Three-dimensional echocardiography in mitral valve disease

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Abstract Three-dimensional echocardiography offers great promise for improving the understanding of the mitral valve anatomy, function, and pathology. It may have important implications for medical or surgical management of different mitral valve disease. In this article we provide an overview of the three-dimensional anatomy of the mitral valve. Based on the studies using three-dimensional echocardiography we describe the topography of the mitral valve, its nonplanarity as well as dynamics of the mitral annulus. Furthermore, we review the use of three-dimensional echocardiography in the evaluation of different mitral valve disease. Three-dimensional echocardiography has become a new clinical standard in the assessment of the severity of mitral stenosis by means of accurate mitral valve area measurement. Also, unconventional indices, like the geometry and mitral valve volume may be assessed by three-dimensional echocardiography. It is a very suitable technique for monitoring the efficacy and complications of percutaneous mitral valvuloplasty. Three-dimensional echocardiography allows accurate identification and quantification of prolapse of individual segments of the mitral valve leaflets. Three-dimensional color flow imaging makes echocardiography an accurate method also in the assessment of mitral regurgitation severity. Finally, we outline three-dimensional echocardiography as a potentially useful guide for a surgeon, particularly in mitral valve repair.

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Introduction

Echocardiography has evolved as the most predominant diagnostic imaging technique in Cardiology. Over the last 5 decades the diagnostic capability of echocardiography has increased dramatically from M-mode to two-dimensional (2D) imaging. Recent advances in ultrasound instrumentation and computer technology have led to three-dimensional (3D) echocardiography, thus introducing a new era in cardiovascular imaging.1

Every imaging technique in Cardiology aims at a complete visualization and comprehensive assessment of cardiac morphology and pathology as the heart is a complex geometric structure. Therefore, analysis of the heart in motion in all three or four (including time) dimensions can further facilitate and enhance the diagnostic capabilities of echocardiography. Three-dimensional echocardiography is still in its evolution and at the phase of early adaptation with respect to its clinical application. It should complement current echocardiographic techniques by providing better understanding of the topographical aspects of pathology and refined definition of the spatial relationships of (intra) cardiac structures. Furthermore, it provides new indices not described by 2D echocardiography and makes the existing ones more accurate.2

The assessment of patients with mitral valve disease is one of the most challenging and promising clinical applications of 3D echocardiography. We discuss the 3D anatomy of the mitral valve as well as the feasibility, accuracy and incremental value of 3D echocardiography in the evaluation of mitral valve disease. Some of the presented data, especially related to mitral valve area measurement and evaluation of three-dimensional echocardiography in percutaneous balloon mitral valvuloplasty, are based on experience of our group at the Department of Cardiology of the VU University Medical Center in Amsterdam.

Three-dimensional reconstruction

There are two main approaches of 3D reconstruction. The first is random or freehand scanning which is based on free motion of the ultrasound transducer. Its position in space is located by an acoustic, electromagnetic or mechanical arm location device. The transthoracic approach is used in this mode of acquisition. The limitation of this method is that the accurate endocardial border identification is restricted because of big gaps between imaging planes. The second approach is sequential scanning where the ultrasound motion is predetermined in linear, fan-like or rotational ways. Transthoracic or transesophageal approach is used for this mode of data acquisition. Both the sequentially or randomly collected 2D images are off-line processed by the computer using interpolation algorithms so that the gaps between individual images are filled and finally a volumetric 3D data set is generated. There are several ways to present the data in the 3D volumetric data set. The most used are:

Anyplane echocardiography: This mode of presentation allows the examiner to generate 2D tomographic images in any desired orientation which can be physically unobtainable by conventional 2D echocardiography.

Volumetric rendering technique: This 3D reconstruction creates images resembling the true anatomy of the heart. By choosing a cutting plane and reconstructing the image beyond this plane the heart can be opened as if it was done by a surgeon. Different structures can be examined en face with better perception of the anatomic relationships.

The major limitation of both aforementioned reconstructive 3D echocardiography techniques is that they are time-consuming. Another problem is sometimes the suboptimal image display. This can be related to misalignment and displacement of the ultrasound probe during acquisition as well as variation of the respiratory phase and/or RR interval. Image reconstruction is also operator-dependent. Furthermore, the original gray value is partially lost in 3D images. For this reason it is not possible to obtain information about tissue characteristics from the images.

The ideal technique for 3D reconstruction is real-time 3D echocardiography (RT3D). The system uses a novel matrix phased-array transducer with parallel processing to scan a pyramidal volume. In a pyramidal volume, the images are displayed via anyplane or volumetric techniques rendering images immediately. Second generation matrix transducer became recently available for clinical studies. Because currently available RT3D visualizes the heart only from the transthoracic approach, one of the main limitations is the image quality in hard to image patients, and rarely image artefacts.

Further advances in computer technology have enabled encoding of color flow Doppler data together with gray-scale imaging and 3D presentation of Doppler flow events with surrounding cardiac anatomy.3
Functional anatomy of the mitral valve

Three-dimensional topography of the mitral valve

Three-dimensional echocardiography by viewing the mitral valve from the left atrium shows that the anterior and posterior mitral leaflets have several indentations dividing them into segments or scallops (Fig. 1). The anterior leaflet has three segments: A1 – anterolateral, A2 – middle, A3 – posteromedial. Similarly, the posterior leaflet has three segments: P1 – anterolateral, P2 – middle, P3 – posteromedial. The anterior and posterior leaflets are fused from 3 to 8 mm medially and laterally at the trigones and usually form distinct commissures (anterolateral and posteromedial). The anterior leaflet comprising roughly two thirds of the valve area, is about twofold longer than the posterior leaflet, and is somewhat triangular. The posterior leaflet is more elongated and rectangular. The anterior leaflet is attached to the septum and fibrous annulus of the heart, and it is relatively nondistensible. Although the anterior leaflet accounts for two thirds of the mitral valve area, its attachment to the mitral annulus accounts for only approximately one third of the mitral annular circumference. The anterior mitral leaflet spans the distance between the two fibrous trigones and is in direct continuity with the non-coronary aortic valve leaflet. The posterior mitral valve leaflet is attached to the posterior two thirds of the mitral annulus, which runs along the free wall of the left ventricle and is primarily muscular with little fibrous tissue (explaining its tendency to distend and elongate).

Nonplanarity of the mitral valve and annulus

Based on the studies conducted in an effort to refine the diagnosis of mitral valve prolapse, the geometric shape of the mitral valve and its annulus was defined. It has been documented that the mitral annulus and leaflets are nonplanar saddle-shaped structures which are equivalent with the so-called hyperbolic paraboloid, a geometric surface of which all sections parallel to one coordinate plane are hyperbolas and all sections parallel to another coordinate plane are parabolas (Fig. 2). There are two high points (peaks) lying anteriorly and posteriorly at the aortic insertion and posterior left ventricular wall and two low points (troughs) closest to the apex located medially and laterally (Fig. 3). According to Levine et al. the maximum deviation from planarity, i.e., the distance between the highest and lowest points of the mitral annulus, is on average $1.4 \pm 0.3$ cm. Regarding the leaflet–annular relations, in mediolateral view (four-chamber view in 2D echocardiography) the leaflets can appear above the mitral annulus but in anterolateral view (parasternal long-axis view in 2D echocardiography) they do not ascend the annulus. This is the reason why in the four-chamber view in the era of 2D echocardiography superior leaflet displacement was wrongly diagnosed as prolapse in otherwise normal individuals. The leaflet–annular nonplanarity is
rational in two ways. First, as the base of the left ventricle decreases in circumference during systole but the leaflets do not contract, the mitral annular area can decrease in some way of folding which is achieved by lowering of the distance between the high and lower points of the annulus. Second, the saddle-shape provides a configuration capable of withstanding the stresses imposed by left ventricular pressure during systole. Salgo et al. studied the effect of nonplanarity on stress reduction. Two shape factors which have synergistic effect on stress reduction have been identified: leaflet billowing and annular nonplanarity. The saddle-shape of the mitral annulus was preserved across 3 mammalian species (human, sheep and baboons) with an annular height commissural width ratio of about 15%. Their data suggest that the nature conserves the saddle-shaped configuration of the annulus for a mechanical benefit.

**Dynamics of the mitral annulus**

There are two studies by Flachskampf et al. and Kaplan et al. which provide insights into the dynamics of the mitral annulus. According to these studies the mitral annular area was on average 5–6 cm²/m² corrected for body surface area (because of nonplanarity an area projected into the least squares plane was measured). This area decreased during systole by about 24%. The mechanism by which it was achieved was elliptic-alization due to the reduced distance between two high points with increase in annular height and eccentricity and smaller amount by reduced distance between the two low points (Fig. 4). At the same time the basic features of nonplanarity (2 high and 2 low points) were preserved throughout the cardiac cycle.

**Mitral stenosis**

The severity of mitral stenosis is assessed mainly by estimation of the mitral valve area. Currently, the available 2D echocardiographic and Doppler
techniques have their well-known limitations. The advent of 3D echocardiography has refined the assessment of mitral valve area to such an extent that today it is considered as a gold standard. Besides, 3D echocardiography has introduced new indices which further improve the diagnosis of mitral stenosis. By means of 3D echocardiography it is possible to assess the morphology of the mitral valve also in balloon mitral valvuloplasty which is important in the evaluation of the mechanism and success of the procedure.

Assessment of mitral valve area

In a 3D homogeneous data set using anyplane echocardiography it is possible to pinpoint the cut plane to the tips of the mitral valve so that the true anatomic valve area can be measured. The most optimal way of mitral valve area measurement is: two long-axis views through the mitral valve, nearly perpendicular to each other, are defined by navigation of the lines of intersection. Short-axis cut plane is further positioned at the mitral valve cusp tips, which is selected for area measurement by planimetry (Fig. 5). The advantage of this method is, contrary to 2D echocardiography, that proper alignment of the cut plane is controlled in a 3D data set. It is important because errors due to malpositioning can be obviated. It has been shown that malpositioning errors can achieve up to 88% (1.5 cm²) in the measurement of the mitral valve area which is not acceptable in the management of patient with mitral stenosis.9 In addition, assessment of the anatomic mitral valve area is advantageous because it is hemodynamically independent contrary to effective mitral valve area (measured by pressure half-time and PISA methods) which is hemodynamically influenced by associated abnormalities (aortic or mitral insufficiency, left atrial

Figure 5 Mitral valve area measurement using anyplane echocardiography. Two long-axis cut planes perpendicular to each other (A and B). By the guidance of line of intersection, optimal short-axis cut plane was selected (C). Three-dimensional data set and spatial alignment of 3D cut planes (D).
and ventricular diastolic properties, heart rate, rhythm, and cardiac index).

In the first studies carried out by Kupferwasser et al. and Chen et al. the mitral valve area was assessed by anyplane 3D transesophageal echocardiography (TEE). The mitral valve area assessed by 3D echocardiography was compared with the mitral valve area measured by 2D methods (2D planimetry and pressure half-time) and invasively assessed mitral valve area according to the Gorlin formula. Only Kasliwal et al. compared the mitral valve areas by 3D echocardiography with the true mitral orifice measured directly at operation. The comparison achieved a high degree of agreement ($r = 0.95$) thus 3D echocardiography, today, can be considered as a new clinical standard in the assessment of the anatomic mitral valve area. Three-dimensional echocardiography has been shown to be accurate in the assessment of mitral valve area also in the transthoracic approach. Sugeng et al. confirmed that freehand 3D transthoracic echocardiography comparing with 2D planimetry, pressure half-time and the PISA methods is the most accurate when it was compared with invasively determined mitral valve area according to the Gorlin formula. The most attractive is definitely RT3D echocardiography which allows on-line assessment of the mitral valve area. Images are displayed as two simultaneous intersecting orthogonal long-axis scans (B-mode scans) and two perpendicular short-axis scans (C-mode scans). These C-mode scans allow the display of short-axis views of the mitral valve from an apical transducer position. Binder et al. found out that RT3D echocardiography comparing with 2D planimetry and pressure half-time methods allows accurate measurement of the mitral valve area from the transthoracic approach. It is of course evident in patients with an adequate acoustic window.

**New indices of mitral stenosis**

Thickening of mitral leaflets in rheumatic mitral stenosis is a well-known phenomenon. Limbu et al. were the first who quantified the mitral valve volume in vivo in normal subjects and patients with rheumatic mitral stenosis. The boundary tracing method was used for this measurement: several slices were reconstructed around the center axis of the mitral apparatus. The boundaries of the mitral leaflets were traced by the mouse-driven cursor. Summing up the corresponding subvolumes the volume of the entire mitral valve was finally calculated (Fig. 6). The mitral valve volume in normal individuals was on average 4.5 ml and 9 ml in patients with mitral stenosis. When they divided patients with mitral stenosis into the sinus rhythm and atrial fibrillation groups, patients with atrial fibrillation had a propensity to have a larger mitral valve volume and were older than patients with sinus rhythm. Thus, etiologic relationship between atrial fibrillation and further enlargement of the mitral valve volume was speculated. Gilon et al. studied in vitro the hypothesis that the stenotic mitral valve influences the pressure and flow not only by cross-sectional area but also by 3D geometry of the stenotic valve proximal to the orifice. With the use of 3D echocardiography and stereolitography they constructed by laser polymerization different shapes of mitral valve: domed, intermediate and flattened. Coefficient of contraction was calculated as effective area divided by anatomic orifice area. Coefficient of contraction decreased as the mitral valve was flattened. The study confirmed that variations in contraction coefficient (i.e., the 3D geometry of the mitral valve) led to varying pressure gradients that were up to 40% higher for the flattest valves. Thus, doming valves permit a higher cardiac output than flat ones.

**Three-dimensional echocardiography in balloon mitral valvuloplasty**

Three-dimensional echocardiography by volume rendering allows visualization of the mitral valve en face either from the left atrium or the left ventricle. Applebaum et al. evaluated the mechanism of balloon valvuloplasty by 3D echocardiography. Volume rendered 3D images enabled visualization of commissural splitting and leaflet tears not seen on 2D (Figs. 7 and 8). They found that balloon mitral valvuloplasty was more successful when complete splitting was achieved as compared with partial splitting. Moreover, in 38% of patients in whom an increase of mitral regurgitation developed, tear was visualized by 3D. Our group, Langerveld et al., conducted a similar study where 3D TEE enabled a better description of the mitral valvular anatomy following balloon mitral valvuloplasty, compared to 2D echocardiography. In addition, significant relation of mitral valve volume before valvuloplasty to a successful procedure was found. In the study by Zamorano et al., RT3D echocardiography had the best agreement with the Gorlin-derived mitral valve area, in contrast to 2D planimetry and pressure half-time derived mitral valve area, particularly in the immediate post-percutaneous mitral valvuloplasty.
Mitral valve prolapse

Echocardiography is the most utilized imaging modality for diagnosis of mitral valve prolapse. M-mode and 2D echocardiography frequently lead to both false-positive and false-negative diagnoses. It is because of the nonplanar leaflet–annular relations of the mitral valve. Prolapse is generally defined as a displacement of a bodily part from its normal position or relations. By 3D echocardiography it is possible to visualize the mitral valve en face from either the left atrium or the left ventricle. In volume rendered images looking down in the left atrium, mitral valve prolapse is viewed as a convexity or bulge, and often as bright area when compared with the rest of the mitral leaflet. Looking up in the left ventricle mitral valve prolapse appears as a spoon-like depression. In patients with mitral valve prolapse and mitral regurgitation a crack due to noncoaptation can be identified (Fig. 9). Three-dimensional echocardiography allows accurate identification and quantification of prolapse of individual scallops/segments of the mitral valve leaflets (Fig. 10). Two intraoperative studies, conducted by Ahmed et al. and Chauvel et al. confirmed that the topography of prolapsing scallops/segments by 3D echocardiography was correct in 78% and 86%, respectively. Contrary to 2D echocardiography, 3D echocardiography allowed measurements of the area and width of the prolapsed portion of the leaflet as well as measurements of the circumference of the
posterior part of the mitral annulus. This information could aid the surgeon in deciding the extent of valvular tissue resection.\textsuperscript{21,22}

**Mitral regurgitation**

Accurate evaluation of mitral regurgitation severity is a challenging task in Clinical Cardiology. The current 2D echocardiographic methods used to quantify mitral regurgitation have their well-known limitations. Three-dimensional echocardiography has the potential to improve the assessment of mitral regurgitation by facilitating the visualization of complex mitral anatomy in three dimensions and providing more accurate quantification of regurgitant color Doppler flow events.\textsuperscript{23–25} Investigators have aimed to validate 3D echocardiography mainly in the measurements of regurgitant jet volumes, flow convergence surface area and anatomic regurgitant orifice area.

**Three-dimensional quantification of regurgitant jet volume**

The first studies used volume rendered gray-scale imaging to visualize Doppler flow in three dimensions.\textsuperscript{26,27} The differentiation of regurgitant jets from the surrounding cardiac structures was difficult. The volume of the mitral regurgitant jet was measured by “summation of discs” method.\textsuperscript{28} Later, De Simone and colleagues proposed a method of color coding of regurgitant mitral jets derived from digital data.\textsuperscript{29–33} Jet volumes were calculated by segmentation with automatic selection of turbulence and high-velocity components.

![Figure 7](https://example.com/f7.png)

**Figure 7** Diastolic frames of the 3D reconstruction of the mitral valve orifice as seen from the left atrium before (A) and after (B) balloon valvuloplasty. A posteromedial commissural split is visualized (arrow). Ao — aorta; LAA — left atrial appendage.\textsuperscript{17}

![Figure 8](https://example.com/f8.png)

**Figure 8** Diastolic frames of the 3D reconstruction of the mitral valve orifice as seen from the left atrium before (A) and after (B) balloon valvuloplasty. A posteromedial (white arrow) and anterolateral (black arrow) commissural split is visualized. Ao — aorta; LAA — left atrial appendage.\textsuperscript{17}
or volume units (voxels) containing the selected Doppler data. This mode of 3D color flow imaging recognized different patterns of eccentric regurgitant jets, not described previously, such as cylinder, tongue, spiral and spoon-like patterns. What is more important is that the calculation of the jet volume was capable to accurately quantify asymmetrical jets. Recently, Sugeng et al. improved the method of color encoding of regurgitant jets together with gray-scale imaging of the surrounding cardiac anatomy. This improved technique provided information on the origin and extent of the dehiscence in case of paravalvular leaks, as well as insight into the direction of the regurgitant jets.

Flow convergence zone and 3D echocardiography

The flow convergence or proximal isovelocity surface area (PISA) method is based on the phenomenon that flow accelerates towards the regurgitant orifice and forms a series of concentric hemispheric shells of increasing velocity. According to the continuity concept, the flow rate is calculated by multiplying the isovelocity surface area and its corresponding aliasing velocity. Thus, accurate measurement of the flow convergence surface area is the most important aspect for obtaining accurate flow rate. Conventional 2D methods rely on assumptions that the isovelocity...
surface is hemispheric or hemielliptic. However, 3D imaging has revealed that the morphology of the flow convergence region is more complex and unpredictable in shape. Since 3D can display the entire flow convergence region en face viewing from the left atrium, a more accurate assessment of its area can be done without the need to make geometric assumptions. Three-dimensional flow convergence based methods have been shown to accurately predict the flow rate.

Regurgitant orifice area measurement by 3D echocardiography

The regurgitant orifice area is a measure of valvular incompetence useful for the assessment of mitral regurgitation. Up to now, measurement of the regurgitant orifice area was based on Doppler methods which calculated the effective orifice area. Three-dimensional echocardiography provides an opportunity to visualize the regurgitant orifice and so the anatomic regurgitant orifice area measurement. It has been shown that the anatomic regurgitant orifice area measured directly by planimetry from 3D volume rendered images correlates well with effective regurgitant orifice area calculated by the proximal convergence method.

Functional mitral regurgitation

Functional mitral regurgitation is defined as an insufficiency of the structurally normal mitral valve developing as a consequence of regional or global left ventricular dysfunction. It is a complication of either chronic ischemic heart disease, dilated or hypertrophic cardiomyopathy. Functional mitral regurgitation is associated with increased mortality independent of left ventricular dysfunction. The mechanisms which participate in the development of functional mitral regurgitation are related to the geometry of the mitral valve, mitral annulus and papillary muscles. Since the relation of these anatomical structures is explicitly three dimensional, 3D echocardiography provides the best mode to study their relationship.

Mitral annular geometry

Flachskampf et al. and Kaplan et al. have shown by 3D echocardiography that functional mitral regurgitation is associated with annular dilation and its reduced cyclic variation. Compared with normal subjects, the annulus in patients with functional mitral regurgitation is larger and has greater mitral annular area, longer perimeter, reduced annular height and eccentricity, and increased distance between high points of the mitral annulus.

Leaflet geometry

Using RT3D echocardiography, Kwan et al. studied the difference of mitral valve deformation between ischemic and dilated cardiomyopathy with significant functional mitral regurgitation. Mitral valve tethering has been found as a strongest determinant of mitral regurgitation severity and the pattern of mitral valve deformation was asymmetrical in ischemic heart disease, whereas it was symmetrical in dilated cardiomyopathy.

Papillary muscles geometry

Several studies have been performed in an effort to elucidate a 3D papillary muscle—mitral relation. The results of these studies show that especially medial and posterior shift of the ischemic medial papillary muscle, measured by 3D reconstruction, is related to the development of functional mitral regurgitation.

Mitral valve repair and 3D echocardiography

Mitral valve repair has become more common in the last decade making up more than half of the mitral valve procedures. Various techniques have been proposed for valve reconstructions. The decision “how to operate” depends on the underlying pathology of the mitral valve diagnosed by preoperative echocardiography. Conventional 2D echocardiography is a useful guide for accurate surgical analysis, however, in complex valvular pathologies some spatial relations and different structural features can be perceived erroneously even by experienced echocardiographer. Therefore, the technique of repair is frequently modified in the operating room by close examination of the mitral valve, but the surgeon is challenged by limited time, operating field and nonphysiologic condition of the heart being devoid of blood. Three-dimensional echocardiography has the potential to overcome these difficulties by showing the heart in “surgeon’s view” even in more physiologic state as during operation.

There are few published data regarding the feasibility of 3D echocardiography in the operation theater. Abraham et al. demonstrated that 3D
Three-dimensional echocardiography can detect new morphologic findings (mainly valve fenestrations) in 25% of cases, not seen on 2D TEE. In 1 patient 3D TEE resulted in a decision to perform valve repair instead of replacement. As it was mentioned previously, 3D TEE has been proved to be accurate in identifying the location of the prolapsing segment and quantifying the amount of the prolapsed tissue by measuring the area or the width. This information could aid the surgeon in deciding the extent of mitral valve resection. In the study carried out by Macnab et al., 3D echocardiography was superior in accurate localization and identification of pathology of the mitral valve. It was particularly striking for the commissural segments.

Conclusion

Three-dimensional echocardiography allows visualization of the heart in a way different from 2D echocardiography, as it looks in reality. The assessment of the morphology, function and pathology of the heart, and especially the mitral valve apparatus by 3D echocardiography is more accurate. Comparing with 2D echocardiography, 3D echocardiography offers advantages for the morphologic and quantitative assessment of mitral valve stenosis, prolapse and regurgitation. It appears that 3D echocardiography has the potential for planning operations and assessing interventional or surgical results. Furthermore, 3D echocardiography provides new quantitative indices unobtainable by conventional 2D imaging. Both technical improvement and larger studies will enhance the clinical applicability of 3D echocardiography in the nearest future.

References


