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Three-Dimensional Echocardiography of Normal and Pathologic Mitral Valve: A Comparison With Two-Dimensional Transesophageal Echocardiography

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Objectives. **This study was done to ascertain whether three-dimensional echocardiography can facilitate the diagnosis of mitral valve abnormalities.**

Background. **The value of the additional information provided by three-dimensional echocardiography compared with two-dimensional multiplane transesophageal echocardiography for evaluation of the mitral valve apparatus has not been assessed.**

Methods. **Thirty patients with a variety of mitral valve pathologies (stenosis in 8, insufficiency in 12, prostheses in 10) and 20 subjects with a normal mitral valve were studied. Images were acquired using the rotational technique (every 2°), with electrocardiographic and respiratory gating. From the three-dimensional data sets, cut planes were selected and presented in both two-dimensional format (anyplane echocardiography) and volume-rendered dynamic display. The data were compared with the original multiplane two-dimensional images. Different features of the mitral valve apparatus were defined and graded by three observers for clarity of visualization and confidence of interpretation as 1) inadequate, 2) sufficient, or 3) excellent.**

Results. **All the techniques provided good visualization of the mitral valve (mean global scores ± SD for multiplane, anyplane and volume-rendered echocardiography were 2.22 ± 0.34, 2.24 ± 0.26 and 2.30 ± 0.25, respectively). With volume-rendered echocardiography, the mitral valve apparatus was scored higher in pathologic than in normal conditions (2.38 ± 0.24 vs. 2.16 ± 0.21, $p < 0.002$). The spatial relationships between the mitral valve and other structures, leaflet mobility, commissures and orifice were scored higher by volume-rendered echocardiography. Prostheses were evaluated equally well by the three methods. Multiplane and anyplane echocardiography were superior for the evaluation of leaflet thickness, subvalvular apparatus and annulus.**

Conclusions. **Transesophageal three-dimensional echocardiography facilitates imaging of some features of the mitral valve apparatus and provides additional information for comprehensive assessment of mitral valve abnormalities.**

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The mitral valve apparatus is a complex structure that can be affected by a multitude of acquired and congenital disorders. An optimal interaction of the different anatomic elements comprising the leaflets, the annulus, the chordae tendineae, the papillary muscles and the left atrial and left ventricular walls is needed for its functional integrity (1). Consequently, a comprehensive assessment of mitral valve pathology requires optimal visualization of all these elements (2).

Echocardiography has become the examination of choice for evaluating valvular heart disease, particularly the mitral valve. Precordial two-dimensional echocardiography provides visualization of mitral valve pathomorphology, and Doppler techniques allow assessment of the hemodynamic consequences of morphologic abnormalities. However, the detailed anatomic analysis of the mitral valve required for reconstructive surgery is not possible with optimal precordial imaging. Recently, the transesophageal approach, particularly the use of multiplane probes, has increased the diagnostic accuracy of echocardiography (3–6), but mitral valve structures are still displayed in a two-dimensional format, and cardiologists must mentally conceptualize the complex three-dimensional relationship of the different elements of the mitral valve.

Dynamic three-dimensional echocardiography would offer the unique advantage of directly visualizing the relationships of cardiac structures in motion (7–15). Recent studies using three-dimensional reconstructions as wire-frame displays in normal subjects have provided new information on mitral valve shape (16). Our initial experience is based on rotational image acquisition using a multiplane transesophageal transducer (17)

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and volume-rendered three-dimensional display of the beating heart. From our experience in an unselected population (18), we felt that three-dimensional reconstruction of transesophageal images could facilitate the interpretation and analysis of the anatomy of the mitral valve apparatus.

In this prospective study we studied the information provided by three-dimensional echocardiography on mitral valve pathology and its potential advantages and limitations in comparison with multiplane transesophageal echocardiography.

Methods

Study subjects. Thirty patients referred for the evaluation of mitral valve disease (stenosis in 8, regurgitation in 12, prostheses in 10, atrial fibrillation in 12) and 20 patients referred for transesophageal echocardiography without clinical signs of mitral valve disease (follow-up after aortic dissection 7, exclusion of embolic source 7, aortic valve disease 6) were prospectively studied. Thirty patients were men, and 20 were women. Mean age ± SD was 57 ± 15.

Clinical examination procedure. Transesophageal studies were performed following precautions, preparation of the patients and insertion of the multiplane probe similar to the standard procedures that are described elsewhere (17). After the diagnostic study to answer the clinical question, the probe was positioned at midesophageal level for the acquisition of the tomographic images of the mitral valve for three-dimensional reconstruction. Patient movement during the image acquisition can be prevented by thoroughly explaining the procedure before the study. The operator has to find the central axis around which the imaging plane is rotated to encompass the mitral valve apparatus. Informed consent was obtained in all patients.

Two-dimensional echocardiography. We used a 5-MHz 64-element multiplane transducer (Delft Instruments Medical Imaging B.V.) connected to a Hewlett-Packard Sonos 1500 system. A complete interrogation of the mitral valve apparatus was performed by obtaining short-, intermediate- and long-axis views with different rotation. Recording was made on VHS video tape for later interpretation.

Three-dimensional echocardiography. During the transesophageal echocardiographic study, an acquisition sequence for dynamic three-dimensional reconstruction was performed as previously described (19). Briefly, the video output of the echocardiographic system is interfaced to the three-dimensional reconstruction system (Echo-scan, TomTec GmbH), and the control knob of the multiplane probe is connected by a mechanical linkage to a step motor. A software control activates the motor with incremental steps of 2°. Spatial and temporal information was optimized by ECG and impedance-based respiratory gating. Ninety sequential cross-sections are obtained during each complete heart cycle, resulting in a conical volumetric data set encompassing the mitral valve apparatus. Data processing was performed off-line by the analysis program of the three-dimensional echocardiographic system. Cardiac cross sections are resampled in their correct sequence according to their ECG phase in cubic data sets. The image data are converted from polar to Cartesian coordinate format and interpolated to "fill the gaps" between sequential cross sections. Several algorithms are used to reduce noise, enhance edges and reduce spatial artifacts.

Table 1. Descriptive Features of the Normal and Pathologic Mitral Valve

Relationship with other structures	Recognition of the anatomic relationship with other cardiac structures
Leaflet mobility	Assessment of systodiastolic excursion of the leaflets, with estimation of their location in the space
Leaflet thickness	Evaluation of the tip of the leaflets
Commissures	Evaluation of the closure line along which the leaflets coapt, from posteromedial to anterolateral extremes
Orifice (area/shape)	Assessment of the minimal dimensions and shape of the mitral orifice
Annulus	Dimension of the annulus
Subvalvular apparatus	Inspection of the chordae tendineae and papillary muscles
Prosthesis	Evaluation of sewing ring and valvar structures

Categories were 1 = inadequate; 2 = sufficient; 3 = excellent.

Image display. *Anyplane and paraplane echocardiography.* From the volume sets, any desired cross-section of the mitral valve can be computed and displayed in a dynamic two-dimensional format (anyplane echocardiography). This allows unlimited cut planes independent of any original ultrasonic window. Moreover, from a selected cut plane up to 8 parallel cut planes at predetermined intervals can be reconstructed and displayed in motion.

Volume-rendered display. Once an appropriate cut plane has been chosen, a threshold value is selected to differentiate cardiac structures from the blood pool and background. The gray scale information of the structures in the volume sets is rendered, and a gradient shading algorithm enhances the views of the structures. The perception of depth can be further enhanced by creating rotational sequences on the output screen.

Image analysis. All the echocardiograms were analyzed by three experienced observers. For multiplane two-dimensional echocardiography, all the images obtained during the diagnostic study with systematic scanning of the mitral valve using manipulation of the probe and different rotations of the transducer were evaluated (3,6). Anyplane computer-reconstructed cross sections were selected through the mitral valve apparatus guided by the orientation on basic image data. Three-dimensional volume-rendered images were derived from the following cut planes: 1) view on the mitral valve from an atrial perspective; 2) short axis of the left ventricle at the level of the papillary muscles (mitral valve from ventricular perspective) with different angulation towards the left ventricular outflow; 3) longitudinal views (atrioventricular views) in multiple planes to optimize the display of the mitral apparatus (20).

Different features of both the normal and pathologic mitral valve were defined (Table 1) and subjectively scored for clarity

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Table 2. Definitions of Individual Feature Grades

Relationship with other structures	
Excellent:	Immediate appreciation of the location of the mitral valve apparatus in the space and its anatomic relationship with other cardiac structures
Sufficient:	Incomplete display of the relationship between mitral valve and other cardiac structures
Inadequate:	Lack of information on the anatomic relationship with other cardiac structures
Leaflet mobility	
Excellent:	Complete analysis of the movement of the leaflets, both in all their extension (space) and throughout the cardiac cycle (time)
Sufficient:	Analysis of the movement of the leaflets is possible in only some phases of the cardiac cycle
Inadequate:	Fair visualization of the movements of the leaflets
Leaflet thickness	
Excellent:	From the images, the thickness of the leaflets can be estimated and measured
Sufficient:	The thickness of the leaflets is less defined, but it can still be measured
Inadequate:	The thickness of the leaflets cannot be assessed
Commissures	
Excellent:	Both commissural areas are identified
Sufficient:	Only one commissure is identified
Inadequate:	No visualization of the commissures
Orifice	
Excellent:	The mitral valve orifice can be analyzed and displayed at different levels, with appreciation of its geometry in the space
Sufficient:	The mitral valve orifice can be analyzed in only a few cut planes; a short-axis cut plane is still possible, but the shape of the orifice is incompletely understood
Inadequate:	Difficult interrogation of the mitral valve orifice with inappropriate short-axis cut plane selection
Annulus	
Excellent:	The annulus can be recognized and located over its whole extension
Sufficient:	The annulus cannot be located over all of its extension
Inadequate:	Fair visualization of the annulus, with no information on its spatial configuration
Subvalvular apparatus	
Excellent:	Visualization of secondary chordae and papillary muscles
Sufficient:	Visualization of primary chordae and papillary muscles
Inadequate:	Chordae and papillary muscles are fairly visible
Prosthesis	
Excellent:	Visualization of both the sewing ring and the mechanical components. These two features can be differentiated
Sufficient:	Visualization of either the sewing ring or the mechanical part. No clear distinction between these two features
Inadequate:	The sewing ring and the mechanical part cannot be identified

of visualization and confidence of interpretation. For each feature, a consensus was achieved on a 3-point scale (1 = inadequate; 2 = sufficient; 3 = excellent) (Table 2). For each patient, a classification form based on the results with different methods (multiplane, anyplane and volume-rendered echocardiography) was completed. A final echocardiographic score index of the visualization of both the normal and abnormal

Table 3. Mean (± SD) Score Index of the Visualization of the Mitral Valve Apparatus

	MPE	APE	VRE
Overall (n = 50)	2.22 ± 0.34	2.24 ± 0.26	2.30 ± 0.25
Normal (n = 20)	2.14 ± 0.20	2.21 ± 0.19	2.16 ± 0.21
Pathologic (n = 30)	2.28 ± 0.41	2.25 ± 0.30	2.38 ± 0.24*

*p < 0.002. APE = anyplane echocardiography; MPE = multiplane echocardiography; VRE = volume-rendering display.

mitral valve apparatus with multiplane, anyplane and volume-rendered echocardiography was obtained for each patient, averaging the sum of the individual scores. Moreover, a score index for each feature was calculated averaging the sum of the scores of the individual features.

Statistical analysis. The global score of each echocardiographic method and the scores of individual features are reported as mean ± SD. However, because the score values are not normally distributed, the comparison of the results obtained with multiplane, anyplane and volume-rendered echocardiography was performed with nonparametric tests (Friedman two-way analysis of variance for paired samples and

Table 4. Mean Scores for the Individual Features of the Mitral Valve

	MPE	APE	VRE	p Value
Relation with other structures				
Overall	2.12	2.12	2.92	< 0.0001
Normal	2.05	2.10	2.80	0.0006
Pathologic	2.16	2.13	3.0	< 0.0001
Leaflet mobility				
Overall	2.48	2.53	2.82	0.04
Normal	2.40	2.45	2.80	0.11
Pathologic	2.57	2.61	2.85	0.33
Leaflet thickness				
Overall	2.73	2.70	1.87	< 0.0001
Normal	2.59	2.59	1.70	< 0.0001
Pathologic	2.85	2.80	2.04	0.0001
Commissures				
Overall	1.92	2.02	2.65	< 0.0001
Normal	1.80	1.90	2.60	0.0006
Pathologic	2.04	2.14	2.71	0.005
Orifice				
Overall	1.36	1.75	2.53	< 0.0001
Normal	1.30	1.65	2.40	< 0.0001
Pathologic	1.42	1.85	2.66	< 0.0001
Annulus				
Overall	2.70	2.65	1.80	< 0.0001
Normal	2.60	2.60	1.70	< 0.0001
Pathologic	2.80	2.71	1.90	< 0.0001
Subvalvular apparatus				
Overall	2.41	2.31	1.21	< 0.0001
Normal	2.20	2.26	1.15	< 0.0001
Pathologic	2.61	2.42	1.28	< 0.0001
Prosthesis (n = 10)	2.00	1.81	2.0	0.7

Abbreviations as in Table 3.

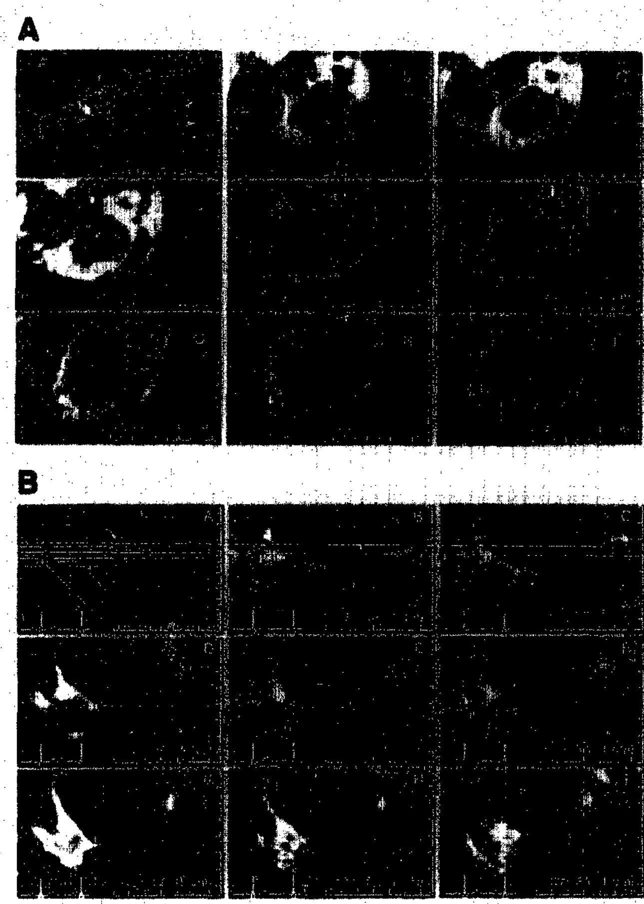


Figure 1. A, Parallel short-axis scanning of the mitral valve (paraplane echocardiography). From the original three-dimensional data set (panel A), a short-axis cut plane at the level of the mitral annulus is selected. The corresponding computer-reconstructed two-dimensional image is displayed in panel B. From this reference plane, seven parallel cut planes are automatically computed at predefined intervals (in this example, every 1.6 mm) and represented in panels C to I. B, The lines in panel A represent the position in the three-dimensional data set of selected cut planes through the mitral valve in the anteroposterior direction. In this example, the first cut plane is chosen at the level of the left ventricular outflow tract (panel B), and then the mitral valve apparatus is sliced in the anteroposterior direction. This allows a detailed morphologic evaluation of mitral leaflets and facilitates a comprehensive analysis of their spatial arrangements.

Mann-Whitney test for unpaired comparison of two groups). A p value ≤0.05 was considered statistically significant.

Results

Both acquisition and reconstruction were possible in all patients. Additional sedation was not required. A total of 72 data sets were acquired (28 patients with single and 22 with double acquisition). The total time needed to optimize the position of the probe, to calibrate the system, to select the parameters for acquisition, and to acquire the images was always less than 10 min. Data postprocessing ranged between 5 and 15 min. The time required for image analysis ranged from 30 to 90 min. All methods provided similar mean global scores, both in normal and abnormal conditions. For volume-rendered echocardiography, the mean score was higher in abnormal than in normal valves (Table 3). The comparison of the scores for the individual features is reported in Table 4.

Normal mitral valve. Anyplane echocardiography allowed optimal selection of the short-axis cut plane, providing direct objective display of the commissures and the closing line of the leaflets from a single cut plane. Paraplane interrogation of the mitral valve allowed detailed analysis of leaflet morphology (Fig. 1). In addition, volume-rendered echocardiography offered the unique advantage of visualizing the mitral leaflets from both an atrial and ventricular perspective. Commissure line, scallops of the leaflets, and right and left fibrous trigones were visualized in detail (Fig. 2). A range of variability in the morphologic features of the leaflets was found. In Figure 3, the appearance of a normal mitral valve from above with multiple scallops of the anterior leaflet closely resembles the anatomic specimen shown for comparison. Leaflets could also be evaluated from a left ventricular perspective. In contrast, leaflet thickness, annulus and subvalvular apparatus were scored lower by volume-rendered echocardiography (Table 4).

Abnormal mitral valve. Thicknesses of the leaflets, annulus and subvalvular apparatus were equally scored by multiplane echocardiography and anyplane echocardiography. For these features, volume-rendered echocardiography was less reliable. In contrast, volume-rendered echocardiography was superior

Figure 2. Volume-rendered display of a normal mitral valve after selection of a tangential cut plane at the level of the atrioventricular junction. This view shows the area of continuity of the anterior mitral leaflets with the leaflets of the aortic valve. The fibrous trigones can be recognized at each end of this area (**arrows**). AML = anterior mitral leaflet; AV = aortic valve.

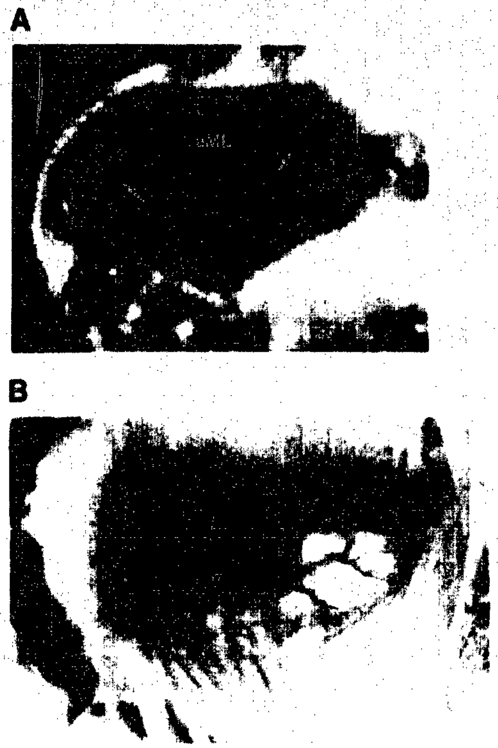


Figure 3. **A,** A mitral valve viewed from above showing the variation that exists in the number of scallops. The anterior leaflet is shown (aML), with several scallops. Both commissures are also clearly visualized (**arrows**). **B,** An anatomic specimen is shown for comparison.

for the evaluation of commissures, orifice and relationship with other structures (Table 4).

Mitral stenosis/regurgitation. In patients with mitral stenosis and/or regurgitation, views from within both the left atrium and the left ventricle allowed proper assessment of leaflet mobility and commissural fusion. Orifice shape and valve surface area were also appreciated. A funnel-like appearance of the mitral valve with a pathologic specimen for comparison is shown in Figure 4. Left atrial appendage could be analyzed in detail (Fig. 5). In a patient with combined stenosis and insufficiency, a thrombus in the left atrial appendage appeared as protruding into the left atrial cavity (Fig. 6).

Mitral valve prolapse. Different degrees of prolapse were present in seven patients. Compared to multiplane echocardiography, additional information from volume-rendered echocardiography was obtained in all these patients. Views from the left atrium were used to appreciate leaflet motion and to recognize which leaflet and which scallops were involved (Fig. 7).

Double-orifice mitral valve. A patient with corrected atrioventricular septal defect was evaluated for residual mitral regurgitation. Three-dimensional reconstruction of the mitral valve and the corresponding pathologic specimen after valve replacement are shown in Figure 8.

Mitral prostheses. In 10 patients, mechanical prostheses of different types were studied (Björk-Shiley 6, St. Jude Medical 1, Medtronic-Hall 1, Hancock 1 [Fig. 9], annular ring 1). All the echocardiographic methods provided similar scores (Table 4).

Discussion

The esophagus represents a relatively stable transducer position for rotational acquisition of images with a multiplane transducer and offers several advantages over other methods for three-dimensional reconstruction (7). In the present study, basic images were acquired with a commercially available multiplane probe during a routine diagnostic study. Border detection was performed by a threshold algorithm, with the advantage of relatively quick access to three-dimensional data that made it possible to select cut planes 15 min after acquisition. From the postprocessed three-dimensional data, unrestricted cut planes were selected and displayed in two-dimensional format. Finally, volume rendering was applied for depth perception.

The main goal of the present study was to compare multiplane, anyplane, and volume rendered echocardiography in terms of visualization of different components of the mitral valve apparatus. The results of this study indicate that three-dimensional reconstruction of the mitral valve complements the morphologic data obtained with multiplane echocardiography. When individual anatomic features were separately analyzed, volume-rendered echocardiography was superior to anyplane and multiplane echocardiography for the evaluation of relationship with other structures, leaflet mobility, commissures and orifice. In contrast, leaflet thickness, subvalvular apparatus and annulus were scored lower by volume-rendered echocardiography.

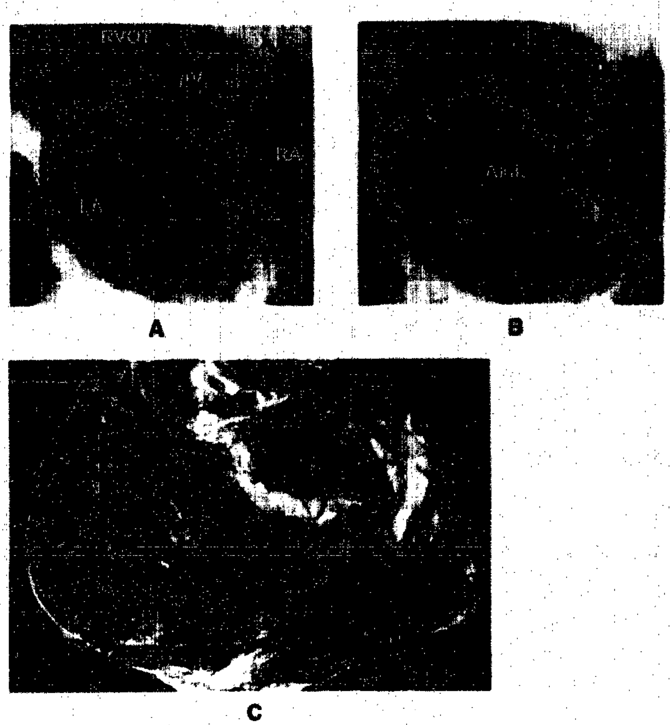
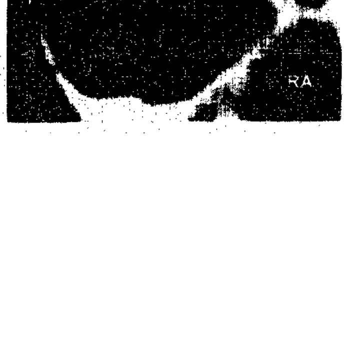


Figure 4. Three-dimensional reconstruction with volume-rendered display of a patient with mitral stenosis. A cut plane at the midatrial level with a viewpoint on the valve allows an immediate definition of the relationship of the mitral valve with the other structures. In systole (**panel A**), the mitral leaflets are closed, and the aortic valve (AV) is open. In diastole (**panel B**), the funnel shape of the mitral valve is viewed from above, and the doming of the anterior leaflet (AML) and the small valve area are also demonstrated. In **panel C**, an anatomic specimen from a patient with severe mitral stenosis is shown for comparison. LA = left atrium; RA = right atrium; RVOT = right ventricular outflow tract.

Advantages of three-dimensional reconstruction. *Anyplane and paraplane echocardiography.* The unrestricted cut planes that can be selected from the original three-dimensional volume data allow interrogation of the mitral valve and its related structures from virtually any point of view. Parallel slicing through the structure in a way similar to computed tomography or magnetic resonance imaging allows a detailed analysis of mitral valve apparatus. Thus, the circumference, leaflet morphology and, particularly, the entire zone of coaptation are more reliably evaluated than is possible with any other ultrasound modality.

Figure 5. In this patient with severe mitral insufficiency and left atrial dilation, a tangential cut plane allows detailed visualization of the caudal part of the left atrial appendage (LAA). The mitral valve orifice (MVO) is clearly seen in diastole. RA = right atrium.



Volume-rendered display. A major feature of three-dimensional echocardiography in assessing the mitral valve is the volume-rendered display. In particular, an atrial cut plane with a viewpoint from above adds the perception of the morphology of the components of the mitral valve. With this technique, we found a variability of the normal mitral valve apparatus, and especially of the leaflet morphology, as already has been demonstrated in anatomic studies (21). The results of our study indicate that the major advantage of volume-rendered echocardiography is in the evaluation of the pathologic mitral valve. This is partially explained by the presence of a dilated left atrium in this subset of patients, which provides an optimal acoustic window. In patients with mitral stenosis, three-dimensional echocardiography can provide spectacular views of mitral leaflets and detailed information on the structure of the mitral apparatus. Because the left atrium is visualized so well with the transesophageal approach, three-dimensional reconstruction gives an excellent view of the stenotic mitral valve from above. The domed leaflets with a funnel-like shape of the valve were appreciated in severe

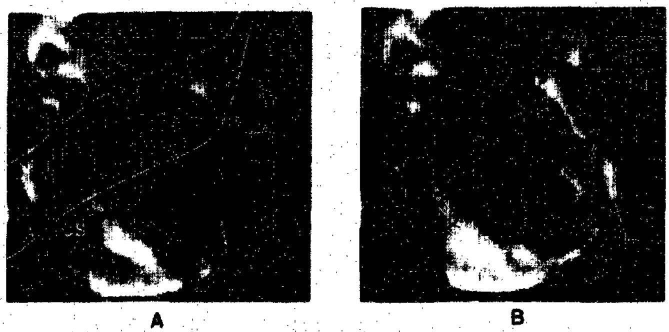


Figure 6. Three-dimensional reconstruction with volume-rendered display in a patient with mitral stenosis and insufficiency. In diastole (**panel A**), retraction of the leaflets and commissural fusion are present (**arrows**). The aortic valve (AV) is visible in closed position. From the left atrial appendage, a mass lesion emerges into the left atrial cavity (**arrow**). Inferiorly, the coronary sinus (CS) is found along the posterior wall of the left atrium within the left atrioventricular groove. In systole (**panel B**), the coronary sinus is not visible because of the movement of the heart relative to the cut plane.

stenoses. From the left ventricle, a fish-mouth shape of the valve was visualized in most cases. Restriction of the leaflets was also recognized.

Mitral valve prolapse is a disease in which three-dimensional reconstruction may provide information not obtainable otherwise. The major advantage of dynamic display of volume-rendered echocardiography relies on the visualization of both leaflets from above, which allows an objective evaluation of leaflet displacement during systole. In all the patients with this syndrome, the size and the location of the affected portion of the leaflets were diagnosed. Using a spark-gap locating device for transthoracic three-dimensional studies, Levine et al. (16) elucidated the saddle-shaped configuration of mitral annulus, which helped to establish a more stringent definition of mitral valve prolapse. Unlike the study by Levine et al. (16), in the present study the images were fully reconstructed into the three-dimensional data set using the whole gray scale information from the cross-section images.

Clinical applications. Three-dimensional echocardiography will become a useful tool in clinical practice (20). The availability of three-dimensional images of the mitral valve in motion enhances the evaluation of both normal and pathologic conditions and will facilitate communication between cardiologists and cardiac surgeons. The mechanism of mitral regurgitation can be clarified, and the surgical approach better defined. In particular, in patients with mitral valve prolapse, knowledge of which portion of the valve has the most abnormal motion is critically important in approaching it correctly for valve repair. This can be achieved with a volume-rendered display, and the possibility of electronic dissection of the mitral apparatus along orientations comparable to the surgical inspection may result in a better preoperative assessment helping the surgeon in planning the type of repair.

Pitfalls of three-dimensional echocardiography. Several factors are crucial for the results of three-dimensional reconstruction and for volume-rendered display in particular. Proper selection of the gain settings of the basic two-dimensional images, filter processing and threshold selection represent critical steps for volume-rendered display. An inappropriate decision during each of these steps may result in artifacts and limit the diagnostic potential of the method.

In the conical volume obtained after rotational scanning, the resolution is nonuniform in two dimensions. In particular, the resolution becomes worse from the top to the bottom and from the central axis to the lateral fields. As a consequence, each point of a tangential cut plane has different resolution, which could result in distortion of images. The lower scores for subvalvular apparatus by volume-rendered echocardiography

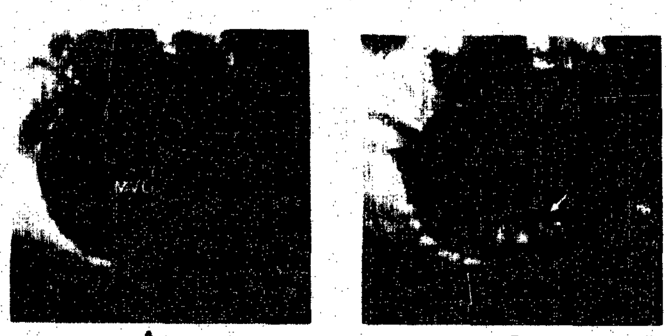


Figure 7. Atrial view of the mitral valve in a patient with severe mitral insufficiency. In diastole (**panel A**), the leaflets are open, and a normal orifice area is present. In systole (**panel B**), the middle scallop of the posterior leaflet prolapses (**arrow**). In the dynamic display the prolapsing portion of the leaflets is appreciated as moving toward the observer in systole.

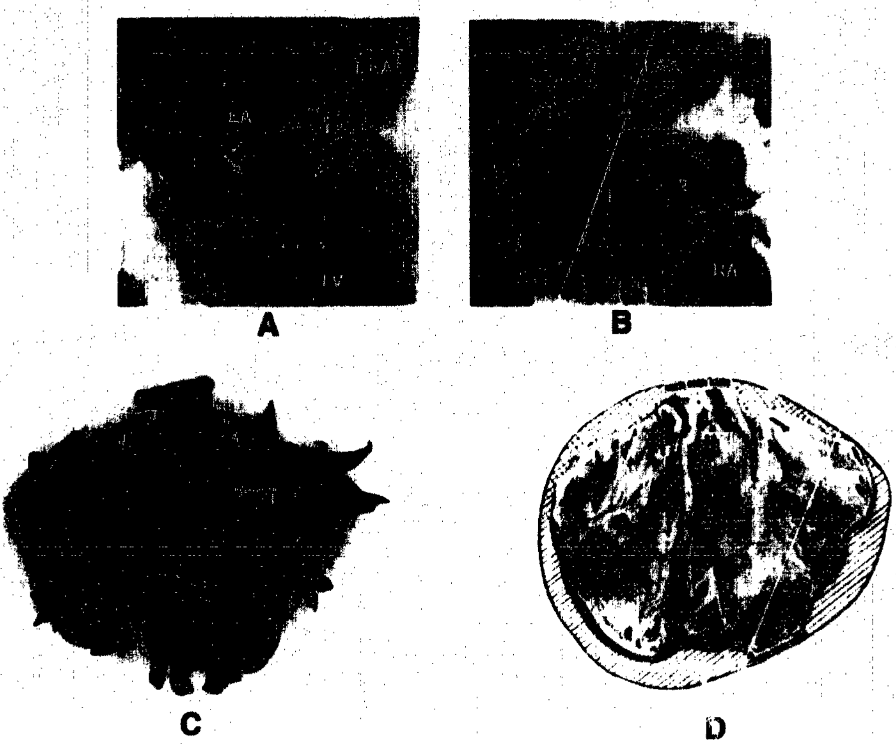


Figure 8. In this patient with mitral insufficiency, a longitudinal cut plane through the mitral valve with a volume-rendered display (**panel A**) reveals two separate holes (**arrows**), suggesting a double-orifice mitral valve. A cut plane from above (**panel B**) exposes to view the structure of the valve, confirming the presence of two separate valve orifices (1 and 2) with bridging tissue completely partitioning the valve annulus. The corresponding pathologic specimen of the anterior mitral leaflet is shown for comparison (**panel C**). **Panel D** is a schematic drawing representing the native mitral valve as viewed from above during operation. The **hatched lines** represent the posterior leaflet; the **crosshatched lines** correspond to the part of the anterior leaflet that has not been removed; the **asterisks** indicate the epicardial patches used for cleft repair. The **thick dashed lines** indicate the edges of the bridging tissue partioning the valve. LA = left atrium; LAA = left atrial appendage; LV = left ventricle; RA = right atrium.

reflect a relative underestimation of this feature compared with multiplane echocardiography and anyplane echocardiography, probably because of suboptimal spatial resolution of this technique. Evaluation of leaflet thickness with volume-rendered echocardiography was also suboptimal. With this technique, views from above do not provide adequate information because of inappropriate view angle, and the display of longitudinal views has been hampered in our experience by the excessive reflected intensity of the light from the structures close to the observer.

Other expected technical problems are probe motion from either patient motion or peristalsis, prolonged acquisition time because of atrial fibrillation, and difficulties in visualizing the valve from the esophagus because of spontaneous contrast. In our experience, these problems can be circumvented with adequate instruction of the patients and optimal selection of electrocardiographic and respiratory gating and gain settings of the basic images.

Finally, the time required for processing the data is still too long for routine use of this method, and the selection of the best cut plane is an interactive time-consuming process. Further developments of software for fast, less operator-dependent three-dimensional reconstruction are needed.

Conclusions. The results of this study indicate that unique imaging planes can be selected from three-dimensional data sets obtained with multiplane transesophageal echocardiography, allowing a comprehensive assessment of the mitral valve apparatus. Dynamic volume-rendered display provides additional qualitative information on leaflet mobility, orifice size and commissures and complements the information obtained with both multiplane echocardiography and anyplane echocardiography. Further technical improvement will make three-

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A B

Figure 9. Volume-rendered display after a tangential cut plane of the left atrium in a patient with a Hancock prosthesis. This view discloses *the strut of the prosthesis bulging into the left atrium (LA)*. A shadow of the strut is also projected on the atrial wall. The three leaflets of the valve can be recognized in systole (**panel A**), but in diastole (**panel B**) only two cusps are visible (**arrows**) because of the tangential view.

dimensional echocardiography the technique of choice for the study of the mitral valve in the future.

References

1. Roberts WC. Morphologic features of the normal and abnormal mitral valve. Am J Cardiol 1983;51:1005-28.
2. Perloff JK, Roberts WC. The mitral apparatus. Functional anatomy of mitral regurgitation. Circulation 1972;46:227-39.
3. Fraser AG. Diseases of the mitral and tricuspid valves. In: Sutherland GR, Roelandt JRTC, Fraser AG, Anderson RH, eds. Transesophageal Echocardiography in Clinical Practice. London: Gower Medical Publishing, 1991: Chapter 6, (6.1-6.2).
4. Omoto R, Kyo S, Matsumura M, et al. Evaluation of biplane color Doppler transesophageal echocardiography in 200 consecutive patients. Circulation 1992;85:1237-47.
5. Stewart WJ, Currie PJ, Salcedo EE, et al. Evaluation of mitral leaflet motion by echocardiography and jet direction by Doppler color flow mapping to determine the mechanism of mitral regurgitation. J Am Coll Cardiol 1992;20:1353-61.
6. Fehske W, Grayburn PA, Omran H, et al. Morphology of the mitral valve as displayed by multiplane transesophageal echocardiography. J Am Soc Echocardiogr 1994;7:472-9.
7. Salustri A, Roelandt JRTC. Ultrasonic three-dimensional reconstruction of the heart. Ultrasound Med Biol 1995;21:281-93.
8. Salustri A, Spitaels S, McGhie J, Vletter W, Roelandt JRTC. Transthoracic three-dimensional echocardiography in adult patients with congenital heart disease. J Am Coll Cardiol 1995;26:759-67.
9. Belohlavek M, Foley DA, Gerber TC, Kinter TM, Greenleaf JF, Seward JB. Three- and four-dimensional cardiovascular ultrasound imaging: a new era for echocardiography. Mayo Clin Proc 1993;68:221-40.
10. Belohlavek M, Foley DA, Gerber TC, Greenleaf JF, Seward JB. Three-dimensional ultrasound imaging of the atrial septum: normal and pathologic anatomy. J Am Coll Cardiol 1993;22:1673-8.
11. Schwartz SL, Cao Q, Azevedo J, Pandian NG. Simulation of intraoperative visualization of cardiac structures and study of dynamic surgical anatomy with real-time three-dimensional echocardiography. Am J Cardiol 1994;73:501-7.
12. Pandian NG, Nanda NC, Schwartz SL, et al. Three-dimensional and four-dimensional transesophageal echocardiographic imaging of the heart and aorta in humans using a computed tomographic imaging probe. Echocardiography 1992;9:677-87.
13. Nanda NC, Pinheiro L, Sanyal R, Rosenthal S, Kirklin JK. Multiplane transesophageal echocardiographic imaging and three-dimensional reconstruction. Echocardiography 1992;9:667-76.
14. Rivera JM, Siu SC, Handschumacher MD, et al. Three-dimensional reconstruction of ventricular septal defects: Validation studies and in vivo feasibility. J Am Coll Cardiol 1994;23:201-8.
15. Ross JJ Jr, D'Adamo AJ, Karalis DG, Chandrasekaran K. Three-dimensional transesophageal echo imaging of the descending thoracic aorta. Am J Cardiol 1993;71:1000-2.
16. Levine RA, Handschumaker MD, Sanfilippo AJ, et al. Three-dimensional echocardiographic reconstruction of the mitral valve, with implications for the diagnosis of mitral valve prolapse. Circulation 1989;80:589-98
17. Roelandt JRTC, Thomson IR, Vletter WB, Brommersma P, Bom N, Linker DT. Multiplane transesophageal echocardiography: latest evolution in an imaging revolution. J Am Soc Echocardiogr 1992;5:361-7.
18. Roelandt JRTC, Ten Cate FJ, Vletter WB, Taams MA. Ultrasonic dynamic three-dimensional visualization of the heart with a multiplane transesophageal imaging transducer. J Am Soc Echocardiogr 1994;7:217-29.
19. Salustri A, Roelandt JRTC. Three-dimensional reconstruction of the heart with rotational acquisition: Methods and clinical applications. Br Heart J 1995;73 Suppl 2:10-5.
20. Pandian NG, Roelandt J, Nanda NC. Dynamic three-dimensional echocardiography. Methods and clinical potential. Echocardiography 1994;11:237-59.
21. Becker AE, De Wit APM. Mitral valve apparatus. A spectrum of normality relevant to mitral valve prolapse. Br Heart J 1979;42:680-9.