doppler imaging for assessing the AV anatomy and function and includes a brief section dedicated to the acquisition and post-processing modalities used to obtain AV images by 3DE.
Examination of the AV and root morphology by 3DE

Normal anatomy and structure of the aortic root

The normal AV is more complex than just its three semilunar cusps may suggest. The aortic root, comprising the Valsalva sinuses and the fibrous interleaflet triangles, provides support for AV leaflets (Figure 1). The AV is attached peripherally at the distal boundary of the aortic root, called the sino-tubular junction. Therefore, both the Valsalva sinuses and the sino-tubular junction are an integral part of the AV mechanism, so any significant dilatation of these structures will result in AV dysfunction. By virtue of its central location in the heart, the aortic root has a complex relationship with the cardiac chambers and valves. The aortic root lies to the right and posterior to the subpulmonary infundibulum. Approximately one-third of the ventriculo-anatomic junction (in correspondence to the non-coronary and left AV cusps) is connected to the anterior mitral leaflet via the fibrous continuity (aortic-mitral curtain) (Figure 2; Supplementary data online, Video S2), whereas the remaining two-thirds of its circumference are muscular and correspond to the interventricular septum.

The 3D spatial configuration of the AV cusps resembles a crown (Figure 1). The cusps are thicker towards their free margin, and the semilunar hingelines at the insertion in the aortic root wall are noticeable as prominent ridges. The basal attachments of the aortic cusps extend within the left ventricle (LV), below the anatomic ventriculo-aortic junction. Hence, the true anatomic aortic annulus is not actually the ring projected at the most basal leaflet insertion—as usually defined and measured with various imaging techniques—but a crown-like 3D structure. For these reasons, the term ‘aortic annulus’ was deemed inappropriate by anatomists. The size of aortic annulus and root is influenced by inner pressure and is dynamically changing during cardiac cycle by 12 and 16%, respectively, and this is relevant for matching among various sizing approaches.

Transthoracic 3DE

In general, obtaining an adequate 3D imaging of the AV from the transthoracic approach is deemed to be more challenging than of the mitral valve; therefore, the recent 3DE literature has focused mostly on the latter. However, the feasibility and the image...
**Figure 2** Spatial relationship of the aortic root with the atrio-ventricular valves. (A) Anatomic specimen showing the base of the heart from above and the anterior position of the aortic root relative to the mitral and tricuspid annulus (courtesy of Professor Cristina Basso, Cardiovascular Pathology, University of Padua, Italy). (B) 3D volume-rendering of the same anatomic structures by transthoracic 3DE, the cropping plane crossing the atria and aortic root (‘surgical view’) (Supplementary data online, Video S2). The 3D data set needs to be rotated in various ways in order to optimally visualize each structure. In this case, the 3D cropping plane is adjusted for the best delineation of the mitral-aortic continuity, whereas the tricuspid leaflets are less well visualized, being oblique and deeper with respect to the mitral valve. LAA, left atrial appendage.

**Figure 3** Acquisition modalities for imaging the AV by transthoracic 3DE. A pyramidal volume containing the aortic root is acquired from parasternal (A) and apical (C) windows, and the corresponding 3D valve renderings are shown (B and D; Supplementary data online, Videos S3 and S2, respectively). Note the higher spatial resolution of the AV structure from the parasternal approach in comparison with the apical approach. AML, anterior leaflet; PML, posterior mitral leaflet; ATL, anterior leaflet; PTL, posterior leaflet; STL, septal tricuspid leaflet; L, left cusp; NC, non-coronary cusp; R, right aortic cusp; LA, left atrium; PV, pulmonary valve; TV, tricuspid valve.
quality of AV rendering by transthoracic 3DE have greatly improved with the cutting-edge technological advances seen with the newer 3DE equipments, which now render a TEE study avoidable in a significant proportion of patients.

The common approaches for AV imaging by transthoracic 3DE are from parasternal and/or from apical approaches (Figure 3; Supplementary data online, Video S2 and S3). As a rule of thumb, the best acoustic window in each patient is usually chosen. For morphological assessment, the acquisitions can be done as ECG-gated (‘stitched’ volumes), real-time, or real-time zoomed 3D images. For assessing regurgitant jets and cusp integrity, colour 3D data can be added as adjunct to 3D morphology and should be integrated with colour Doppler information provided by 2DE.

The smaller AV size allows for higher temporal resolution to be achieved (e.g. up to 60 volumes per second with narrow-angle, 6-beat acquisition) in comparison with mitral valve imaging. During acquisition, it is advisable to set the gain/compression in the mid-range, with a slightly higher time gain/compression setting; this is because there are limits to how much gain and/or compression can be added or removed after the 3D acquisition has been completed. As with 2DE, optimizing the image with the best lateral–axial resolution and respiratory manoeuvres remains equally important during 3DE acquisition.

Once a 3DE data set is acquired, there are multiple display options to review the information. 3D volumes containing aortic root can be cropped and rotated for an anatomically sound, dynamic 3D rendering of AV, which can be visualized from both aortic and ventricular perspectives (Figure 4; Supplementary data online, Video S3 and S4), as well as from any desired longitudinal or oblique plane. The aortic aspect of the AV is best suited for assessing valve morphology, although the ventricular aspect may delineate aortic tumours/vegetations or subvalvular obstructions more adequately. Conversely, by transthoracic 2DE, the AV can be visualized only as seen from the LV. The circular- or triangular-shaped opening orifice in systole is important to discriminate a normal (i.e. tricuspid) AV from its congenital variants (uni-, bi-, and quadric-cuspid AV), typically showing characteristic opening orifices.

Pitfalls of 2DE

When using 2DE, a parallel alignment of the tomographic plane to the AV orifice is sometimes impossible to obtain in short-axis views, especially in the setting of an enlarged ascending aorta (Figure 5; Supplementary data online, Videos S5 and S6) or horizontalized hearts. In addition, the through-plane motion of the aortic annulus due to the active longitudinal excursion of LV base may hamper an adequate visualization of AV morphology continuously.
throughout the cardiac cycle (Figure 6; Supplementary data online, Video S3). By 3DE, the proper alignment to the aortic annulus has no restrictions, irrespective of the actual spatial orientation of the aortic root. Moreover, the third dimension (i.e. depth) of the AV short axis overcomes the problems of through-plane motion and allows a full visualization of the AV by 3DE in both systole and diastole.

The ‘correct’ 2D longitudinal plane of the AV from the parasternal approach is usually considered the view showing most symmetrical Valsalva sinuses and cusps with a central closure line, and by assuming a circular LV outflow (LVOT) shape, with the largest LVOT diameter. Even if these precautions are carefully applied, significant errors can result even with experienced hands, particularly in the setting of morphological/geometric changes of AV or asymmetrical root dilation. Owing to the lack of anatomical landmarks, the correct cut-plane position cannot be reliably verified from a single-plane 2D view of the AV. For this reason, the left and the non-coronary cusp cannot be reliably differentiated from the parasternal longitudinal view of AV, since the cut plane may cross the right cusp and either of the two, at similar LVOT diameters. 3DE enables multi-plane imaging of AV (e.g. simultaneous display of the AV in both long and short axis); therefore, the uncertainties about the visualized structures in one view can be rapidly solved by real-time-checking the cut-plane position in the orthogonal view.

As opposed to 2DE, 3DE from the apical approach allows the en face visualization of AV even when the parasternal approach is inadequate. Even though the AV is located farther from the transducer in apical images and the spatial resolution is lower, an accurate diagnosis of AV morphology (number of cusps and mobility, opening orifice, regurgitant orifice, etc.) and LVOT geometry is frequently possible.

**Transoesophageal 3DE**

A proper visualization of AV can be at times difficult by transthoracic 3DE, particularly in normal AV (having very thin cusps that...
cause dropouts of the leaflet bodies with regular thresholding) or in heavily calcified AV, or when the acoustic window is suboptimal. 3D TEE from upper oesophageal views provides superior spatial resolution and image quality for AV assessment and it is the method of choice when a definite diagnosis cannot be made by transthoracic 3DE.

By rotating the 3D data set and visualizing AV from different angles, important information on the spatial relationship of AV with surrounding structures can be readily obtained, without the need of mental reconstruction from multiple 2D views. The 3D volumetric acquisition of aortic and atrio-ventricular plane (Figure 2; Supplementary data online, Video S2) enables the study of the reciprocal changes in the in vivo shape and position of the mitral valve and AV.9 Hence, 3DE can provide insights into the intervalvular functional coupling and may actually change our way of artificially interpreting the function of valves separately from each other.

**Congenital AV abnormalities**

Congenital abnormalities of the AV include the bicuspid valve, and rarely the uni- or quadricuspid valve (Figure 7). A reliable assessment of AV morphology is crucial, since bicuspid AV is the most frequent cause of aortic stenosis (AS) and/or regurgitation in young adults and the most prevalent congenital abnormality.10 More frequently, the two cusps are unequal in size, the larger having a central raphe resulting from the fusion of the commissure between two cusps (Figure 7C). Rarely, the leaflets are symmetrical and no raphe is present (‘pure’ bicuspid valve, Figure 7B). The 3D AV rendering in motion allows discrimination between a tricuspid valve and a bicuspid valve with a raphe that mimics a commissure, the latter showing a fish-mouth opening. By 3DE, false-positive diagnosis of bicuspid AV may arise from incomplete demonstration of all three-valve closure lines due to inadequate AV cross-section.

Precise description of AV morphology (bicuspid vs. tricuspid) is important also to guide patient management [e.g. indication for transcatheter aortic valve implantation (TAVI) or surgical replacement of ascending aorta, screening of family members, etc.] and to schedule follow-up examinations or to plan surgical AV repair techniques. Various spatial morphologies of the fused cusps—right and non-coronary cusps, right and left cusps—have different outcomes: the former seems to be associated with a more rapid progression of AV stenosis/regurgitation, whereas the latter with a higher incidence of aortic wall degeneration and of aortic coarctation.11 By its ability to display the en face view of AV from the aorta (best displaying AV leaflet margins and commissures), trans-thoracic 3DE may obviate the need for an uncomfortable and invasive (although minimally) TEE study. However, diagnosis can be difficult in calcified bicuspid valves from the transthoracic approach. Although transthoracic 3DE for assessing AV morphology has been validated against surgical findings 12 and preliminary reports are promising,13,14 evidence from clinical studies is needed to ascertain if the superiority of transthoracic 3DE vs. 2DE may improve the diagnostic yield in AV pathology. By its outstanding image quality, 3D TEE is particularly suited for an optimal delineation in great detail of the congenital morphological abnormalities of the AV.15 3D TEE has been validated against anatomic examination of autopsy specimens, demonstrating a reliable morphological characterization of bicuspid AV.16,17

**Aortic stenosis**

Current standard for AS quantification by echocardiography is based on the determination of both flow-dependent variables (transaortic velocities or gradients) and a flow-independent...
variable (valve area calculated by the continuity equation). In cases in which Doppler methods have known limitations [small aorta, LV dysfunction, subaortic stenosis or increased LVOT gradients, eccentric jets, significant aortic regurgitation (AR), etc.], AV planimetry becomes critical for diagnosis. Calculation of the AV area by continuity equation with conventional echocardiography is based on several assumptions: LVOT geometry is circular and adequately described by its anteroposterior diameter in 2D parasternal long-axis view; the 2D cut plane is parallel to LVOT spatial orientation; Doppler tracings of LVOT flow are acquired at the same site where the LVOT diameter is measured. These assumptions have proved to be inaccurate, especially when the heart is rotated or horizontalized. Since the LVOT area is calculated based on the LVOT-squared diameter, the LVOT diameter becomes the greatest potential source of error in the continuity equation. Moreover, both 3DE and multislice cardiac tomography (MSCT) studies showed that LVOT geometry assumes more frequently an elliptical configuration rather than a circular one. Accurate LVOT size and geometry is not only critical for the quantitation of AS severity, but also for correct annulus sizing during TAVI, calculating stroke volume and shunt ratio, or for guiding the muscle reduction therapies in septal hypertrophic cardiomyopathy.

Direct planimetry of aortic annular/LVOT areas by 3D TEE (Figure 8C) showed the best agreement with MSCT as gold standard, whereas the calculations based on the LVOT diameter measured by 2D TEE or 3D TEE led to significant area underestimation (by 16.4 and 12.9%, respectively). This translates into a reclassification of 10% patients from severe to moderate AS when using the calculated 3D TEE area and of 25% patients when using the planimetered 3D TEE area. In another study, the geometry of aortic complex (annular and LVOT areas, distances between aortic annulus and coronary ostia) quantified by 3D TEE correlated very well with the measurements obtained by multi-detector computer tomography. In addition, the LVOT area measured from biplane imaging by transthoracic 3DE improved the accuracy of stroke-volume assessment and of AS severity assessment, when compared with invasive or direct planimetry. 3D colour Doppler can also overcome inaccuracies of spectral Doppler for stroke-volume calculation, with no geometric assumptions about LVOT shape. 3D

**Figure 7** Morphological variants of the AV by 3DE. (A) Unicuspid valve. (B) ‘True’ bicuspid valve with no raphe. (C) Bicuspid valve with raphe (arrow). (D) Quadricuspid valve (asterisks mark the number of cusps of each variant).
colour-derived stroke-volume for AV area calculation proved to be more accurate than 2D approach, particularly in situations with distorted LVOT geometry.24

Another way to avoid the usual pitfalls of conventional continuity equation is the direct measurement of LV stroke volume by subtracting the end-systolic from the end-diastolic 3D LV volume, taking advantage of the good accuracy and reproducibility of the 3DE method.25 Gutierrez-Chico et al.26 used this approach and found a significantly better agreement with the invasive AV area by using the Gorlin equation than by using conventional continuity equation. The method is also time-saving, since LV volumes are already measured in any routine echocardiographic study to obtain LV ejection fraction.

Direct measurement of the AV anatomic orifice area (by 2DE or 3DE) (Figure 8D) should circumvent the haemodynamic and geometric assumptions of continuity equation. Cross-sectional measurement of the AV area by 2DE is subject to errors caused by off-axis imaging of the non-planar 3D AV orifice, especially in bicuspid or degenerative stenosis when the orifice is distorted. In addition, aortic annulus shows a dynamic movement during cardiac cycle, characterized by a more cranial position at early systole and a more caudal position during isovolumic relaxation27 (Figure 6). A fixed 2D cut plane may not capture the leaflet tips at the maximal systolic opening because of their rapid systolic movement, and frequently displays larger orifices than the true narrowest opening, leading to underestimation of stenosis severity. 28 After comparison with orifice planimetry by 3D-guided AV imaging, it was postulated that optimal 2D short-axis view of the AV for measuring the anatomic area is in fact when aortic cusps are viewed only during systole, but not during diastole, which is actually counter to the principles that guide image optimization of AV by 2D TTE or TEE. 27

Volumetric 3DE and 3D-guided biplane imaging may optimize the positioning of the cut plane at the level of leaflet edges and, therefore, improve the accuracy and reproducibility of AV orifice planimetry. This is critically important for the identification of the minimal orifice area, particularly in congenital AS with a

![Figure 8](https://academic.oup.com/ehjcimaging/article-abstract/13/7/541/2397386/Downloaded from https://academic.oup.com/ehjcimaging/article-abstract/13/7/541/2397386)
Doming valve. The 3D TEE planimetered area (Figure 8D) has very good agreement with the AV area by continuity equation and moderately with that by the Gorlin formula at catheterization. 3D TEE planimetry showed superior accuracy than 2D TEE, which significantly overestimated the AV area.

When there is an associated obstruction at the subvalvular level and Doppler methods cannot be reliably applied, orifice planimetry by 3DE can provide critical information about stenosis severity for both valvular and subvalvular narrowings (Figure 9; Supplementary data online, Video S7).

However, AV planimetry is not flawless. Heavy valvular calcifications make the orifice area difficult to planimeter due to shadowing or reverberations with both 2D and 3DE. The lower temporal resolution of 3DE limits its ability to exactly capture the maximal systolic opening of the aortic cusps. Moreover, planimetry may overestimate the severity of AS in low cardiac output patients, as the anatomic area of AV opening is reduced.

The impact of a stenotic AV on pressures and flows in the heart depends also on the 3D geometry of the valve leaflets proximal to the orifice. Patients with flat valves and steeper flow convergence have smaller AV effective orifice areas than those with more gradually tapering domed valves for the same anatomic area and flow rate. 3D valve shape, therefore, provides additional information beyond the planimetered orifice area in determining the impact of AS on patient haemodynamics.

Aortic regurgitation

Whereas AV replacement is an effective treatment for AS, AV repair is an excellent alternative to replacement for aortic insufficiency. The advantages of AV repair include a lower risk of infective endocarditis, plus avoidance of typical complications associated with mechanical valves (i.e. thromboembolic and haemorrhagic complications) and bioprostheses (i.e. structural valve deterioration). However, AV repair is technically more demanding than replacement, and careful preoperative echocardiographic assessment is pivotal to identify the mechanism of regurgitation (Figure 10; Supplementary data online, Video S8) and to provide the surgeon...
quantitative data about the morphology of the AV complex for proper patient selection and surgical planning. Having the opportunity to non-invasively gather all information about valve structure in motion before aortic clamping significantly shortens the time length of surgical intervention and lowers the odds of unforeseen situations. In a comparative study of 2D TEE and epicardial 3DE

Figure 10 Identification of the AV regurgitation mechanism by transthoracic 3DE. In comparison with 2D long-axis images suggesting prolapse (A: arrow) as the possible mechanism of the AR jet (B), a single zoomed 3D view of the AV from the outflow tract perspective enables the clear detection of cusp prolapse seen en face, its precise identification (right cusp), and the visualization of regurgitation orifices (Supplementary data online, Video S8).

Figure 11 Aortic root morphology assessment by high-resolution 3D TEE imaging. 3D volume rendering of Valsalva sinuses, cropped for the en face visualization of the ostium of the left main coronary artery (arrow, A; Supplementary data online, Video S9). Transversal and longitudinal 2D images of the ostium of the left main coronary artery (arrow, B and C), obtained by cropping the 3D volume, showing the quantitation of the leaflet hinge-to-ostium distance (red dashed arrow). From the same data set, the selection of a mid-systolic frame allows the measurement of aortic leaflet length (light blue dashed arrow, D). (Supplementary data online, Video S9.)
against surgical findings, epicardial 3DE was more sensitive than 2D TEE in detecting morphological abnormalities of the AV documented intraoperatively (leaflet deficiency, prolapse/perforation, commissural fusion). Advanced tools to quantify the geometry of AV leaflets and aortic root from 3DE data sets are currently being evaluated (Figure 11; Supplementary data online, Video S9). Preliminary experience with automated quantitative, patient-specific modelling of the aortic root and the valve from 3DE data has shown promise. A range of parameters can be automatically and rapidly measured from 3DE data sets (Figure 12; Supplementary data online, Video S10), many of which have only been possible to measure intraoperatively in the surgically exposed aortic root. These preoperative data from 3DE are valuable to predict optimal graft size and determine the need for leaflet remodelling in patients with AR selected for valve-sparing root surgery.

3DE is feasible and accurate to precisely describe the mechanism of AR (Figure 13; Supplementary data online, Videos S11 and S12), and the complementary use of colour 3D enables the quantitation of its severity. The exact size and shape of the vena contracta are important parameters in the quantitation of regurgitant lesions. Calculations from 2DE are based on the geometric assumption that the vena contracta area is either circular or elliptical. Yet, 3DE revealed that this assumption is frequently incorrect. 3D TTE colour Doppler data sets can be cropped in multiple transversal planes exactly perpendicular to the AR jet direction viewed in long axis, at or just below the AV level, in order to identify and planimeter the smallest colour jet area. This approach had a good accuracy to quantify the AR severity in animal models and in patients, when compared with angiography, magnetic resonance, or comprehensive conventional Doppler evaluation; however, additional clinical validation is required.

**AV repair and prostheses**

3D can be effectively used to assess the morphological integrity and function of the repaired/prosthetic AV and to screen for complications. Although the visualization scores are lower than for mitral valve prostheses, AV prostheses can be well imaged by the 3D TEE approach. The view from LVOT was found superior to the aortic perspective for optimal visualization of both prosthetic AV leaflets and annulus.

**AV endocarditis and tumours**

In the assessment of AV endocarditis, 3DE is capable of defining the size and shape of vegetations, their mobility and insertion, providing more detailed information and greater accuracy in comparison with 2DE (Figure 14; Supplementary data online, Video S13). The actual size of the masses can be precisely quantified by measuring minimal and maximal diameters, cross-sectional area, and/or volume. Conversely, irregularly shaped, highly mobile masses are extremely difficult to assess from a fixed cross-sectional 2D view that frequently does not capture their maximal length in a single view. Although tissue characterization is not reliable by 3D to discriminate the nature of the attached mass (Lambli’s excrescence/thrombus/tumour/vegetation), 3DE, especially 3D TEE, provides invaluable morphological information regarding the type and extent of leaflet involvement (aneurysms, vegetations, perforations, etc), annulus (abscess/dehiscence in AV prostheses), and surrounding structures from unlimited perspectives.

Prosthetic infective endocarditis is characterized by vegetations which, in mechanical prostheses, are usually attached to the prosthetic ring, whereas in bioprostheses they may also arise from the leaflets. The exact extension of prosthetic dehiscence can be assessed in both circumferential and longitudinal directions (Figure 15; Supplementary data online, Videos S14 and S15). The dehiscence orifice area and shape can be planimetered for a quantitative assessment of paravalvular regurgitation and to select patients needing suture/valvular replacement or percutaneous device occluder procedure.
**Figure 13** Severe regurgitation in bicuspid aortic valve. Colour Doppler imaging from apical 2D long-axis view showing severe aortic regurgitation (A) with massive diastolic flow reversal in aortic arch (B). 3D echocardiography (zoomed acquisition from transthoracic parasternal approach) depicts the longitudinal (C) and en face view (D) of the aortic valve, with rupture and flail of the larger cusp, and a sizeable regurgitant orifice (Supplementary data online, Videos S11 and S12).

**Figure 14** Aortic valve endocarditis by 2D and 3D transthoracic echocardiography. Parasternal 2D long-axis image showing a pathologic mass in the left ventricular outflow in a patient with a calcified bicuspid aortic valve; the insertion point of the mass was carefully sought, but it could not be clearly identified (A). In contrast, unconventional perspectives (B and C) obtained from 3D apical acquisitions allowed the clear and complete visualization of the mass in motion, to appreciate its irregular shape and mobility, as well as its attachment point close to the annular insertion of the right aortic cusp (arrow) (Supplementary data online, Video S13).
AV percutaneous interventions

It is axiomatic that both interventional cardiologists and surgeons performing various interventions on the AV need a thorough understanding of its geometrical configuration and of the relationship with vital adjacent structures, like coronary arteries. TEE is progressively evolving from an adjunct to angiography into a primary imaging technique during interventional procedures, enabling an improved catheter control with reduced contrast media use and radiation load.

Before TAVI, the aortic annulus diameter is of critical importance for the selection of prosthetic size, and biplane imaging by 3DE is superior to single-plane 2D measurement for this purpose (Figure 8). This may be further improved upon by the automated 3D modelling algorithm described above. Using this approach, it is now possible to measure both the antero-posterior and medio-lateral annular diameters. Which of these (or a combination of these) diameters proves to be the best predictor of the optimal prosthesis size remains to be tested prospectively, but there is growing evidence that 3D annulus sizing may be the best predictor of optimal outcome post-TAVI. Furthermore, the 3D annulus-coronary ostia distances can be reliably measured by 3D TEE (Figure 11), possibly improving the correlation between angiography and dual-source CT measurements. Sinus width and height can also be quantified using dedicated offline software to assess the extent of longitudinal and horizontal remodelling (Figure 12). Both of these parameters may be useful to predict/anticipate complications during TAVI, especially in small aortic roots.

Using real-time 3D TEE during TAVI, the shape, the spatial orientation, and the navigation of various catheters or stents/prostheses can be recorded online and stereoscopically depicted. Deployment of the prosthesis can be 3D-TEE-guided. Immediately after deployment, 3D TEE is essential to evaluate prosthesis position, its relationship with anterior mitral leaflet, and the degree of AR, which if severe and paraprosthetic may prompt re-insufflation of the deployment balloon in the prosthesis in order to improve the apposition of the prosthetic ring to the aortic wall.

Current limitations and caveats of 3DE

Multi-beat acquisitions of the AV are subject to artefacts related to probe motion, patient’s respiration, or irregular heart cycles. In these challenging situations, real-time scanning or narrow-angle single-beat data sets may be alternatively used, with the noted shortcomings related to the small field and relatively lower frame rates, respectively. Reducing the number of stitched subvolumes (to two or three) or waiting for a sequence of fairly equal cardiac cycles can be attempted in the setting of arrhythmias. As with 2D, 3D off-angle cut planes can lead to faulty conclusions and/or measurements. Multi-plane 2D imaging (side-by-side simultaneous display of the structure of interest from two or three angles; Figure 6) using 3D probe may verify and correct this error.

Limited temporal resolution may be problematic with some 3D equipments, but seems adequate to study AV morphology using the latest 3D transthoracic and transoesophageal technology (able to provide 10–15 volumes per second (vps) in single-beat and 60–70 vps in multi-beat acquisition modality—depending on the volume size—while maintaining a satisfactory spatial resolution). However, dropout artefacts in very thin valves and acoustic shadowing in heavily calcified valves/annuli or prostheses cannot be avoided by 3D ultrasound modality. Colour Doppler, either 2D multi-plane or 3D, can be of help when artefacts vs. true pathology are in question.

Colour-vs.-tissue gain, wall filter settings and variability of aliasing velocities, limited temporal and spatial resolution may affect the accuracy and reproducibility of 3D flow convergence images.
Although 3D colour Doppler seems promising in overcoming some of the limitations of 2D colour Doppler, the former requires further validation before its routine application in clinical settings.

In conclusion, 3DE complements the conventional echocardiographic assessment of AV with more accurate and reproducible quantitative analysis of aortic root morphology, determination of the AV area, detailed information on leaflet morphology and spatial geometry, mechanism and severity of AR in native/prosthetic AV and will potentially become the standard echo monitoring during percutaneous interventions.

Supplementary data

Supplementary data are available at European Heart Journal – Cardiovascular Imaging online.

Acknowledgements

The authors acknowledge the valuable contribution of Professor Cristina Basso and Professor Gaetano Thiene for providing the anatomical specimens, and Dr Carlo Dal Lin for the illustrations in this paper.

Conflicts of interest: D.M. has received equipment and research funding from GE Healthcare.

L.P.B. has received equipment grants from GE Healthcare and is on the Speakers’ Bureau of this company.

M.V. has received research/equipment support and speaker’s honoraria and is a per diem consultant for Siemens.

S.I. has no conflicts of interest to disclose.

Funding

D.M. was supported by a research grant programme awarded by the European Association of Echocardiography.

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A third ventricular cavity

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A 29-year-old female patient with no previous notable medical history was referred to our hospital because of a 2–3/6 systolic murmur. Her electrocardiogram showed normal sinus rhythm. On the parasternal short-axis view of transthoracic echocardiography, a third ventricular chamber on the right ventricular side of the inferoseptal left ventricular wall was seen (Panel A; see Supplementary data online, Video S1). On the apical four-chamber view, the cavity was seen extending from the basal interventricular septum almost up to the apex, with walls made up of the myocardium (Panel B; see Supplementary data online, Video S1). On colour Doppler examination, a jet towards the right ventricle was noted at the apical segment of this unusual contractile ventricular structure (Panels C and D; see Supplementary data online, Video S1). A gradient of 128 mmHg was measured with continuous-wave Doppler. The cardiac magnetic resonance imaging confirmed this peculiar third ventricular cavity and the muscular defect with a left-to-right shunt (Panels E–H; see Supplementary data online, Video S2). As the patient who was diagnosed with the ventricular septal defect and the double-chambered left ventricle was asymptomatic and the calculated Qp/Qs was 1.1, we decided to follow the patient without any intervention.

Supplementary data are available at European Heart Journal – Cardiovascular Imaging online.

Panels A–J. Transthoracic parasternal short-axis view showing a third ventricular chamber (white asterisk) at the inferoseptal left ventricular wall (A). On the apical four-chamber view, the cavity (white asterisk) is seen extending from the basal interventricular septum almost up to the apex, with walls made up of the myocardium (B). Parasternal short-axis view using colour Doppler (C) and apical four-chamber (D) views showing a jet (white arrows) from the apical segment of this unusual contractile ventricular structure towards the right ventricle. The cardiac magnetic resonance imaging shows this peculiar third ventricular cavity (E, G, and H; asterisks) and the small muscular defect (black arrow) with a left-to-right shunt (F). Schematic diagrams (I and J) show a peculiar third ventricular cavity (asterisks) and the muscular defect (dotted arrows).

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doi:10.1093/ehjci/jes004
Online publish-ahead-of-print 29 January 2012

A third ventricular cavity

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A 29-year-old female patient with no previous notable medical history was referred to our hospital because of a 2–3/6 systolic murmur. Her electrocardiogram showed normal sinus rhythm. On the parasternal short-axis view of transthoracic echocardiography, a third ventricular chamber on the right ventricular side of the inferoseptal left ventricular wall was seen (Panel A; see Supplementary data online, Video S1). On the apical four-chamber view, the cavity was seen extending from the basal interventricular septum almost up to the apex, with walls made up of the myocardium (Panel B; see Supplementary data online, Video S1). On colour Doppler examination, a jet towards the right ventricle was noted at the apical segment of this unusual contractile ventricular structure (Panels C and D; see Supplementary data online, Video S1). A gradient of 128 mmHg was measured with continuous-wave Doppler. The cardiac magnetic resonance imaging confirmed this peculiar third ventricular cavity and the muscular defect with a left-to-right shunt (Panels E–H; see Supplementary data online, Video S2). As the patient who was diagnosed with the ventricular septal defect and the double-chambered left ventricle was asymptomatic and the calculated Qp/Qs was 1.1, we decided to follow the patient without any intervention.

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