

Review

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3D echocardiography to plan aortic valve surgery and evaluate the results

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Abstract

Three-dimensional transesophageal echocardiography (3D TEE) has become an indispensable tool for the anatomical and functional assessment of the aortic valve (AV). Accurately identifying the degree of regurgitation or stenosis is critical for therapeutic decision making; 3D TEE provides comprehensive morphological and functional descriptions, which have been improved by the introduction of new analytic methods. This review examines the development of 3D echocardiography in evaluating AV disorders, emphasizing its advantages over conventional 2D imaging. 3D TEE improves the accuracy of measures crucial to surgical planning and prosthesis selection, enabling real-time visualization of valve shape and dynamics. The widespread adoption of 3D echocardiography will contribute to improving the treatment of AV diseases as technology advances, thereby opening new horizons for more patient-tailored therapeutic strategies.

Keywords: Aortic valve, three-dimensional echocardiography, aortic surgery, transcatheter aortic valve replacement, multimodality imaging

INTRODUCTION

In the past 20 years, reparative cardiac surgery and transcatheter procedures have become increasingly prominent in the treatment of structural heart disease, particularly valvulopathies. Therefore, a comprehensive understanding of the etiology and pathological components is essential for selecting the optimal therapeutic strategy for each patient. Echocardiography, both transthoracic (TTE) and



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transesophageal (TEE), plays a key role in assessing the anatomy and function of the heart valves. In particular, three-dimensional echocardiography (3DE) represents one of the most significant advances in cardiovascular imaging and has overcome many of the limitations of the two-dimensional (2D) echocardiogram. Indeed, 3D TEE has become critical for procedural planning, intraprocedural guidance, and the assessment of procedural results^[1]. This revolution has been made possible by advances in new image rendering methods, software and crystal technology, which have led to innovative array transducers capable of acquiring a pyramidal volumetric dataset rather than a single cross-section displaying 3D echocardiographic images in real time^[2]. An inverse relationship exists between volume rate, volume size, and spatial resolution; increasing any one of these parameters decreases the other two. The resolution and accuracy of 3D images are contingent upon multiple factors, including patient-specific acoustic windows and tissue characteristics, the imager's experience, and, most importantly, the quality of the 2D image. Indeed, the 2D image must be optimized before 3D acquisition.

To obtain an optimal image, the pyramidal volume containing the anatomical structures of interest should be as small as possible. The depth and the elevational and azimuthal planes should be adjusted in biplane mode before the 3D volume is acquired. Acquiring the full 3D volume in a multibeam mode is recommended to increase spatial and temporal resolution^[3].

Modalities to acquire a 3D dataset for aortic valve assessment

X-plane imaging is one of the most widely used modalities. Two simultaneous cross-sectional views are obtained from the same heartbeat, with the default images being orthogonal (90°) to each other. Typically, the left sector displays the reference imaging plane, while in the right sector, the rotation angle and position of the secondary plane can be changed. X-plane imaging enables the simultaneous visualization of anatomical structures, thereby improving measurement accuracy^[4] [Figure 1]. With the increasing use of aortic valve repair and transcatheter replacement, X-plane imaging has become indispensable for studying the aortic valve (AV) and selecting the optimal treatment. Each leaflet is analyzed in detail in its three distinct anatomical regions (hinge line, body, and lunula) and their interrelationships. Morphological changes in the cusps, such as calcification, prolapse, billowing, and fenestrations, can be described. Cusp parameters (e.g., area, height, length, and depth) should be measured not only for treatment selection but also for estimating the postoperative status^[5,6]. Color flow Doppler can be superimposed to define the regurgitant jet origin, direction, and vena contracta (VC)^[7].

The real-time single-beat modality is obtained from the 2D TEE by pressing a single button. It is the most frequently used modality during percutaneous procedures, as it is unaffected by stitching artifacts. The image obtained is a solid pyramidal dataset with a narrow angle (usually 30° × 60°) that can be increased by modifying the azimuthal and elevational planes (up to 90° × 90°). In contrast, the electrocardiogram (ECG)-gated multi-beat acquisition modality is prone to stitching artifacts but has higher spatial and temporal resolution. This acquisition method constructs an image by stitching up to six narrow sectors (subvolumes) and requires a regular heart rhythm and a breath-hold. It is the optimal method for detailed anatomical and functional analysis of the aortic root and AV. Color Doppler can be added in both modalities, but it reduces the frame rate^[2] [Table 1].

Regardless of the acquisition mode, it is important to consider how 3D structures are displayed on a 2D screen. There are different 3D image displays:

Volume rendering uses various algorithms to preserve all 3D information. Various shades of a blue-bronze combination are used to generate a 3D display of the depth and textures of cardiac structures. The 3D

Table 1. Comparison of 3D echocardiographic acquisition modalities

Acquisition modality	Advantages
X-plane	Displays two views from the same heartbeat using a single acoustic window. The default views are orthogonal (90°) to each other
Real-time single-beat	Free from stitching artifacts; commonly used during percutaneous procedures
ECG-gated multi-beat	May exhibit stitching artifacts but offers higher spatial and temporal resolution
3D color Doppler	Enables 3D flow imaging but reduces the frame rate

ECG: Electrocardiogram; 3D: three-dimensional.

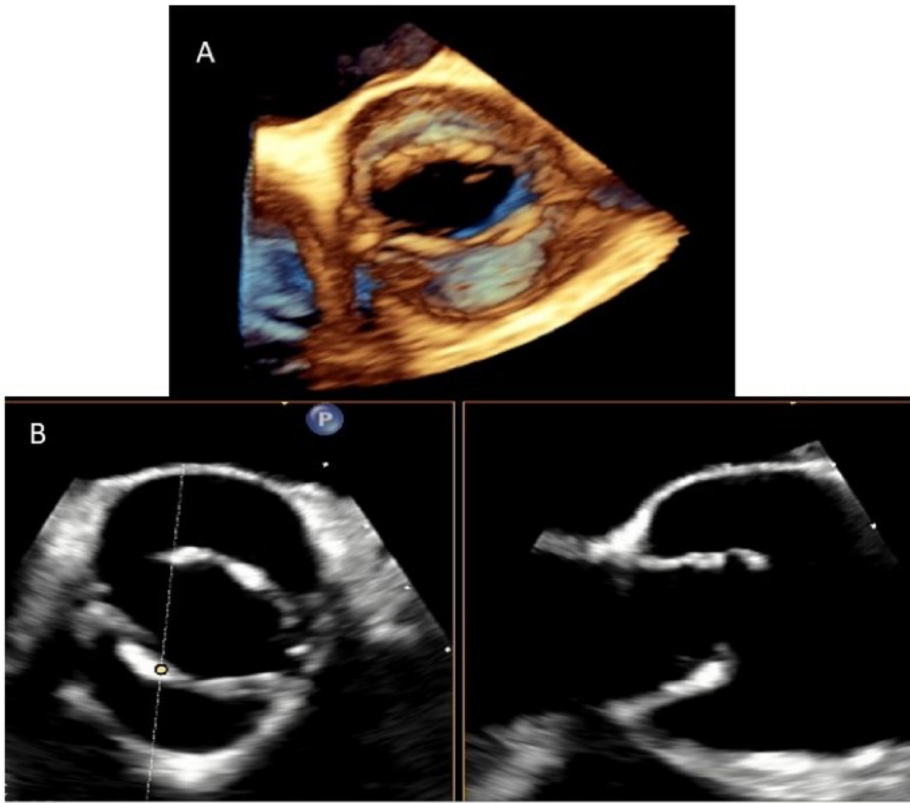


Figure 1. 3D TEE of a BAV in the short-axis (Panel A). X-plane mode at the level of the aortic valve shows BAV without raphe, anteroposterior phenotype (Panel B). TEE: Transesophageal echocardiography; BAV: bicuspid aortic valve.

dataset can be sectioned, cropped, and rotated^[8] [Figure 2].

Surface rendering enables the visualization of organ surfaces with a solid appearance, through manual or semi-automatic boundary tracing. These automated algorithms utilize forms of artificial intelligence to identify fiducial anatomical landmarks.

2D Tomographic Slices show multiple simultaneous 2D views of the single pyramidal dataset. Multiple slicing methods are available, such as arbitrary plane, simultaneous orthogonal (or arbitrary angle) slices, and parallel slice planes.

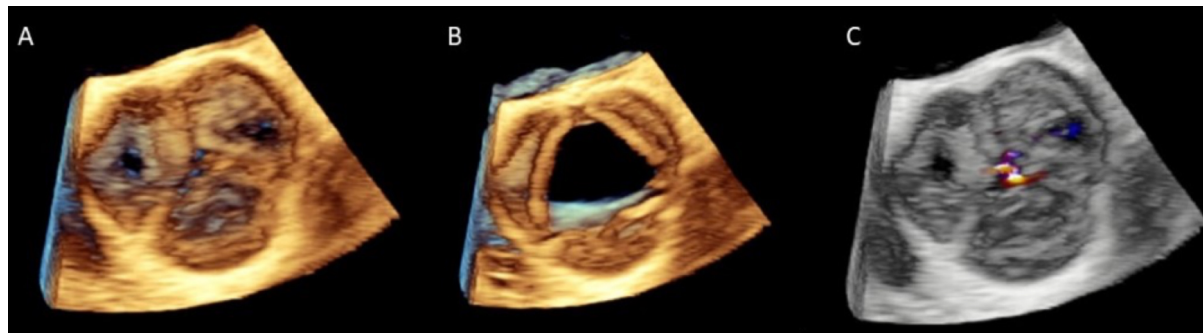


Figure 2. Multi-beat 3D TEE acquisition in zoom modality of the AV in diastole (Panel A) and systole (Panel B). 3D TEE mid-esophageal short-axis view with color-flow Doppler demonstrates moderate AR with a central origin (Panel C). TEE: Transesophageal echocardiography; AR: aortic regurgitation.

Photorealistic vision (true-view) with Glass is the newest volume rendering mode, with editing tools such as transparency and light source manipulation. Transparency allows the user to navigate through cardiac structures while retaining anatomical landmarks and overlying tissues. Light source manipulation permits backlighting the anatomical structure of interest to enhance contrast and refine borders. This photorealistic imaging offers more natural and realistic images, facilitating the detection of fine-drawn structures and pathologies^[9].

Multiplanar reconstruction (MPR) of acquired 3D datasets is the most accurate rendering mode for performing measurements. Initially, this technique was used after the acquisition of 3D datasets; currently, live MPR is available, which improves the accuracy of real-time measurements through the simultaneous visualization of cardiac structures in multiple planes^[10] [Figure 3]. Specifically, live 3D MPR simultaneously displays the structure of interest in the three spatial planes (axial, coronal, and sagittal), enabling a more detailed assessment of cardiac structures than biplane imaging alone. With MPR, the imager can manipulate three distinct 2D sections of a 3D volume as needed. MPR is widely established for planning and guiding transcatheter procedures. For the AV, however, it is the cornerstone for patient selection and for predicting the likelihood of a successful repair. Understanding the interaction between the leaflets, annulus, commissural structures, and sinotubular junction (STJ) allows the surgeon to propose a tailored repair for isolated aortic regurgitation (AR). MPR is the optimal method for quantifying AR by reconstructing the 3D VC area, assessing leaflet tissue quality (i.e., grading thickening and calcification), and defining specific measurements of leaflet geometry, such as coaptation height (cH), effective height (eH), geometric height (gH), and free margin length^[11].

However, 3DE has some limitations. Its accuracy depends on image quality: a poor acoustic window can result in suboptimal 3D acquisitions and artifacts (e.g., stitching errors). Furthermore, 3DE is an operator-dependent modality that can lead to inter-observer variability. These aspects can reduce 3DE diagnostic power and increase variability. Emerging technologies, such as 4D TEE and artificial intelligence, and hybrid imaging, may overcome these limitations.

4D TEE produces realistic, easily interpretable images. It enables the acquisition of a large amount of information in a single step, constructing multidimensional images from the same heartbeat without requiring probe movement. It provides real-time color flow to assess hemodynamic information within the same cardiac cycle, which is particularly useful for quantifying valvular regurgitation. We use 4D TEE in candidates for transcatheter aortic valve replacement (TAVR) or valve-in-valve procedures who have kidney disease and may not have undergone adequate multidetector computed tomography (MDCT), or in

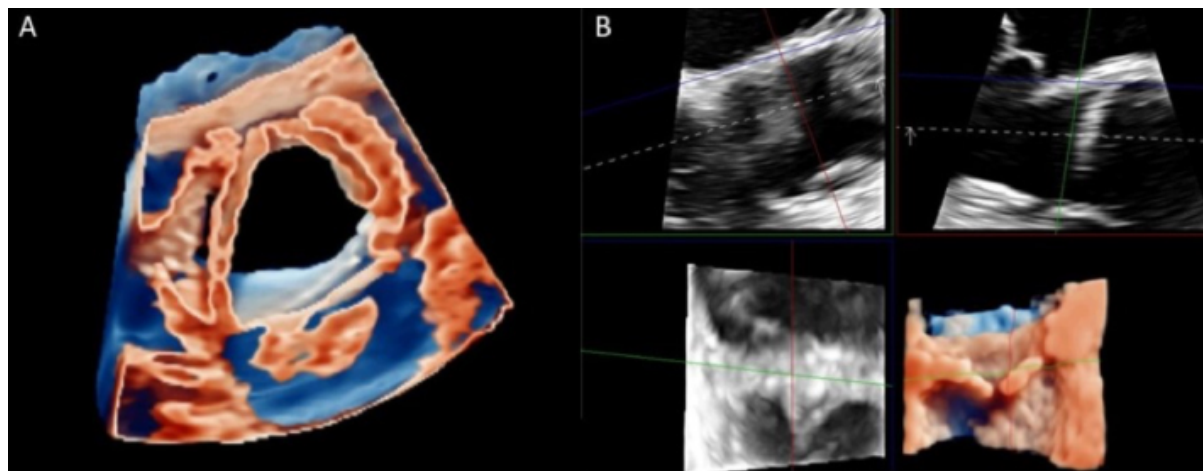


Figure 3. Glass (transparency) allows the imager to adjust the degree of transparency of both cardiac and extra-cardiac structures (Panel A). Multiplanar reconstruction allows live rotation of perpendicular planes on a 3D image to display any desired 2D imaging plane (Panel B). 2D: Two-dimensional; 3D: three-dimensional.

patients with poor-quality MDCT for whom annular dimensions require confirmation^[12].

THE ROLE OF 3D ECHOCARDIOGRAPHY FOR AORTIC VALVE STENOSIS ASSESSMENT

Aortic stenosis (AS) is the most prevalent valvular heart disease, largely as a consequence of an aging population^[13]. Echocardiography is the gold standard for confirming the diagnosis, estimating severity, and establishing indications for intervention. Current international recommendations for the echocardiographic evaluation of patients with AS are mainly based on peak transvalvular velocity, mean pressure gradient, and valve area assessment evaluated by TTE^[14], using the simplified Bernoulli equation: $\Delta P_{\max} = 4V_{\max}^2$ ^[15].

From an interventional perspective, accurate preoperative measurement of the aortic annular diameter is crucial for selecting a suitable prosthesis, and TEE is one of the most useful tools. Several studies have shown that measurements by 3D TEE and MDCT have better accuracy than 2D TEE in assessing the aortic annulus^[16-18].

Compared with MDCT and cardiac magnetic resonance (CMR), 3D TEE has several advantages: (1) it can be performed in real time, enabling intraoperative evaluation during surgical aortic valve replacement (SAVR) or as an intraoperative guide during TAVR; (2) it clarifies the etiology of AS (e.g., calcific, degenerative, or rheumatic); (3) it does not require iodinated contrast, making it useful for patients with chronic kidney disease and elderly patients; and (4) it enables the prompt evaluation of procedural complications, such as annular rupture, transvalvular or paravalvular regurgitation, and pericardial effusion.

A comprehensive evaluation of severe AS includes the assessment of the diameters and area of the virtual basal ring (VBR). The aortic annulus is a complex, crown-shaped structure. The VBR, a plane connecting the nadirs of the cusp insertion lines, represents its caudal border, while the STJ marks its cranial extent. Thus, the VBR is virtual, and it varies in shape and size, typically being elliptical in diastole and becoming more circular and larger in systole. Interestingly, studies showed that in severe AS, the aortic annulus becomes less distensible and undergoes remodeling, leading to an ovoid shape^[19]. Due to calcium shadowing, 2D echocardiography may underestimate the left ventricular outflow tract (LVOT) size, potentially leading to inaccurate measurements of the AV functional area. 3D TEE may overcome this limitation by allowing for direct planimetry of the LVOT area, which is more accurate than relying on a

single diameter measurement. Furthermore, 3DE properly delineates non-circular anatomy, which has implications for the correct assessment of AS severity when calculated by the continuity equation, a method that assumes a circular annulus [Figure 4].

Peak transvalvular velocity and mean pressure gradient are flow-dependent parameters, so they can be significantly influenced by cardiac output states, which may potentially lead to inaccurate assessments of valve stenosis severity. The AV functional area is a relatively flow-independent variable that can be calculated using the Bernoulli continuity equation.

Using a flow-independent method, such as planimetry, to calculate the aortic valve area (AVA) is essential, especially for intraoperative evaluation under general anesthesia^[20]. In 2D methods, it may be difficult to detect the tips of the AV leaflets at peak systolic opening for AVA planimetry calculation; this can result in an overestimation of AVA due to a 'funnel' configuration. TEE should be considered the echocardiographic modality of choice for calculating AVA planimetry. 3D TEE is more effective than 2D planimetry for assessing AVA^[21] and correlates better with continuity equation-derived AVA^[22]. Consequently, 3DE improves accuracy and provides a validated alternative to MDCT and CMR for accurate sizing of both the aortic annulus and AVA [Figure 5].

FOCUS ON TAVR PROCEDURE: FROM THE PROSTHESIS SELECTION TO THE POST-PROCEDURAL ASSESSMENT

Randomized clinical trials have established SAVR and TAVR as complementary treatment options. TAVR was initially performed as an alternative to SAVR in patients with high surgical risk^[23,24]. Recent trials have shown that TAVR is non-inferior to SAVR in low-risk patients at 5-year follow-up^[25,26]. However, the lack of long-term outcomes regarding structural valve deterioration creates uncertainty about TAVR durability, particularly in younger patients, for whom re-intervention might be a future concern. Thus, TAVR is a valid alternative to conventional SAVR, especially in elderly patients with favorable anatomical and procedural characteristics^[27], while SAVR remains more suitable for patients with a bicuspid aortic valve (BAV) and AS, as well as those with associated disease (e.g., aortic dilatation, complex coronary disease, or severe mitral regurgitation requiring a surgical approach).

While preoperative imaging assessment for TAVR primarily relies on MDCT^[28,29], 3D TEE serves as a useful tool to assess valvular size, monitor the procedure, and provide real-time evaluation of procedure results. The first step in planning the TAVR procedure is to correctly measure VBR to avoid complications that can affect short- and long-term outcomes. A recent meta-analysis^[30] demonstrated a strong correlation between the LVOT area, aortic annular area, perimeter, and diameter measured using 3D TEE and those obtained from MDCT. Thus, 3D TEE remains a valid alternative for LVOT and VBR quantification, especially when MDCT is contraindicated.

Dynamic changes in the aortic annulus during the cardiac cycle could lead to misinterpretation of annular sizing for prosthesis selection^[31]. As the annulus becomes progressively more elliptical, the area decreases disproportionately to the perimeter, leading to potential underestimation of annular size. For accurate prosthesis selection, perimeter-derived measurement of VBR correlates well with the manufacturer's prosthesis sizing charts and predicts accurate prosthesis size^[18]. Annular shape and perimeter are not the exclusive factors for valve choice: each component of the aortic root, including STJ, aortic sinuses, LVOT, and coronary ostia height, is crucial in determining what type and size of prosthesis is appropriate. The intentional oversizing of implants is a recognized strategy to reduce the risk of paravalvular regurgitation (PVR)^[32], but it can negatively affect outcomes such as the risk of root rupture, significant conduction

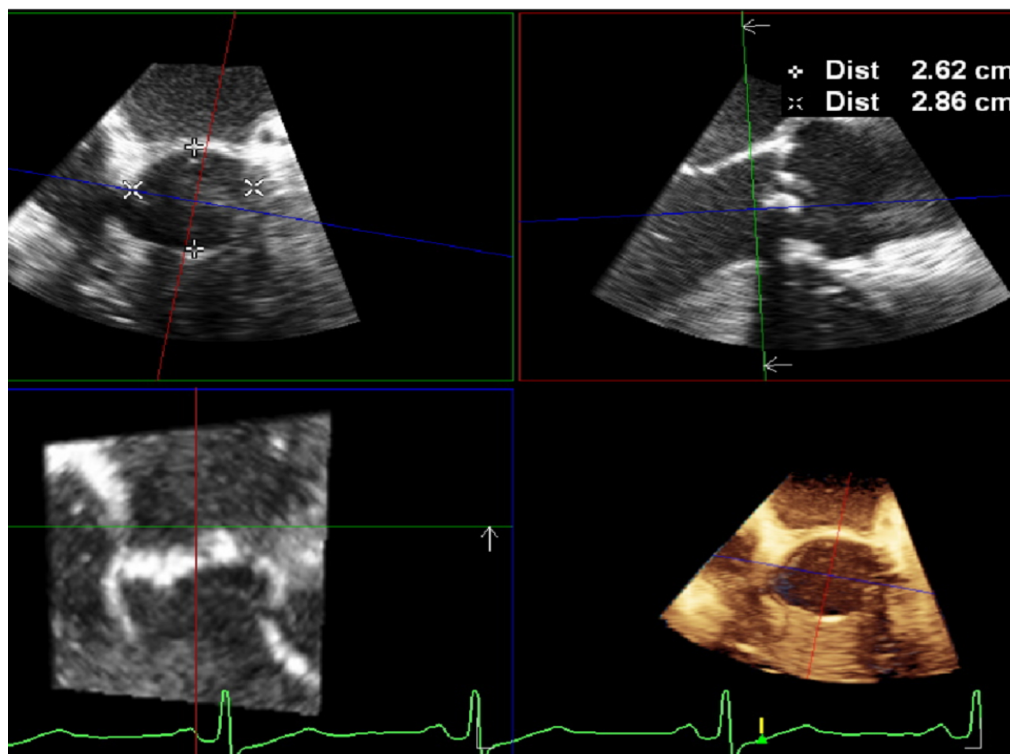


Figure 4. Annular evaluation begins by acquiring a high-quality 2D mid-esophageal short axis (30°-60°) or long axis (110°-120°) image, then selecting the 3D single-beat “zoom modality”. Choose the mid-systolic frame for measurements, as the aortic root is more circular during systole. The sagittal and coronal planes must bisect the AV long axis. The cross-sectional plane should be positioned at the ventricular-aortic junction, with the transverse plane adjusted to display the VBR. 2D: Two-dimensional; 3D: three-dimensional; AV: aortic valve; VBR: virtual basal ring.

disturbances, and device underexpansion.

One of the most feared complications during TAVR is myocardial ischemia due to coronary ostia occlusion. This occurs when a very high prosthesis deployment causes the calcified native leaflets to be crushed against the aortic wall by the expanding metallic stent frame. MDCT is the gold-standard tool for evaluating coronary ostia height^[33,34]. Although 3D TEE is not the primary modality for measuring coronary height, a good correlation exists between TEE (including with 4D software reconstruction) and MDCT in estimating left coronary height^[35]. The right coronary ostium can be identified through a 2D TEE mid-esophageal long-axis view at 120°, but the distance from the annulus to the left coronary ostium can be obtained only with post-processing 3D MPR imaging. A coronary height measurement below 11 mm is considered a high risk for coronary ostial occlusion. [Figure 6].

Real-time imaging guidance throughout implantation offers prompt diagnosis of complications and indicates the proper landing zone. In the short-axis view, the prosthesis must be circular, and the proximal edge must be a few millimeters inside the LVOT, without significant protrusion. In the case of a suboptimal result, self-expanding prostheses can be repositioned, while balloon-expandable ones may require post-dilation^[36].

After proper deployment, PVR and intravalvular leaks must be excluded. Transvalvular leaks are primarily associated with incomplete stent frame expansion, an elliptical prosthetic shape, and malpositioning^[37].

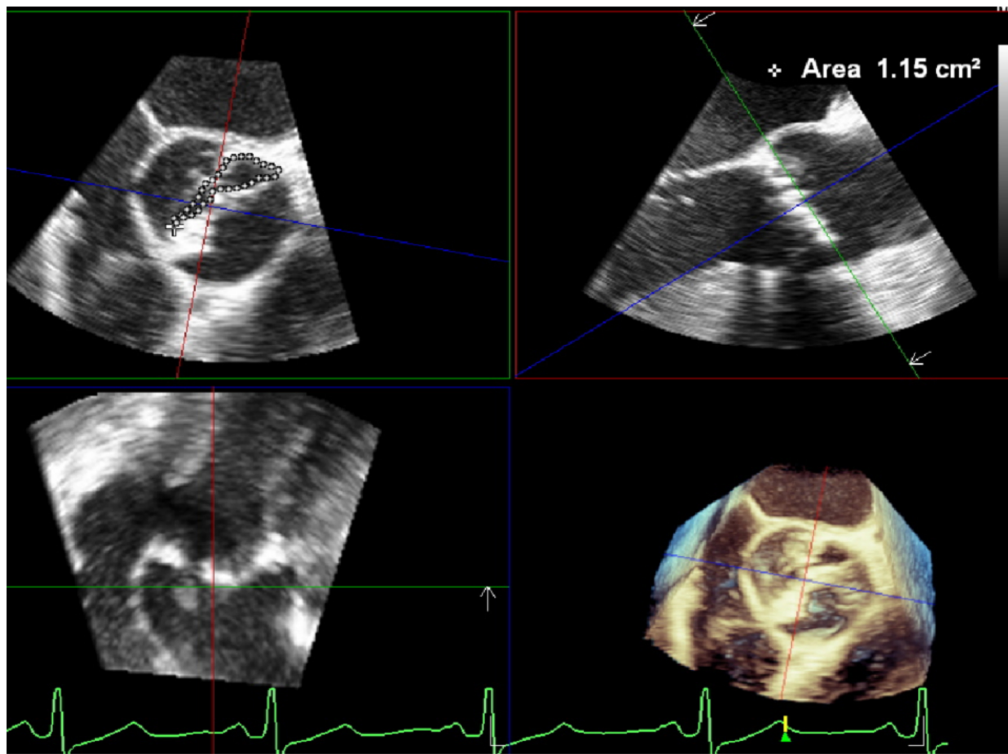


Figure 5. 3D image planes are carefully repositioned towards AV leaflet tips during the mid-systolic phase of the cardiac cycle. This repositioning allows for generating a short axis MPR, where planimetry can be precisely traced to determine the AV area. 3D: Three-dimensional; AV: aortic valve; MPR: multiplanar reconstruction.

Prosthetic expansion assessed by 3D TEE was defined as the ratio of the mid-edge area of the prosthetic frame to the nominal external valve area, and this ratio was significantly higher in patients with transvalvular AR. PVR remains the most frequent complication of TAVR. Moderate or severe PVR is an independent predictor of mortality after TAVR implantation. MDCT and 3D TEE predicted PVR with similar accuracy^[38] [Figure 7].

SAVR: OLD BUT STILL GOLD

Similar to TAVR, accurate preoperative measurement of the aortic annular diameter is crucial for selecting the appropriate prosthesis size to avoid patient-prosthesis mismatch (PPM)^[39], which negatively impacts short- and long-term outcomes^[40,41]. Predicting PPM before surgery is critically important. In fact, after selecting the prosthesis model and size, the predicted indexed effective orifice area (EOA) must be calculated to estimate the risk of postoperative PPM. A predicted indexed EOA $\leq 0.65 \text{ cm}^2/\text{m}^2$ (or $\leq 0.55 \text{ cm}^2/\text{m}^2$ in obese patients) indicates a risk of severe PPM^[42,43]. Pibarot *et al.*^[44] showed that patients with severe PPM after SAVR have worse survival and less left ventricle (LV) mass regression than those without PPM. TAVR may be preferable to SAVR in patients with a small aortic annulus to avoid PPM, to enhance LV mass regression, and to reduce postoperative mortality. MDCT and 3D TEE are essential to identify patients with a small aortic annulus who are at high risk of PPM. The inability to accurately predict PPM before surgery is a significant challenge. A significant contributing factor is the lack of a standardized definition for valve size in the cardiac surgery community. Valve manufacturers often do not strictly adhere to ISO definitions, leading to valve-specific charts that lack uniformity and result in the inaccurate prediction of severe PPM^[45,46]. Currently, prosthetic valve choice depends on intraoperative sizing to determine the largest prosthesis that can be safely implanted.

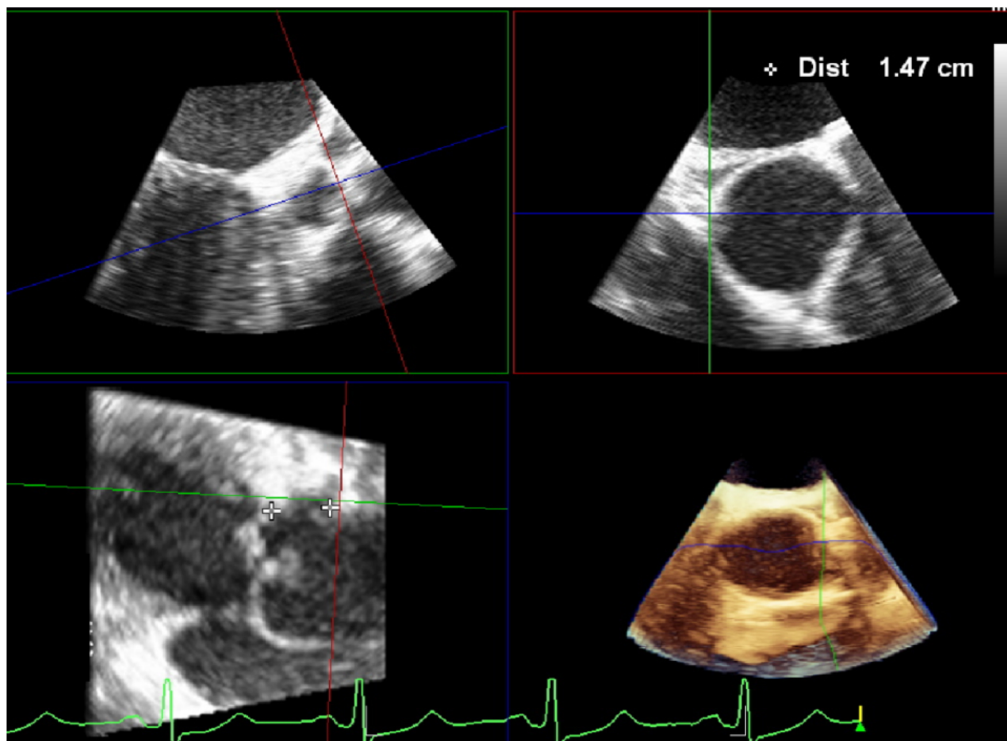


Figure 6. Combine the sagittal and coronal images to cut the AV long axis. In the sagittal plane, search for an indentation at the 10 o'clock position, which represents the left main coronary origin. Then move the marker along the aortic root in coronal view. Rotate the marker in the transverse image anticlockwise until it is perfectly aligned with the left major ostium. Finally, carefully measure the distance between the left main ostium and the left cusp in the sagittal plane. AV: Aortic valve.

AORTIC REGURGITATION: MECHANISM AND ASSESSMENT FOR VALVE REPAIR PLANNING

AR is a condition caused by various etiologies, including degenerative AV disease, congenital abnormalities, infective endocarditis, and most commonly, aortic root dilatation. The accurate assessment of AR severity is crucial for appropriate patient management and timing of intervention. In the thorough assessment of AR, 3D echocardiography offers significant methodological advantages over traditional 2D imaging techniques. Currently, the multimodality imaging approach is mandatory to establish diagnosis, identify complications, and determine the appropriate surgical treatment. The most common treatment is still AV replacement. Conversely, valve repair and valve-sparing procedures are increasingly adopted, especially for AVs with structurally normal leaflets. Therefore, 3D echocardiography, alongside MDCT, is becoming increasingly important in assessing the feasibility of AV repair. This surgical option is still underutilized but represents a valid alternative to prosthetic replacement and should be recommended when feasible^[47]. A standardized echocardiographic assessment protocol is required to select patients with suitable characteristics for repair^[48,49] and make this surgical option reproducible^[50] with excellent long-term durability^[51].

First, it is essential to understand the mechanism of AR. While 2D TEE views permit useful measurements, 3D images provide a more comprehensive view of the AV anatomy, focusing on a detailed assessment of leaflet morphology, coaptation, and the dynamic nature of the regurgitant orifice. Volumetric datasets acquired by 3D echo enable the reconstruction of the AV in multiple planes, facilitating the identification of specific anatomical abnormalities that contribute to AR^[52]. One of the key advantages of 3D echo in surgical planning is its ability to provide a “surgeon’s view” of the AV^[53], enabling a complete assessment of valve

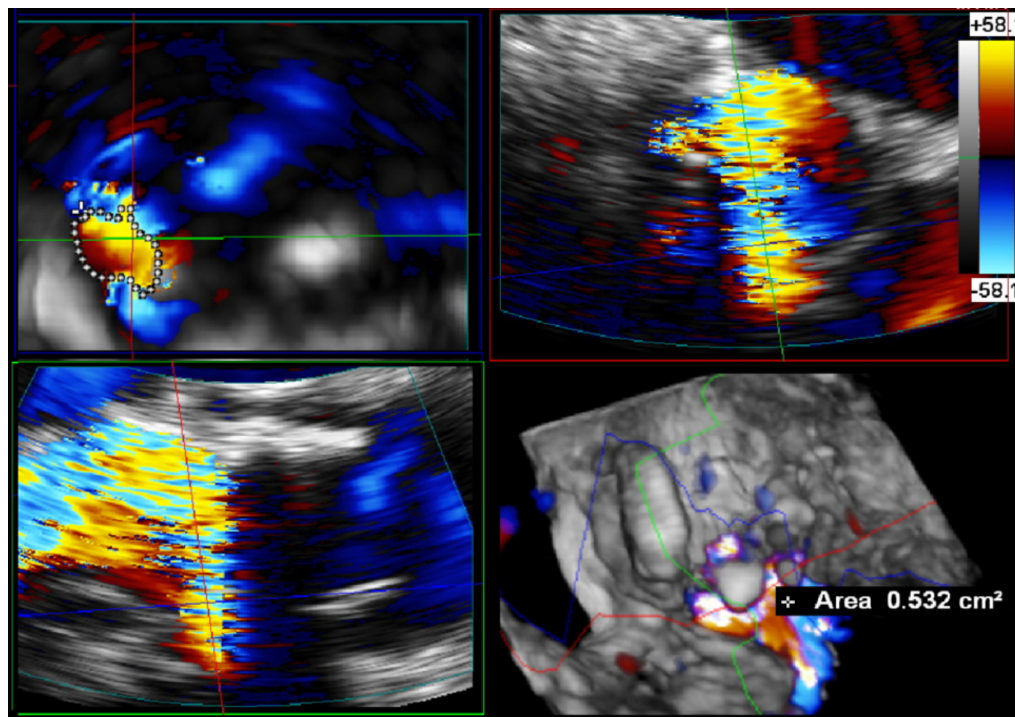


Figure 7. Following AV short-axis imaging, a 3D “zoom modality” with color is applied. The resulting image is presented in four distinct portions: sagittal, coronal, transverse, and whole-volume render. The diastolic frame is carefully selected for optimal visualization. To comprehensively demonstrate the paravalvular leak, the sagittal and coronal planes must be precisely bisected in the transverse plane. By methodically tracing the circular path, a 3D VC of the paravalvular leak can be generated. It is important to note that regurgitation is classified as severe when the VC area exceeds 0.3 cm^2 . 3D: Three-dimensional; VC: vena contracta.

configuration and detecting anatomical or functional cusp abnormalities-such as prolapse, flail, fenestrations, or retraction-which is critical for identifying the AR mechanism^[54].

Cusp prolapse is a common cause of AR. Prolapse can be missed by 2D echo, especially if only the left cusp is involved, due to limitations of imaging alignment in long-axis views. Therefore, MPR reconstruction or X-plane imaging should be performed if eccentric AR jets are found^[55]. MPR imaging, derived from full-volume acquisition, provides precise analysis of prolapse localization and extension, enabling accurate surgical planning. In bicuspid aortic valves (BAVs), prolapse of the fused cusp is very common. MPR analysis can help identify which segment of the cusp exhibits the most significant prolapse, which often results from tethering caused by the raphe insertion at the free margin [Figure 8].

AR severity assessment using 3D echocardiography involves both qualitative and quantitative measures. Qualitatively, 3D color Doppler imaging enhances the understanding of the regurgitant jet’s spatial distribution and its relationship with adjacent structures. This is particularly useful for eccentric jets, the severity of which may be underestimated by 2D approaches^[56]. Quantitatively, 3D echo enables direct planimetry of the VC area, a measure that correlates strongly with Effective Regurgitant Orifice Area (EROA)^[57]. Unlike 2D, 3D echocardiography can accurately measure non-circular and irregularly shaped regurgitant orifices, providing a more precise assessment of AR severity and showing a superior correlation with invasive measures compared to 2D parameters^[58] [Figure 9]. Clinical decision making depends on the precise measurement of regurgitant volume (RVol). 3D echocardiography has significantly enhanced RVol measurement, providing new and more accurate quantification techniques^[59]. Ewe *et al.* conducted an innovative study that compared RVol derived from 3D with that acquired from CMR, which is recognized

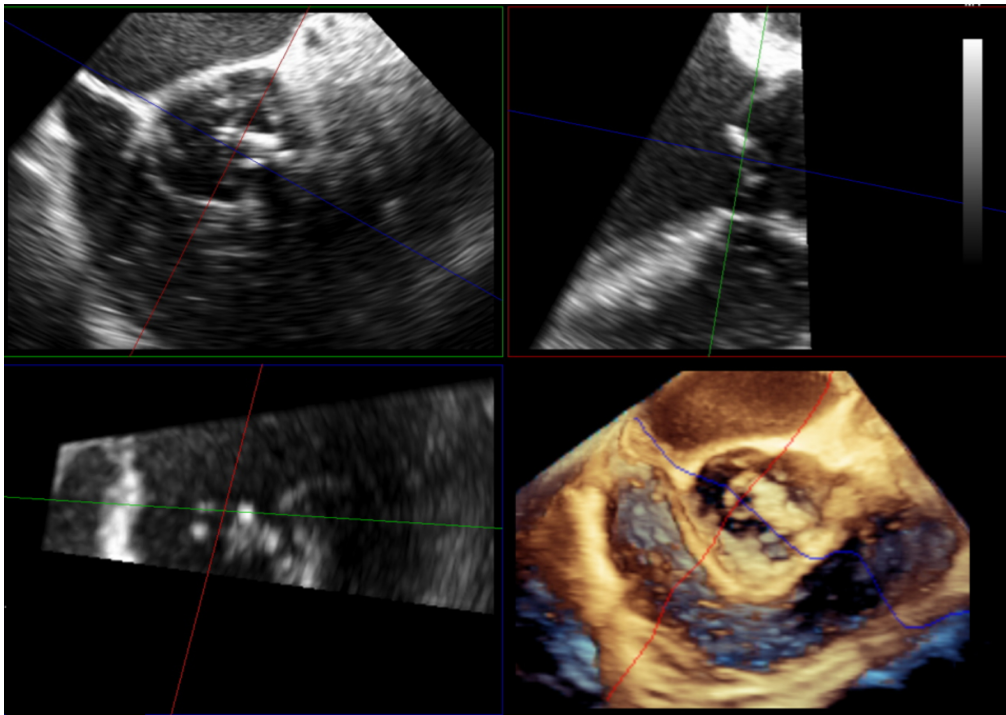


Figure 8. MPR reconstruction of BAV with severe AR provides a detailed assessment of conjoint cusp prolapse. MPR: Multiplanar reconstruction; BAV: bicuspid aortic valve; AR: aortic regurgitation.

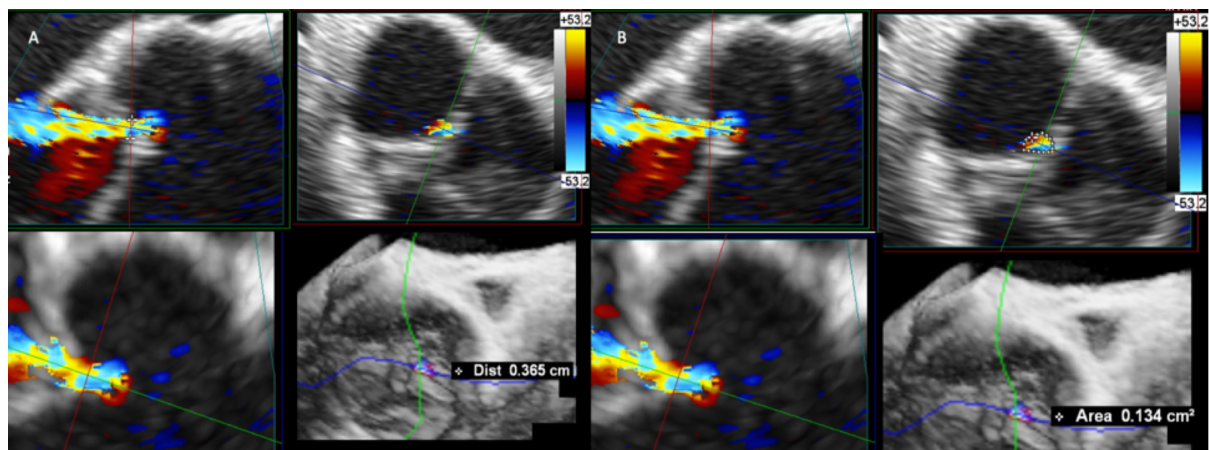


Figure 9. Determination of 3D VCA using multiplanar reconstruction in the 3D color Doppler dataset. In panel A, the 2D VC measure obtained by MPR orthogonal alignment to AR jet. In panel B, cross-sectional plane through the VC with direct planimetry of VC area. 3D: Three-dimensional; VC: vena contracta; MPR: multiplanar reconstruction; AR: aortic regurgitation; VCA: vena contracta area.

as the gold standard. The study found that 3D echo measurements outperformed 2D echo methods in terms of correlation with CMR values^[60]. Using this methodology, AR severity grading is classified based on EROA and/or RVol, with severe AR defined for an EROA ≥ 30 mm² or an RV ≥ 60 mL^[56].

3D echo also enables the calculation of RVol using the difference between the total stroke volume derived from 3D LV volumes and the forward stroke volume measured by Doppler across the LVOT^[61]. Moreover, to quantify RVol directly, 3D color flow quantification techniques have also been developed. These

techniques determine the flow rate and volume during the cardiac cycle by semi-automatically analyzing the 3D color Doppler information. Shanks *et al.* showed that this 3D color flow quantification method is more accurate and reproducible compared to 2D approaches, and it has an excellent intraclass correlation coefficient, indicating low interobserver variability^[62]. RVol quantification using 3D TEE presents certain challenges: the accuracy of measurements may be affected by variables such as temporal resolution, gain modifications, and Nyquist limit settings. However, many of these issues have been addressed by recent developments in image acquisition and analysis software, enhancing measurement accuracy^[63].

Although 3D is widely used in the evaluation of AR, in some cases, such as those with limited acoustic windows, eccentric and/or multiple regurgitant jets, or complex outflow tract geometries, it can be challenging to quantify the severity of the valvulopathy precisely. CMR provides precise, operator-independent estimates of LV volumes, function, and mass, as well as quantification of aortic dilatation and transvalvular flow. Specifically, the 4D flow sequence enables the measurement of RVol under non-laminar flow states by retrospectively analyzing a single 3D volume within the acquired dataset^[64]. The main disadvantage of CMR is the temporal resolution, but recent developments in artificial intelligence technology, particularly machine learning algorithms (e.g., Philips HeartModel), have enabled the automated measurement of chamber quantification and valve regurgitation, significantly reducing CMR analysis times while maintaining equally high reliability^[65].

3D echocardiography enables the precise measurement of three critical parameters that are fundamental for valve-repair assessment and have become a cornerstone of the preoperative, intraoperative, and postoperative evaluation:

Effective height: which is defined as the vertical distance from the annular plane to the free margin of each cusp during diastole. Normal values are about 9 mm to 19 mm^[66].

Geometric height: characterized as the curved length of each cusp during diastole from its point of insertion at the nadir of the sinus to the free margin; it defines the amount of cusp tissue substrate for repair. Normal values are above 17 mm to 18 mm in the tricuspid aortic valve (TAV) and 20 mm in the BAV^[67].

Coaptation length: which refers to the degree of overlap of cusp tissue in diastole. Normal values are about 2 mm to 5 mm^[68]. All these parameters are displayed in [Table 2](#).

These measurements should be obtained using specific sectional planes during the diastolic phase, created by processing 3D datasets, and should be performed on all three cusps in TAVs. In BAVs, these measurements are typically made only on the non-fused cusp due to the marked heterogeneity of the fused cusp^[69]. The gH cannot be correctly measured using 2D echocardiography in TAVs, because the measurement requires an orthogonal plane to the central part of the cusp^[70] [[Figure 10](#)]. In cases of BAV-associated AR, 3D echo provides detailed information about leaflet morphology and quality, fusion patterns, and commissural orientation, which are essential considerations in planning repair techniques^[71]. Evaluation of the aortic phenotype and genetic profile completes the comprehensive assessment needed to select BAV patients suitable for repair^[72]. The multimodality imaging approach provides a comprehensive evaluation, contributing significantly to therapeutic guidance and appropriate patient management^[73].

Finally, 3D echo facilitates the assessment of LV volumes and function, which are crucial in determining the hemodynamic impact of AR^[5]. In clinical practice, 3D echocardiography, particularly with automated software quantification, is essential for detecting LV remodeling and subclinical dysfunction^[74]. Subclinical

Table 2. Definitions and clinical relevance of key parameters in aortic valve assessment by 3D echocardiography

Parameter	Description	Clinical relevance
Geometric height (gH)	The curvilinear distance from the leaflet attachment(nadir) to the leaflet free edge. It is measured in diastole. It represents the amount of cusp tissue	Crucial for assessing intrinsic leaflet pathology. Reduced geometric height can be seen in restrictive leaflet, often due to calcification or fibrosis, contributing to aortic stenosis or impaired coaptation in regurgitation. A sufficient amount of tissue is essential for valve repair techniques
Effective height (eH)	The orthogonal distance from the VBR plane to the coaptation plane of the cusps in diastole. It represents the functional height available for leaflet coaptation	Preoperative negative eH suggests the presence of leaflet prolapse. A key indicator of post repair leaflet competence permits to exclude residual prolapse
Coaptation length (cL)	The length of overlap between the opposing leaflets at the coaptation point when the valve is fully closed	Post-repair quantitative parameter that directly reflects the efficacy of leaflet closure. After valve repair a short coaptation length indicates poor leaflet apposition, increasing the likelihood of repair failure

3D: Three-dimensional; VBR: virtual basal ring.

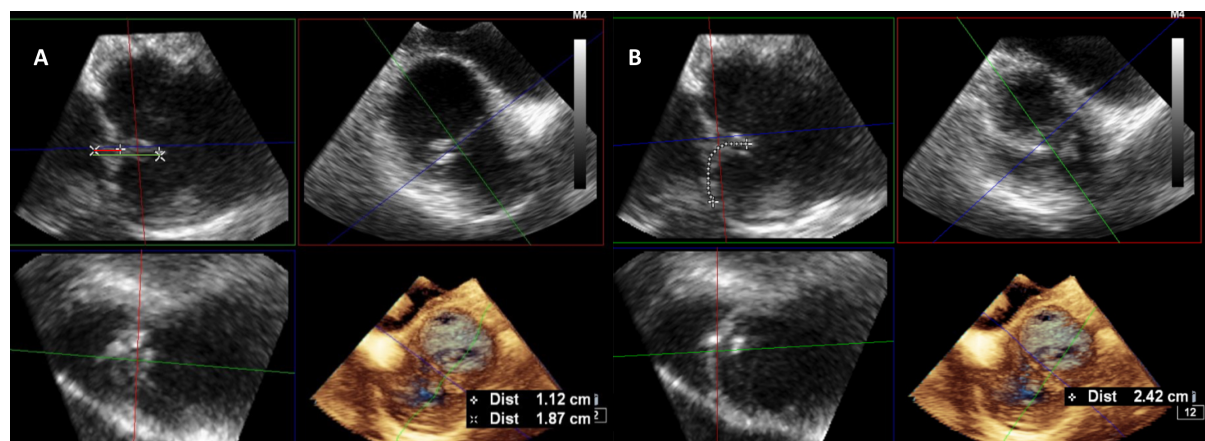


Figure 10. The eH, gH, and cL in TAV can be properly determined by measuring the distances between the right and non-coronary cusps, the non-coronary cusp and the left coronary cusp and the left and right coronary cusps. This is accomplished with a plane near the center of the aortic valve. In patients with BAV, both cL and eH must be examined in a plane perpendicular to the commissures and near the center of the valve (panel A), whereas gH should be examined in a sectional plane perpendicular to the center portion of both cusps (panel B). eH: Effective height; gH: geometric height; cL: coaptation length; TAV: tricuspid aortic valve; BAV: bicuspid aortic valve.

and potentially irreversible cardiac damage can occur in clinically well-compensated patients awaiting surgery. This may be averted by using multimodality imaging parameters, specifically left ventricular global longitudinal strain and CMR^[75].

The role of 3D echocardiography extends beyond preoperative planning. Intraoperative 3D TEE is also a valuable tool for real-time decision making during AV repair procedures^[76]. 3D color Doppler techniques can precisely locate and quantify any residual regurgitation^[77]. Post-repair valve function, assessed by parameters such as cL and eH, is crucial. An eH greater than 9 mm is usually associated with a durable repair and a low risk of significant recurrent regurgitation^[78]. An eH below 4 mm is associated with a higher risk of repair failure^[7].

CONCLUSION

3D echocardiography has transformed the assessment, management, and follow-up of patients with AV disease. From the initial diagnosis and evaluation of severity to surgical planning and post-repair assessment, 3D echocardiography offers unparalleled insights into both the anatomy and function of the AV. As technology advances, the role of 3D echocardiography is expected to expand even further,

potentially enhancing patient outcomes through more personalized and timely interventions.

DECLARATIONS

Authors' contributions

Conceptualization: Italiano G, Belli M, Lassandro Pepe F
writing-original draft preparation: Italiano G, Belli M, Lassandro Pepe F
writing-review and editing: Italiano G, Belli M, Lassandro Pepe F
All authors have read and agreed to the published version of the manuscript.

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All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

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