Real-Time Three-Dimensional Transesophageal Echocardiography in the Intraoperative Assessment of Mitral Valve Disease

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Background: The aims of this study were to evaluate the feasibility of real-time 3-dimensional (3D) transesophageal echocardiography in the intraoperative assessment of mitral valve (MV) pathology and to compare this novel technique with 2-dimensional (2D) transesophageal echocardiography.

Methods: Forty-two consecutive patients undergoing MV repair for mitral regurgitation (MR) were studied prospectively. Intraoperative 2D and 3D transesophageal echocardiographic (TEE) examinations were performed using a recently introduced TEE probe that provides real-time 3D imaging. Expert echocardiographers blinded to 2D TEE findings assessed the etiology of MR on 3D transesophageal echocardiography. Similarly, experts blinded to 3D TEE findings assessed 2D TEE findings. Both were compared with the anatomic findings reported by the surgeon.

Results: At the time of surgical inspection, ischemic MR was identified in 12% of patients, complex bileaflet myxomatous disease in 31%, and specific scallop disease in 55%. Three-dimensional TEE image acquisition was performed in a short period of time (60 $\pm$ 18 seconds) and was feasible in all patients, with optimal (36%) or good (33%) imaging quality in the majority of cases. Three-dimensional TEE imaging was superior to 2D TEE imaging in the diagnosis of P1, A2, A3, and bileaflet disease ($P < .05$).

Conclusions: Real-time 3D transesophageal echocardiography is a feasible method for identifying specific MV pathology in the setting of complex disease and can be expeditiously used in the intraoperative evaluation of patients undergoing MV repair. (J Am Soc Echocardiogr 2009;22:34-41.)

Keywords: Real-time 3D TEE, Mitral valve, Diagnosis, Intraoperative

Surgical mitral valve (MV) repair is the therapeutic intervention of choice in the treatment of severe mitral regurgitation (MR).[1,2] Valve repair, rather than replacement, allows for earlier surgical intervention in patients with severe MR who are only mildly symptomatic before left ventricular dilatation and dysfunction develop.[3] In >1,400 patients, Suri et al[4] demonstrated that MV repair is superior to MV replacement in affording long-term survival and that both are similar in durability.

MV repair is currently facilitated by the accurate assessment of MV anatomy and MR mechanisms using comprehensive multiplane 2-dimensional (2D) transesophageal echocardiography. This technique can become challenging in situations in which complex disease of the MV apparatus is present. Furthermore, a high level of expertise is required for the accurate interpretation of 2D images, and occasional errors still occur, even in the most experienced hands. Many of these shortcomings can be overcome by 3-dimensional (3D) transesophageal echocardiography, which has been shown to be both a feasible and accurate technique to further define MV pathology.[5-7] However, to date, the widespread use of 3D transesophageal echocardiography has been limited by prolonged acquisition and reconstruction times.[5-7] Also, images are often rendered unusable because of difficulty with electrocardiographic gating in the setting of arrhythmias and artifacts resulting from respiration and patient movement. In the operating room, other factors, such as patient preparation, ventilation, and electrocautery, may also pose challenges. Many of these issues are now of minimal consequence with the advent of new real-time 3D transesophageal echocardiographic (TEE) technology, with instant imaging of the MV possible in clinical situations in which traditional 3D transesophageal echocardiography proved difficult or impossible.

The aims of this study were (1) to determine the feasibility of using a new-generation, real-time 3D TEE imaging technology to define MV pathology in the operating room, and (2) to compare the

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accuracy of 2D versus 3D transesophageal echocardiography using surgical findings as the "gold standard" in defining the pathologic anatomy of the MV leaflets.

METHODS

Patient Population

Consecutive patients referred for MV surgery (repair or replacement) with established diagnoses of MR were enrolled prospectively on the day of their planned surgery. All patients had moderate to severe MR quantified using transthoracic 2D and Doppler echocardiography according to the American Society of Echocardiography task force consensus recommendations.[8] Exclusion criteria were contraindications to transesophageal echocardiography and MV stenosis. The Institutional Review Board of the Mayo Clinic approved the study. Written informed consent was obtained from all patients.

Transesophageal 2D and 3D Echocardiography

After the induction of anesthesia, endotracheal intubation, and before cardiopulmonary bypass, a complete 2D TEE intraoperative examination was performed, followed by a 3D TEE assessment of the MV apparatus. The same ultrasound platform was used for both 2D and 3D acquisitions. Imaging was performed using the real-time 3D imaging probe (model X72t) and the iE33 echocardiographic imaging platform (Philips Medical Systems, Bothell, WA).

The 2D images were acquired by level III–trained echocardiographers with specialized training in intraoperative echocardiography. A number of different such operators are assigned to the daily intraoperative schedule, per routine practice. A total of 6 echocardiographers acquired the 2D images in this consecutive series; all operators acquired a similar number of cases, and no preference was given to any specific operator. We did not perform a specific analysis of interoperator variability. Multiplane 2D TEE evaluation included a standardized approach. This evaluation was performed as previously described using the Carpentier nomenclature.[9] The MV was examined in multiple image projections. At 0°, 3 positions were used: anterior or 5 chamber (P1 and A1), middle or 4 chamber (P2 and A2), and posterior (A3 and P3). Between 45° and 90°, with clockwise and counterclockwise rotation and withdrawal or advancement of the probe, anterior (A1-A2-A3), middle (P1-A2-P3), and posterior (P1-P2-P3) projections were obtained. At 120°, the anterior (A1-A2) and posterior (P2) projections were visualized. Transgastric views were also acquired when available.

As the intraoperative 2D TEE study was being completed, one of two 3D TEE operators (J.G., S.M.) was paged and performed the live 3D TEE imaging, blinded to the 2D TEE results. Both 3D TEE operators were also level III–trained echocardiographers with additional training in 3D TEE.

A live 3D zoom mode was performed of the MV in the long-axis view and provided a live "en face" surgical view of the MV from the left atrial perspective. This particular view incorporated the aortic valve, which served as a landmark for the anterior leaflet. The 3D acquisition was performed as a part of the complete TEE exam, and no changes to the regular routine of the operating room or extra time was allotted for this study protocol. This allowed for a "real-life" feasibility study of live 3D MV assessment. The 3D echocardiographer acquiring the images determined when an image of sufficient quality was obtained. Feasibility was based on two major factors: (1) 3D TEE images could be obtained within the expected time allotment, as discussed previously, and (b) final 3D TEE study quality was rated at least satisfactory by the 3D TEE reader who analyzed the recorded images offline at a later time.

The duration of 3D image acquisition, including manipulation of the images, was measured in 16 of the study patients during the latter half of the study by one of the investigators (J.G.) acquiring the 3D TEE images. As part of routine intraoperative practice, the echocardiographers who acquired the 2D TEE images were aware of all clinical and operative data, including preoperative transthoracic echocardiographic findings. However, the echocardiographers who independently acquired the intraoperative 3D TEE images were blinded to this information. Per current clinical practice, the 2D TEE MV anatomy findings were immediately provided to the surgeon; for the purposes of this study, the 3D TEE findings were not. The 3D data set was stored on a DVD. The left ventricular ejection fraction was visually estimated from the 2D TEE images, because quantitative left ventricular analysis is not routinely performed during intraoperative transesophageal echocardiography.

Table 1 Participant characteristics

Variable	Value
Age (years)	63 ± 15
Men	31 (74%)
Hypertension	23 (55%)
Diabetes mellitus	3 (7%)
Hyperlipidemia	17 (40%)
Smoking	7 (17%)
Coronary artery disease*	6 (14%)
History of atrial fibrillation	5 (12%)
Body mass index (kg/m^2)	27 ± 5
Systolic blood pressure (mm Hg)†	123 ± 18
New York Heart Association functional class	
I	15 (36%)
II	15 (36%)
III/IV	12 (28%)

*Presence of coronary artery disease (>50% lesions) or history of coronary artery bypass grafting or percutaneous transluminal coronary angioplasty.
†At the time of surgery.

Table 2 Anatomic mitral valve characteristics by surgical inspection

Characteristic	Number
P1	7 (17%)
P2	20 (48%)
P3	8 (19%)
A1	2 (5%)
A2	9 (21%)
A3	3 (7%)
Bileaflet involvement*	13 (31%)
Ischemic mitral regurgitation	5 (12%)
Associated lesions	
Chordal rupture	20 (48%)
Perforation†	1 (2%)
Cleft valve	1 (2%)

*Includes multiscallop disease involving both leaflets and/or diffuse bileaflet involvement.
†P2 prolapse with no endocarditis.

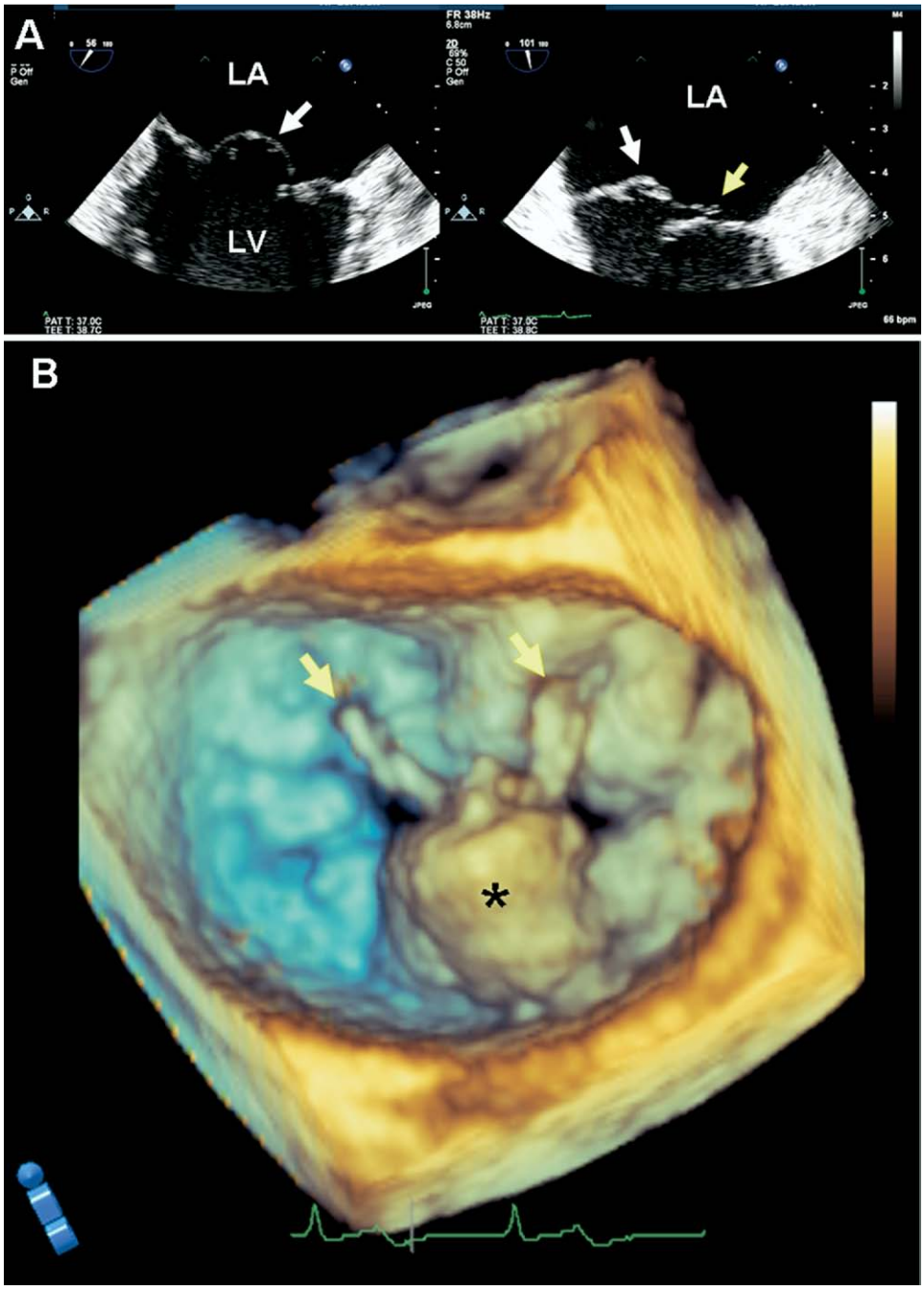

Figure 1 Classic flail P2 scallop. (**A**) Two-dimensional TEE end-systolic views demonstrating a flail middle scallop of the posterior mitral leaflet (P2); the flail P2 scallop is highlighted by the *white arrow* in the commissural 60° view on the *left* and a long-axis 110° view on the *right*; a torn chordae tendineae is noted on the long-axis view *(yellow arrow)*. (**B**) Live 3D TEE en face view of the MV at end-systole from the left atrial perspective demonstrating the flail P2 scallop *(black asterisk)* and clearly demonstrating multiple torn chordae tendineae *(yellow arrows)*. *LA*, Left atrium; *LV*, left ventricle.

Image Analysis

Recorded 2D and 3D TEE images were analyzed separately at a later time. Two experts in 2D transesophageal echocardiography, blinded to the 3D TEE information, evaluated all 2D TEE images. Two separate experts in 3D echocardiography, who were blinded to the 2D TEE information, analyzed the recorded 3D TEE MV images. In this paper, the reported interpretations of 2D TEE findings are those of a single 2D reader, while 3D TEE interpretations are those of a single 3D reader. The 2D and 3D TEE data sets were also each reviewed by a second blinded reader, to calculate interobserver variability. Each reader was unaware of the interpretations of all other readers and also blinded with regard to clinical information and surgical findings.

Analyses of the 3D images were made using 2 or 3 movie clips of the MV from the left atrial view. We had initially evaluated the possibility of using other imaging planes but concluded that this was

the single best view that would yield the most information intraoperatively. The reader did not have the option to change image orientation or cut and crop planes, because we wanted to replicate and hence determine the feasibility of 3D versus 2D transesophageal echocardiography in a busy intraoperative practice, where this is not always possible.

Notation of any protruding or billowing segments beyond the mitral annulus toward the left atrium was based on the following: (1) excessive segment mobility or tissue volume relative to adjacent segments, (2) at least one of each acquired image was color coded to provide depth data and hence qualitative assessment of segment disease, and (3) slight angulation of image orientation was provided to increase depth perception and hence detection of movement past the annulus. A flail leaflet was identified if one or multiple torn chordae tendineae were present, with the flail scallop noted protruding into the left atrium. Ischemic MR was defined as focally reduced excursion of a scallop with resultant malcoaptation of the leaflets. The quality of the live 3D images recorded and saved in the operating room was determined by the 3D reader and rated as optimal, good, satisfactory, or unsatisfactory on the basis of the MV anatomy resolution, the ability to identify all scallops, and the presence or absence of artifacts.

Surgical Inspection and Validation

The surgeon was aware of the 2D TEE findings only. The surgical evaluation of the MV anatomy was obtained from the complete surgical report and was used as the reference gold standard for both the 2D and 3D TEE comparisons. The diagnosis of ischemic MR by the surgeon required the presence of coronary artery disease.

Statistical Analysis

Parametric data are expressed as mean ± SD and as percentages for categorical variables. The overall accuracy of the 2D and 3D TEE methods in identifying the predominant valve lesion causing MR was determined. The accuracy of these methods in defining specific scallop disease was also determined and calculated as the sum of true-positive and true-negative results divided by the number of scallops involved. The sensitivity and specificity of 2D and 3D transesophageal echocardiography were determined with respect to specific scallop disease, using surgical findings as a reference. Differences in diagnostic accuracy among the methods were assessed using the McNemar statistic. A 2-tailed P value $< .05$ was considered statistically significant. Interobserver agreement between these two methods was assessed using the κ statistic, an index that compares agreement against what might be expected by chance. Possible values range from 1 (perfect agreement) via 0 (no agreement above that expected by chance) to −1 (complete disagreement).

RESULTS

Population Characteristics

A total of 42 consecutive patients with established diagnoses of MR who were referred for possible MV repair or replacement were included. Patient demographic and clinical characteristics are listed in Table 1.

MV Disease Characteristics

All patients underwent both intraoperative 2D and real-time 3D TEE imaging. Intraoperative MR severity as determined on 2D transesophageal echocardiography was grade 4 in 76% of patients (n = 32) and grade 3 in 17% (n = 7). The mean ejection fraction was visually estimated at 60 ± 10%. The most frequent cause of MR as determined by surgical inspection was myxomatous degeneration, in 86% of patients (n = 36), followed by functional or ischemic MR related to underlying coronary artery disease in 12% (n = 5) and a cleft MV in 2% (n = 1). The specific leaflet pathology of the patients is described in Table 2. Multiscallop disease was confined to the anterior leaflet in 5% (n = 2) and to the posterior leaflet in 7% (n = 3). In 31% of patients (n = 13), segmental disease was present in both leaflets as either multiscallop disease (n = 8) involving both leaflets or diffuse bileaflet myxomatous degeneration (n = 5). Overall, the scallop most frequently involved was P2 (48%; Figure 1, Video 1), followed by A2 (21%), P3 (19%), and P1 (17%). Of these patients, 93% (n = 39) had MV repair procedures. The remaining 3 patients had MV replacement for the following reasons: presence of residual moderate MR after complex posterior leaflet repair, complex anterior leaflet disease and ischemic MR. Concurrent coronary artery bypass grafting was performed in 17% of patients (n = 7) and other valve surgery in 10% (n = 4; aortic valve, n = 2; tricuspid valve, n = 2).

Table 3 Detection of mitral valve pathology with 2D and live 3D transesophageal echocardiography compared with surgical findings

Characteristic	Sensitivity (%)		Specificity (%)		Accuracy (%)	
	2D	3D	2D	3D	2D	3D
P1	86	100	86	100	86	100*
P2	90	100	86	91	88	95
P3	63	100	82	94	79	93
A1	100	100	100	100	100	100
A2	78	100	88	100	84	100*
A3	0	100	92	97	86	98*
Bileaflet disease	77	100	89	100	86	100*
Chord rupture	95	95	91	91	93	95
Ischemic MR	60	80	100	100	95	98

*$P < .05$, 3D versus 2D transesophageal echocardiography.

Comparison of 2D and 3D Transesophageal Echocardiography

The mean 3D TEE acquisition time was 60 ± 18 seconds. This was the time required to obtain multiple 3D acquisitions (2.5 ± 1.2 acquisitions) until an image of sufficient quality was obtained. It is important to note that this acquisition time was recorded in the latter half of the study, by which time significant experience in acquiring 3D images had been attained by the echocardiographer. Review of the 2 or 3 videos provided to the 3D readers was reported as requiring a total of 2 to 3 minutes. Interpretable live 3D TEE acquisition was feasible in all patients, with optimal (36%) and good (33%) imaging quality in the majority of cases and satisfactory imaging in 31% of cases. No patients were excluded on the basis of unsatisfactory image quality. Similarly, 2D image acquisition was also feasible in all patients.

The predominant MV pathology was correctly identified in 98% of patients with 3D transesophageal echocardiography and in 90% of patients with 2D transesophageal echocardiography ($P = .56$). Sensitivity, specificity, and accuracy were also calculated and broken down by involved scallop, chordal rupture, and ischemic MR (Table 3). Real-time 3D TEE imaging was superior in identifying specific scallop disease, particularly involving the A2, A3, P1, and P3 segments. This was statistically significant for all these segments except P3 ($P = .07$). This was likely due to the low frequency of P3 lesions; however, comparative evaluation revealed that sensitivity, specificity,

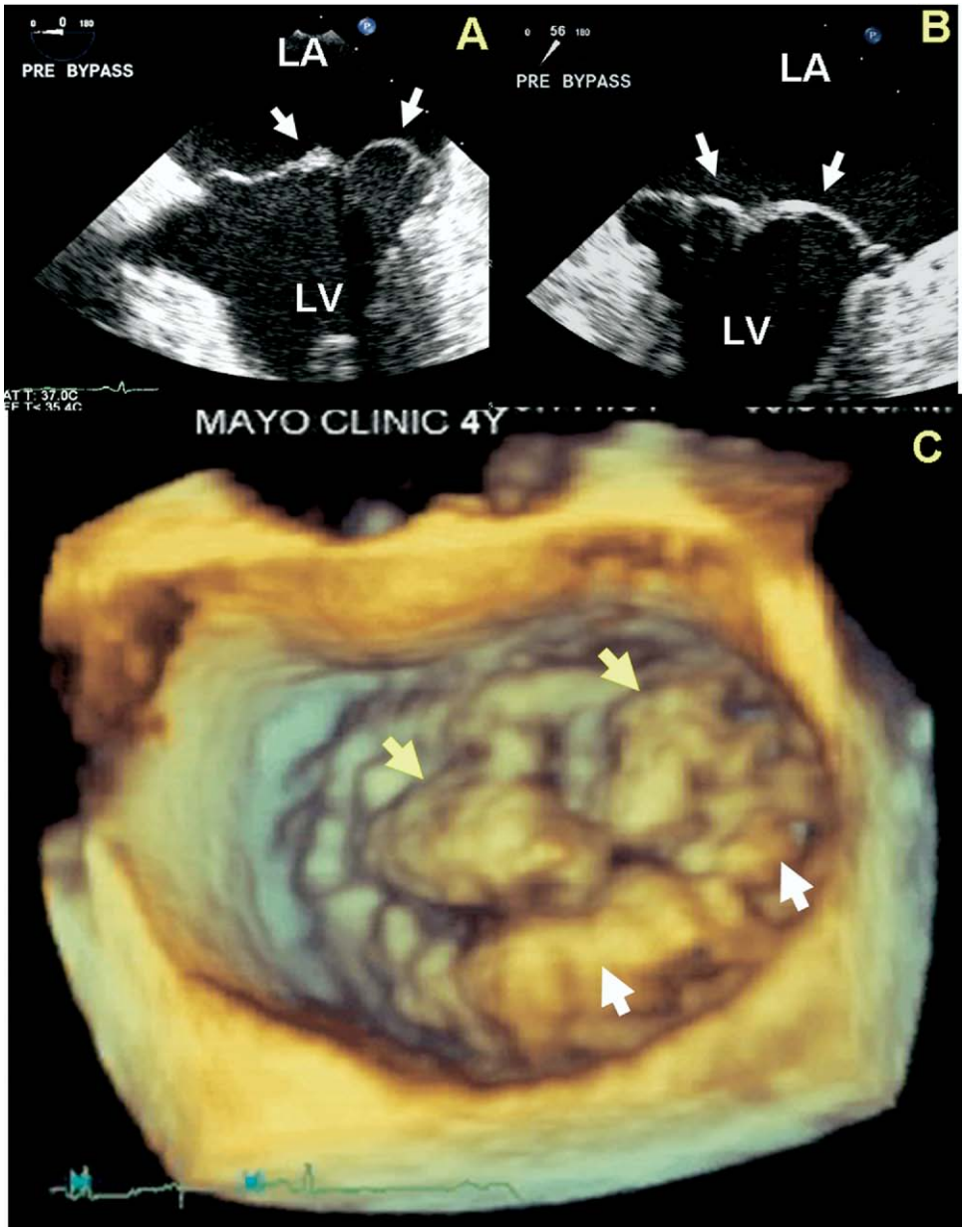

Figure 2 Bileaflet myxomatous disease. End-systolic 2D TEE views at (**A**) 0° and (**B**) 56° (commissural view). Severe bileaflet prolapse (Barlow's disease) is shown, involving both the anterior and posterior middle scallops of the MV (A2 and P2), noted by the *white arrows* in (**A**) and (**B**). (**C**) Live 3D TEE en face view of the MV at end-systole from the left atrial perspective demonstrating severe bileaflet prolapse; the severe redundancy of leaflet tissue and more prominent prolapse of A2 and A3 *(yellow arrows)* as well as P2 and P3 *(white arrows)* are clearly evident. *LA*, Left atrium; *LV*, left ventricle.

and accuracy were all higher than with 2D TEE imaging. This was true for all valve segments except A1, for which it was equivalent. The overall diagnostic accuracy of 3D TEE imaging was demonstrated to be higher than of 2D TEE imaging with respect to bileaflet disease (Figure 2). The overall diagnostic accuracy of detecting a ruptured chord was similar between 2D and 3D TEE imaging. Both diagnostic approaches reliably detected cases of ischemic MR. Interobserver agreement for the diagnosis of the predominant mechanism of MR was very good for 2D TEE diagnoses ($\kappa = 0.76$) and very good for 3D TEE diagnoses ($\kappa = 0.70$).

DISCUSSION

The main finding of this study is that new-generation real-time 3D TEE imaging technology for the intraoperative evaluation of MV disease is both feasible and accurate. Three-dimensional TEE imaging was superior to 2D TEE imaging in the diagnosis of bileaflet (Figure 2, Video 2), P1/P3, and A2/A3 segment disease (Figure 3, Video 3). Importantly, with increasing experience, 3D TEE was uncomplicated to use in the operating room, and useful data were acquired easily and rapidly. Furthermore, we have shown that the concerns associ-

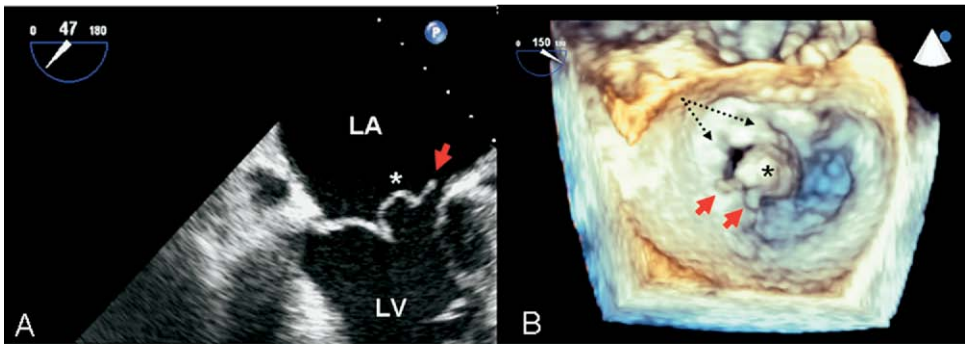

Figure 3 Anterior leaflet disease. (**A**) Two-dimensional TEE end-systolic view demonstrating a flail middle scallop of the anterior mitral leaflet (A2); the flail A2 scallop is noted by the *white asterisk*, and a torn chordae tendineae is noted by the *red arrow*. (**B**) Live 3D TEE en face view of the MV at end-systole from the left atrial perspective, demonstrating the flail A2 scallop *(black asterisk)*; also delineated are an unsupported lateral scallop (A1), noted by the *dotted black arrows*, and multiple torn chordae tendineae *(red arrows)*. The unsupported A1 segment was also diagnosed on 2D TEE imaging, but with less certainty and after imaging from multiple planes. *LA*, Left atrium; *LV*, left ventricle.

ated with traditional 3D TEE imaging in the operating room have a negligible impact on the 3D assessment of MV pathology using real-time 3D TEE imaging.

Two-dimensional transesophageal echocardiography has been established as a reasonable approach to determine MV pathology.[10-12] However, it can also take several minutes to acquire and examine the multiple MV planes to provide a description of MV pathology.[13] Two-dimensional TEE imaging is not always an optimal preoperative diagnostic tool, because the accuracy with which specific MV scallop involvement is identified is dependent on operator expertise. As demonstrated in our study, this can be very good in the hands of echocardiographers who are experts in MV assessment, but not all operators have this level of expertise. Also, the sensitivity and specificity tend to decrease with more complex multisegment and bileaflet disease.[14] Previous reports on 2D TEE accuracy in the localization of mitral scallop morphology traditionally included higher percentages of simple surgical prolapse (isolated P2).[15] Hence, the diagnostic accuracy of this technique varies among studies, such that reported sensitivity values have ranged from 78% to 95% and specificity values from 85% to 96%.[16-18] At our center, the overall accuracy of this new live 3D TEE technique in an unselected population undergoing MV repair tended to be better than with 2D TEE imaging alone. We have shown that real-time 3D imaging performs well in a population characterized by a large percentage of complex MV disease. Approximately 43% of our cases had multisegment disease involving one or both leaflets. These results were achieved by solely interpreting the 3D TEE left atrial view. Certainly, as more experience is gained, other views could be added to routine practice and would further improve the diagnostic accuracy of live 3D TEE imaging. As is the case with 2D TEE imaging, 3D TEE imaging is certainly also an operator-dependent technique, and training in this modality is required. However, in our study, this experience was gained rapidly by operators who were already expert users of 2D transesophageal echocardiography. We were also able to demonstrate that real-time 3D TEE imaging can identify various etiologies of MR in an undifferentiated population referred for MV repair and is not specific to the diagnosis of myxomatous valve disease. Specifically, it was able to differentiate between cases of myxomatous valve disease and ischemic MR, and its accuracy in doing so was similar to that of 2D TEE imaging. This highlights the possibility that real-time 3D TEE

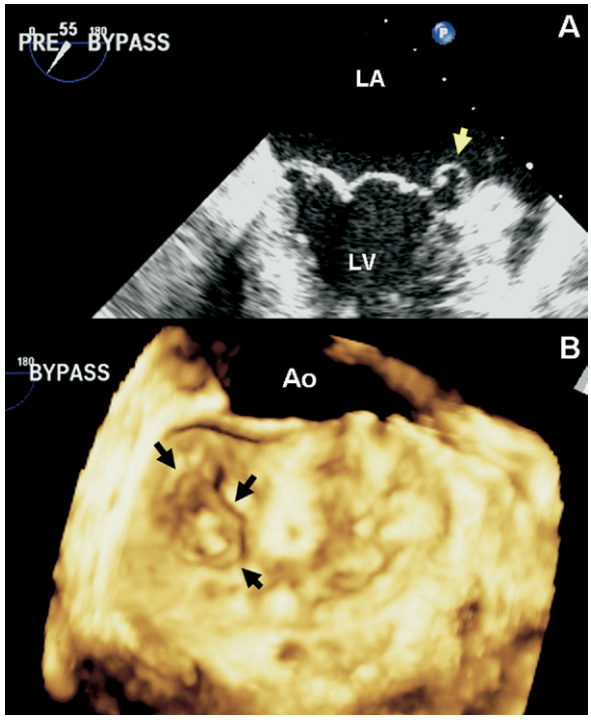

Figure 4 P1 prolapse. (**A**) End-systolic 2D TEE commissural view demonstrating severe prolapse of the lateral scallop of the MV posterior leaflet (P1), indicated by the *yellow arrow*. (**B**) Live 3D TEE en face view of the MV at end-systole from the left atrial perspective, which not only demonstrates the P1 prolapse but also presents a clearer picture of the severe degree of leaflet surface area involved *(black arrows)*. *Ao*, Aorta; *LA*, left atrium; *LV*, left ventricle.

imaging could have a role in the spectrum of MV pathology and not remain limited to assessment of myxomatous valve disease.

Our data regarding real-time 3D MV assessment are in complete agreement with previous work looking at traditional 3D TEE imaging.[14,19-21] The majority of these studies showed that 3D echocardiographic findings correlate closely to surgical findings, achieving an exact anatomic description in approximately 90% to 95% of seg-

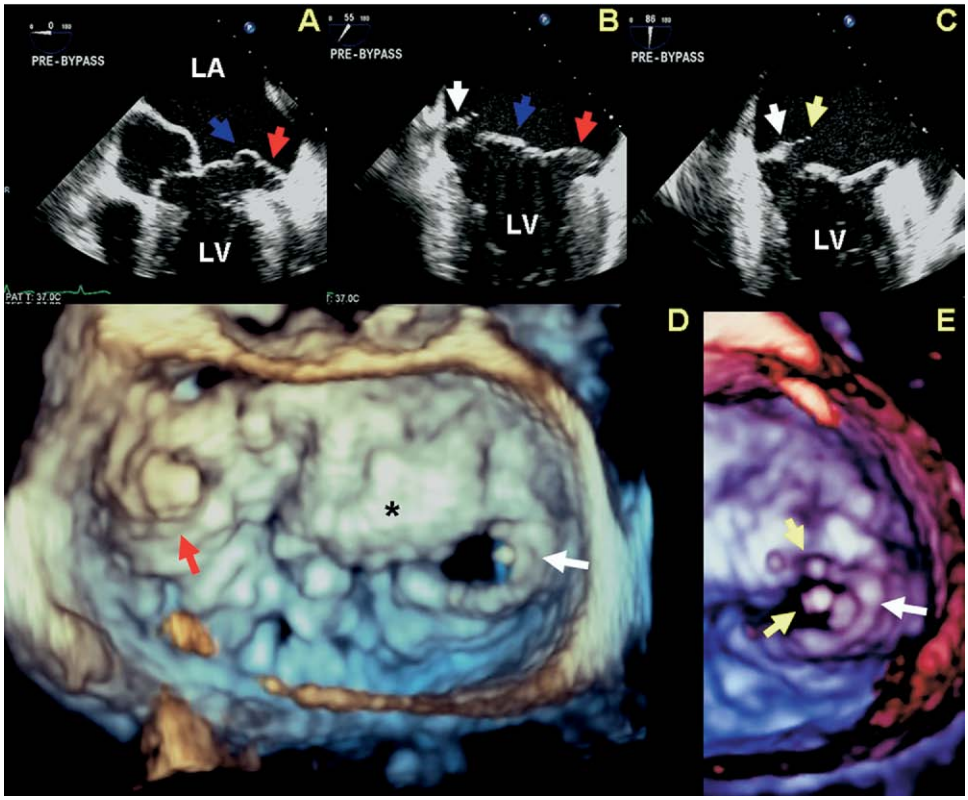

Figure 5 Bileaflet myxomatous disease. Systolic 2D TEE views showing (**A**) the high esophageal 0° view, (**B**) the midesophageal 60° commissural view, and (**C**) the midesophageal 90° view; the *blue arrow* indicates the prolapsing middle scallop of the anterior mitral leaflet (A2), the *red arrow* indicates the prolapsing lateral scallop of the posterior mitral leaflet (P1), and the *white arrow* indicates the flail medial scallop of the posterior leaflet (P3); a torn chordae tendinea is highlighted by the *yellow arrow*. (**D**) Live 3D TEE en face view of the MV from the left atrial perspective, with the *red arrow* noting P1 prolapse, the *white arrow* noting the flail P3, and the *black asterisk* noting A2 prolapse; note how the severity of leaflet tissue redundancy is well visualized on the live 3D TEE image. (**E**) Zoomed view of the flail P3 scallop, with the *yellow arrows* demonstrating multiple torn chordae tendineae. *LA*, Left atrium; *LV*, left ventricle.

ments, whereas 2D echocardiography is less accurate. This incremental value was mainly seen in complex disease involving both leaflets and the anterior leaflet. We also found that 3D TEE imaging demonstrated improved accuracy in identifying most scallop lesions compared with 2D TEE imaging, and this was most impressive for P1, A2, A3, and bileaflet disease. A trend for improved diagnostic utility with 3D TEE imaging was also seen for P3 segments. However, this did not reach statistical significance and is likely related to the smaller number of these less common lesions.

MV repair is becoming the intervention of choice in treating MR.[2,3] The success and planning of surgical MV repair rests on accurate MV anatomic assessment and the detection of those lesions that may predict unsuccessful repair, such as extensive bileaflet disease or anterior leaflet pathology.[22] Moreover, a true left atrial view of the MV may aid surgeons in determining the degree of leaflet resection required when faced with a limited operating field and an immobile heart devoid of blood (Figure 4, Video 4, Figure 5, Video 5). Accordingly, an alternate strategy may be to use real-time 3D transesophageal echocardiography as a part of the routine preoperative assessment of MV pathology. This would entail going beyond MV lesion identification, to encompass detailed planning and optimization of MV procedures to facilitate even more complex MV repair techniques.

Study Limitations

We used surgical findings as the gold standard against which to evaluate 2D and live 3D TEE images. However, the surgeon inspects the valve in an immobile nonphysiologic state, as opposed to echocardiographic assessment, which visualizes the valve in a dynamic state. There is no practical way to overcome this limitation. It has been reported that 3D echocardiography may identify small areas of prolapse that are not readily apparent to surgeons. Finally, in this study, the surgeon was informed of the 2D but not 3D TEE results when inspecting the valve, introducing a potential bias in the surgical interpretation of the findings.

CONCLUSIONS

New generation real-time 3D transesophageal echocardiography is a practical and feasible intraoperative technique for the rapid and accurate identification of complex MV pathology in patients referred for surgical correction of MR. Real-time 3D image acquisition is less time consuming than both traditional 3D and 2D TEE assessment of the MV and in our study was superior to 2D TEE imaging in defining specific MV pathology. Comprehensive 2D multiplanar TEE imaging

remains invaluable in the Doppler assessment of MR; hence, 2D and 3D TEE imaging should be regarded as complementary, not competitive, imaging modalities. On the basis of our findings, we would encourage formal 3D echocardiographic training and the expanded use of this modality in routine clinical practice. As clinicians and centers gain experience, studies with larger numbers should be pursued to corroborate our results.

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