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Head-to-Head Comparison of Two- and Three-Dimensional Transthoracic and Transesophageal Echocardiography in the Localization of Mitral Valve Prolapse

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OBJECTIVES The aim of this study, undertaken in patients who underwent mitral valve (MV) repair surgery, was to evaluate the feasibility and accuracy of 3-dimensional (3D) transthoracic (TTE) and transesophageal (TEE) echocardiography in the evaluation of MV pathology.

BACKGROUND A pre-operative assessment of MV anatomy is essential to surgical design in patients undergoing MV repair. Although 2-dimensional (2D) echocardiography provides precise information regarding MV anatomy, 3D TTE and 3D TEE could increase the understanding of MV apparatus and individual scallop identification.

METHODS One-hundred-twelve consecutive patients with severe mitral regurgitation due to MV prolapse underwent a complete 2D and 3D TTE the day before surgery and a complete 2D and 3D TEE in the operating room. Echocardiographic data obtained by the different techniques were compared with surgical inspection.

RESULTS Three-dimensional techniques were feasible in a relatively short time (3D TTE: 7 ± 4 min; 3D TEE: 8 ± 3 min), with good (3D TTE 55%; 3D TEE 35%) and optimal (3D TTE 21%; 3D TEE 45%) imaging quality in the majority of cases. Three-dimensional TEE allowed more accurate identification (95.6% accuracy) of all MV lesions in comparison with other techniques. Three-dimensional TTE and 2D TEE had similar accuracies (90% and 87%, respectively), whereas the accuracy of 2D TTE (77%) was significantly lower.

CONCLUSIONS Three-dimensional TTE and TEE are feasible and useful methods in identifying the location of MV prolapse. They were superior in the description of pathology in comparison with the corresponding 2D techniques and should be regarded as an important adjunct to standard 2D examinations in decisions regarding MV repair. (J Am Coll Cardiol 2006;48:2524–30)

A pre-operative assessment of mitral valve (MV) anatomy is essential to surgical design in patients undergoing MV repair for organic MV prolapse. Although 2-dimensional (2D) transthoracic (TTE) and transesophageal (TEE) echocardiography provide precise information regarding MV anatomy (1–5), 3-dimensional (3D) TTE and 3D TEE could increase the understanding of more complex abnormalities of MV apparatus and individual scallop identification (6–9). Three-dimensional TEE has been applied to the evaluation of surgical MV prolapse, and it has been demonstrated that it might play a valuable role in the assessment of patients undergoing mitral repair surgery (10–14). Three-dimensional TTE is a feasible, accurate, and very promising new technique for assessing MV morphology; however, the usefulness and accuracy of this technique for evaluating MV prolapse has not been established. Moreover, a head-to-head comparison of 2D and 3D TTE and TEE in a large consecutive series of patients undergoing MV repair has not been evaluated. This comparison might demonstrate the potential clinical impact of 3D technologies in this field.

The aim of this prospective study, undertaken in a consecutive series of patients who underwent MV repair surgery for MV prolapse was 2-fold: 1) to demonstrate the feasibility and quality of a routine 3D TTE and 3D TEE imaging of the MV (image acquisition and reconstruction) with new generation real-time TTE and 3D TTE and 3D TEE softwares; and 2) to evaluate and compare the accuracy of 2D and 3D TTE and TEE versus surgical inspection in the recognition and localization of all components of the MV leaflets and apparatus.

METHODS

Patient population. A total of 112 consecutive patients (mean age 60 ± 10 years; 66 men/46 women) with an established diagnosis of severe mitral regurgitation due to degenerative MV prolapse were enrolled in the study (from February 2003 to January 2005). They were all suitable for surgical MV repair. Exclusion criteria were contraindications to TEE, associated MV stenosis, previous endocarditis, history of coronary artery disease (previous myocardial

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Abbreviations and Acronyms

2D = 2-dimensional
3D = 3-dimensional
ALC = anterolateral commissure
MV = mitral valve
PMC = posteromedial commissure
TEE = transesophageal echocardiography
TTE = transthoracic echocardiography

ischemia or infarction, previous bypass graft surgery, or coronary stent implantation).

Study protocol. All patients underwent a complete 2D and 3D TTE the day before MV surgery. Immediately before surgery in the operating room, under general anesthesia, a complete 2D TEE examination was performed as well as a 3D TEE acquisition of the MV apparatus. Three-dimensional data were acquired on a magneto-optical disk and immediately reconstructed in the echocardiography laboratory. Echocardiographic data obtained by the different techniques were compared with a very detailed and complete surgical inspection of the MV performed by the operating surgeon (M.Z., F.A.). The local ethics committee approved the study. Informed consent was obtained from all patients.

Transthoracic 2D and 3D echocardiography. A complete TTE study was performed in all patients with a Sonos 7500 ultrasound unit and an S3 probe (Philips Medical Systems, Andover, Massachusetts). Two-dimensional echocardiography included all standard parasternal, apical, and subcostal views. With a transthoracic approach derived by the TEE evaluation of the MV (1–3), the Carpentier nomenclature was applied to the MV leaflets (anterior leaflet: A1, A2, and A3 = lateral, middle, and medial scallop, respectively; posterior leaflet: P1, P2, and P3 = lateral, middle, and medial scallop, respectively). The anterolateral commissures (ALC) and posteomedial commissures (PMC) were also inserted in the 2D TTE examination. All segments were classified as normal, prolapsing (>3 mm beyond the annulus plane), or flail. The presence of ruptured chordae was annotated. All images were recorded on videotapes and acquired in digital cine-loops on magneto-optical disks.

Real-time 3D TTE was performed at the end of the 2D examination with the same ultrasound unit by using an X4 probe (matrix probe with 3000 channels). The protocol included real-time (pyramidal data scans of 60° × 30°) parasternal views (long- and short-axis views) including 3D zoom technology that allowed a more focused visualization of the entire MV. "Full volume" analysis was also performed in all cases from the apical view. This method consists of the acquisition of 4 cardiac cycles (during a breath-hold period) that generates a larger single pyramid of data. Immediately after the acquisition of these data sets, 3D cine loops were stored in the machine. Reconstruction of the valve (volume rendering imaging) allowed a complete visualization of all segments of the MV. In particular, from the atrial point of view the MV was visualized in the so called "surgical view." Segments of the MV were classified as previously described for the 2D TTE, and the ALC and PMC were also examined as well as chordal ruptures.

Three-dimensional acquisition and reconstruction times were measured in each patient.

Transesophageal 2D and 3D echocardiography. Two-dimensional TEE and 3D TEE were performed intraoperatively, after induction of anesthesia and endotracheal intubation, using a 5-MHz multiplane probe (model 21354A, Philips Medical Systems) inserted in the esophagus and connected to a Philips Medical Systems echocardiography system (Sonos 5500, Philips, Bothell, Washington). Multiplane 2D TEE evaluation included a complete standard protocol for the evaluation of the MV (1–3), allowing a complete description of all segments of the valve. Protrusion, billowing, or flail (plus chordal rupture) of individual segments (6 scallops and 2 commisures) were annotated. All images were recorded on videotapes and acquired in digital cine-loops on magneto-optical disks.

Three-dimensional TEE acquisitions were obtained with the same ultrasound unit used for the 2D TEE, which incorporated 3D data acquisition software. Protocol of acquisition has been described in previous studies (15). In brief, rotation of the TEE probe from 0° to 180° allowed 61 sequential cross-sectional acquisition at 3° intervals with electrocardiography and respiratory gating. The reference position (area of interest) was a 5 chamber view from the lower esophagus position, in an effort to obtain a complete visualization of the entire MV and left atrium. The 3D data set was stored in a magneto-optical disk. The off-line postprocessing and 3D reconstruction were performed (in the echocardiography laboratory) through a dedicated system (Echo View, Tom Tec Imaging Inc., Munich, Germany). From the volumetric data sets, specific cut planes were used to visualize the MV. The "surgical view" was always reconstructed from the atrial view. By rotating the 3D images (in dynamic loops), commissural planes and individual segments of the MV were also visualized from longitudinal or intermediate planes.

Three-dimensional acquisition and reconstruction times were measured in each patient.

Imaging analysis and intraobserver and interobserver variability. All 2D TTE and 3D images were analyzed by 4 experts in 2D and 3D echocardiography (M.P., G.T., A.M., C.G.) blinded to the surgical findings. Two of them (M.P., G.T.), independently and without knowledge of the 2D findings, reviewed the 3D reconstructed images, and the others reviewed the transthoracic 2D images. Three-dimensional transthoracic images (stored in the ultrasound unit) and 3D TEE images (stored in the dedicated computer system) were analyzed by the 2 3D experts in a random sequence. Two other experts in intraoperative TEE (E.S., L.S.) reviewed the 2D TEE images blinded to 3D results. The quality of 3D reconstructed images, judged on the basis of the resolution of MV anatomy and on the presence or absence of artifacts throughout the cardiac cycle, was rated as optimal, good, sufficient, or insufficient. In 30 randomly selected data sets, 2 of the authors reviewed 3D TTE and 3D TEE images and identified and annotated all anatomical details. One of the authors re-reviewed the 3D reconstructed images 1 month later to assess intraobserver variability.

Surgical inspection and validation. The surgeon described the anatomy of the valve with the same Carpentier classification. He was aware of the 2D TEE findings but not of the 3D analysis.

Statistical analysis. The sensitivity and specificity of echocardiographic evaluation of the involved scallops (or chordal rupture) was calculated with surgical findings as a reference. Accuracy between the methods and surgery was defined as the sum of true positive and true negative results divided by the number of scallops (or prolapsed valves). Differences in diagnostic accuracy among the methods were assessed with the McNemar statistic. A 2-tailed p value < 0.05 was considered statistically significant. Interobserver and intraobserver correlations were made with the Pearson coefficient.

RESULTS

Three-dimensional TTE was obtained in all patients. The time to obtain and analyze the 3D TTE images was 7 ± 4 min. Quality of 3D TTE was insufficient in 8% of cases, sufficient in 16% , good in 55%, and optimal in 21% of cases. Three-dimensional TEE was obtained in all cases without any complication. In 7 cases, a second acquisition was performed, because at the end of the first one the rotational display showed that 0° and 180° images were not aligned. Mean acquisition time was 4 ± 1 min, and mean reconstruction time was 4 ± 2 min (post-processing time included). Three-dimensional TEE reconstruction allowed insufficient imaging in 7%, sufficient in 13%, good in 35%, and optimal in 45% of all cases. Therefore, 10 cases were excluded because of inadequate (insufficient score) 3D TTE and/or 3D TEE.

Table 1. Anatomical (Surgical Inspection) Characteristics of the Study Population

	n
Isolated P1	5
Isolated P2	37
Isolated P3	3
Isolated A1	0
Isolated A2	4
Isolated A3	2
Posterior leaflet (>1 scallop)	17
Anterior leaflet (>1 scallop)	2
Anterior + posterior leaflets	32
Associated lesions	83
Chordal rupture	62
Total commissural lesions	21
Anterolateral commisure	8
Posteromedial commissure	13

Table 2. Detection of Pathology With the Four Echocardiographic Techniques

	Sensitivity (%)	Specificity (%)	Accuracy (%)
PML			
2D TTE	74	75	74
3D TTE	87*	91†	89†‡
2D TEE	83†	83*	83†
3D TEE	97†§‖	92†	96†§‖
AML			
2D TTE	71	88	84
3D TTE	88†§‖	95	94†
2D TEE	72	97*	91†
3D TEE	96†§‡‖	97*	97†§‡‖
AML + PML			
2D TTE	73	83	78
3D TTE	87†	93†	91†
2D TEE	80†	91†	87†
3D TEE	96†‡‖	95†‡‖	96†‡‖
Chordal rupture			
2D TTE	77.5	80	78
3D TTE	93†	92	92.5†
2D TEE	98†	92*	95.5†
3D TEE	100†	94†	98†
Anterolateral commissure			
2D TTE	40	85	78
3D TTE	55	98†	91†
2D TEE	54	95†	89†
3D TEE	89†‡§	99†	97†‡‖
Posteromedial commissure			
2D TTE	54	84	75
3D TTE	82†¶	92	89†
2D TEE	66	90*	82†
3D TEE	92†‡‖	95*	93*†‖

*$p < 0.05$ and †$p < 0.01$ versus 2D TTE; ‡$p < 0.05$ and §$p < 0.01$ versus 3D TTE; ‖$p < 0.01$ versus 2D TEE and ¶$p < 0.05$.
2D = 2-dimensional; 3D = 3-dimensional; AML = anterior mitral leaflet; PML = posterior mitral leaflet; TEE = transesophageal echocardiography; TTE = transthoracic echocardiography.

In 102 cases the 4 echocardiographic methodologies were analyzed and compared with surgical findings. Table 1 shows anatomical (surgical inspection) characteristics of the study population. Even though approximately one-third of the patients had isolated P2 lesions, the majority had more complex pathologies (more than 1 segment involved, bileaflet pathologies, commissural lesions). Sensitivity, specificity, and accuracy of the 4 echocardiographic methods for each of the segmental lesions and for chordal rupture are reported in Table 2. Figure 1 shows overall accuracy of the 4 techniques. Three-dimensional TEE allowed more accurate identification (95.6% accuracy) of all MV lesions in comparison with the other techniques. Three-dimensional TTE and 2D TEE had similar accuracies (90% and 87%, respectively), whereas the accuracy of 2DTT (77.2%) was significantly lower.

There was close agreement in recognition scores both between the 2 different observers (interobserver variability: 3D TTE: $r = 0.68$, $p < 0.001$; 3D TEE: $r = 0.78$, $p < 0.001$) and between the repeated measurement of the first observer (intraobserver variability: 3D TTE: $r = 0.85$ $p < 0.001$; 3D TEE: $r = 0.86$, $p < 0.001$).

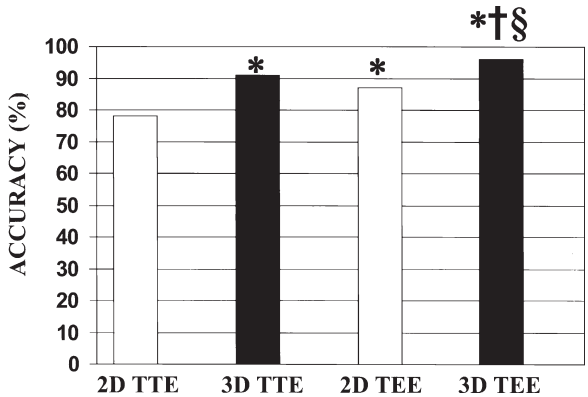

Figure 1. Overall accuracy of the 4 techniques in the identification of mitral valve pathology. *p < 0.001 versus 2D TTE; †p < 0.001 versus 3D TTE; §p < 0.001 versus 2D TEE. 2D = two-dimensional; 3D = three-dimensional; TEE = transesophageal echocardiography; TTE = transthoracic echocardiography.

Figure 2 shows examples of cases with P1, P2, P3, and A2 prolapses correctly identified by 3D TTE and 3D TEE. Figure 3 shows the example of a patient with a complex bileaflet MV prolapse in whom 3D TTE allowed a non-complete definition of the pathology.

Figure 4 shows an example of 3D TTE and 3D TEE identifications of chordal rupture.

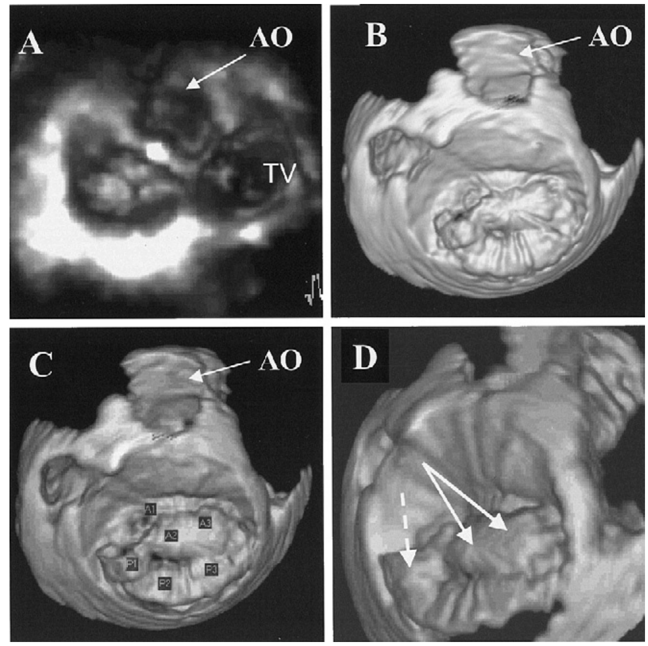

Figure 3. Example of a patient with a complex bileaflet mitral valve prolapse in whom 3D TTE **(A)** allowed a non-complete definition of the pathology, whereas 3D TEE **(B and C)** correctly identified the prolapse of P1, A2, and A3. **(D)** Shows in an oblique surgical view involvement of the anterior (A2, A3, **arrows**) and of the posterior (P1, **dashed arrow**) scallops. TV = tricuspid valve; other abbreviations as in Figures 1 and 2.

DISCUSSION

This study demonstrates that 3D TTE and 3D TEE may be used routinely to better evaluate MV morphology in an unselected population with MV prolapse undergoing surgical repair. It also compares 2D and 3D transthoracic and transesophageal techniques, showing that 3D TTE and 3D TEE are superior for the accurate localization and identification of MV pathology in comparison with the respective 2D methodologies.

A main finding of this study is the demonstration that 3D technologies are feasible and may be routinely used, providing a detailed anatomic depiction of the MV in a relatively short time. From the transthoracic approach, we used real-time 3D echocardiography at the end of the standard 2D examination. We indicated that 3D TTE is not time-consuming (7 ± 4 min), and this was accomplished with new generation 3D technology that reduces the acquisition and reconstruction times. By using the dedicated probe and a protocol that was specifically oriented to a complete study of the MV apparatus, it was in fact possible to visualize leaflets and chordae of the valve from both the parasternal and apical

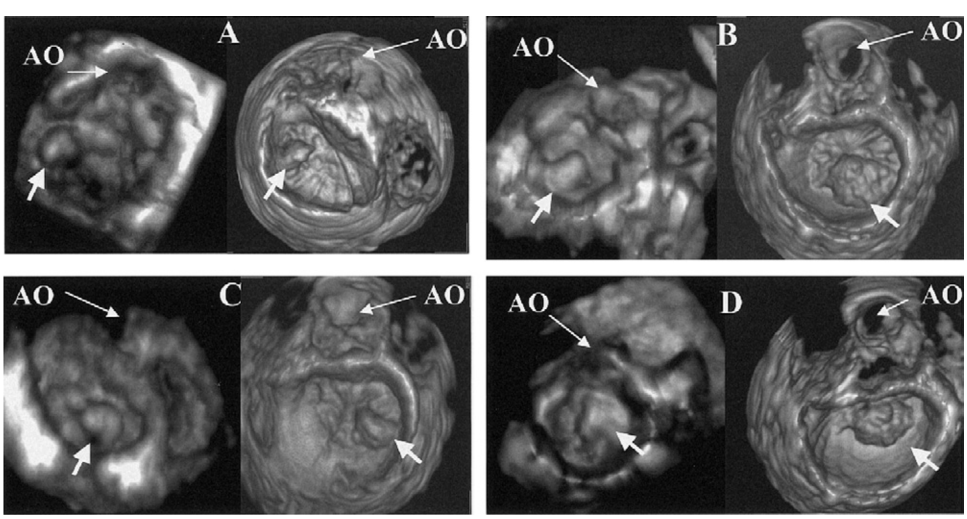

Figure 2. Four examples of prolapses of different scallops **(arrows)** of the mitral valve correctly identified by 3D TTE and 3D TEE. Each of the 4 panels shows head-to-head comparison of 3D TTE **(left side)** and 3D TEE **(right side)** techniques by imaging the valve in the surgical view (from the left atrium). **(A)** P1 prolapse; **(B)** P2 prolapse; **(C)** P3 prolapse; **(D)** A2 prolapse. AO = aorta; other abbreviations as in Figure 1.

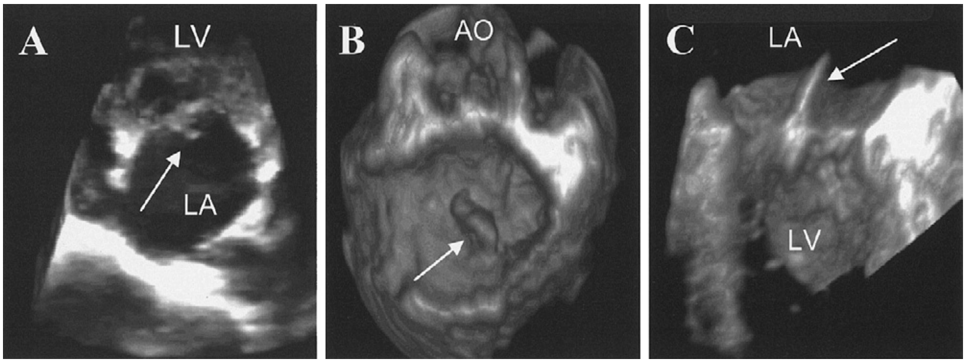

Figure 4. Examples of chordal rupture **(arrows)** associated with mitral valve prolapse. **(A)** 3D TTE reconstruction from the apical windows. **(B)** Surgical view (from the left atrium) and **(C)** longitudinal view in a 3D TEE reconstruction of mitral valve. LA = left atrium; LV = left ventricle; other abbreviations as in Figure 1.

windows in a few minutes. We showed that from the parasternal view (including real-time standard images and zoom images), leaflet and chordae morphology is easily detected, while apical full-volume analysis allowed the generation of a larger single pyramid of data and a complete visualization of all segments of the valve in the so-called atrial "surgical view." Limitations of the transthoracic 3D technology are mainly related to lower quality of images, in comparison with the 3D TEE approach. In fact, optimal images were obtained in 21% and 45% of cases with real-time 3D transthoracic and transesophageal approaches, respectively. However, good image quality was achieved in 55% of cases with real-time 3D, and therefore accurate evaluation (good and optimal quality of images) of the valve might be obtained in the majority of unselected patients undergoing a transthoracic study before MV repair (76% of cases). Acquisition of transesophageal 3D images was performed inside the operating room in the pre-operative phases. We preferred to validate this method under general anesthesia to avoid discomfort to the patient and to work in ideal conditions. As we recently demonstrated in the catheterization laboratories in patients undergoing percutaneous atrial septal closure, this protocol (15,16) allowed us to obtain good and optimal 3D images in the majority of cases in a few minutes. Acquisition (4 ± 1 min) and reconstruction (4 ± 2 min) times were in fact short and MV morphology may be dynamically displayed in approximately 10 min. Alternatively, 3D transesophageal acquisition may be performed outside the operating room as part of a routine TEE study (12).

To the best of our knowledge this is the first study comparing 2D and 3D transthoracic and transesophageal technologies for the evaluation of MV organic prolapse in a consecutive, large series of patients undergoing valve repair. The potential of 3D echocardiography for imaging the MV was recognized early in the development of the method. Three-dimensional echocardiography with the transesophageal approach has been demonstrated to be feasible and to provide accurate depiction of the valve. In particular, it allowed the precise location of the diseased portion of the leaflets, and the majority of studies showed that 3D echocardiography matches more closely to surgical findings, achieving exact functional description in approximately 90% to 95% of segments, whereas 2D echocardiography is less accurate (6,10,11,13). This incremental value was mainly seen in complex prolapse involving both leaflets, the anterior leaflet, or commisures. Our data are in complete agreement with these observations. We found a 96% overall accuracy by 3D TEE for the identification of MV pathology in an unselected population undergoing MV prolapse, compared with an 87% accuracy of 2D TEE. Our population was characterized by a large percentage of complex MV disease, including only approximately one-third of cases with isolated prolapse of the middle posterior scallop (P2). Previous reports on transesophageal echocardiographic accuracy in the localization of mitral scallop morphology included a higher percentage of simple surgical prolapse (isolated P2 prolapse) (3). These differences are mainly due to recent surgical improvements in surgical techniques and surgical results in complex disease (therefore our population undergoing mitral repair is less selected on the basis of MV anatomy) and might account for the significant superiority of 3D versus 2D and for the relatively low accuracy of 2D methodology. In fact sensitivity and specificity of 3D TEE was particularly high in complex lesions and in particular in commissural lesions.

Real-time 3D TTE is an accurate and novel approach for several pathologies (17,18). Zamorano et al. (19,20) demonstrated that this technique is a feasible, accurate, and highly reproducible method for assessing MV area in patients with MV stenosis. To date, routine transthoracic 3D echocardiography has not been validated in MV prolapse. Our study shows that real-time 3D is a rapid (7 ± 4 min) and an accurate method for the assessment of MV organic prolapse with an overall accuracy of 91%. Its high accuracy in identifying pathomorphology of the valve is superior in comparison with 2D echocardiography (78%) and might have a clinical impact on decision-making and planning of surgical strategy. We might in fact postulate that real-time TTE, which has an accuracy similar to that of 2D TEE in our study (even though inferior to 3D TEE), may be integrated in the standard 2D examination. Even though 2D transesophageal images have excellent agreement with intraoperative morphology of the MV, 2D techniques still might be insufficient to demonstrate exact spatial localization of pathological structures, and they suffer from the limitation of the need for mental reconstruction of 3D valve anatomy by the examiner. However, because 3D transthoracic images have poor quality in one-third of cases or insufficient frame rate and resolution in others, 2D TEE still remains the ideal technique for surgical planning in these patients. Alternatively, we might suggest a complementary role of the 2 techniques with a diagnostic work-up including as first step a complete 2D and 3D transthoracic examination and as a second step a 2D transesophageal study oriented on the basis of transthoracic data to confirm and complete the diagnosis. Obviously, in the follow-up of patients without surgical indication (in whom serial examinations are very useful to determine the correct surgical timing), a complete 2D and 3D transthoracic examination might reduce the need for a TEE approach. Our data support the concept that these different strategies might be particularly useful in complex pathologies, owing to the high accuracy of 3D TTE in the identification of P1, P3, and bileaflet prolapses and commissural lesions.

Two-dimensional and 3D TEE might finally be performed inside the operating room to confirm and complete the examination and to aid the surgeon who is challenged by the limited operative field and the nonphysiological state of the heart being devoid of blood in deciding the extent of valvular tissue resection (11,13).

Study limitations. We used anatomical findings at surgery as the gold standard against which to judge 2D and 3D echocardiography. Even though surgeons involved in the study analyzed carefully all valves with the techniques developed by Carpentier (21), the inherent problem in this approach is that the surgeon assesses an immobile valve in an empty heart whereas echocardiography assesses a dynamic valve. There are no practical alternatives to this method, but Ahmed et al. (11) suggested that 3D technologies are probably more sensitive in defining MV prolapse, because the surgeon might miss smaller areas of prolapse by inspection.

In analyzing the anatomy of the MV by echocardiography the individual scallops were identified in the standard 2D and 3D transesophageal views. We arbitrarily applied the same methods for 2D and 3D transthoracic approaches. Even though no standard guidelines or previous data described a method to judge MV morphology in transthoracic views, we applied a 2D transthoracic examination that comprehensively visualized the valve with the same TEE protocol (including all main parasternal and apical views that might represent a surrogate for the lower esophagus and transgastric transesophageal views). Similarly for the 3D real-time transthoracic examination, parasternal and apical acquisitions allowed reconstruction of the valve from longitudinal views and surgical (from the left atrium) views, with images that might be easily compared with standard 3D transesophageal ones.

The surgeons who described the anatomy of the valve were aware of the 2D TEE findings, in order to plan the surgical strategy, but not of the 3D analysis. Even though this is a potential limitation of the study, it does not detract much from our results, because 2D data were less correlated to surgical findings than 3D data.

Conclusions. In conclusion, 3D TTE and 3D TEE are feasible, not time consuming, and useful methods in identifying the location of MV prolapse in patients undergoing MV repair. Three-dimensional methods were superior in the description of pathology in comparison with the corresponding transthoracic and transesophageal 2D techniques. These 3D techniques should be regarded as an important adjunct to standard transthoracic and transesophageal 2D examinations in decisions regarding MV repair. Further studies are needed to ultimately determine whether the additional morphologic and complementary information revealed by 3D echocardiography might influence surgical planning and clinical outcome.

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