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Echocardiography

Multiplane Two-Dimensional versus Real Time Three-Dimensional Transesophageal Echocardiography in Ischemic Mitral Regurgitation

Khalil Fattouch, M.D., Ph.D.,* Sebastiano Castrovinci, M.D.,* Giacomo Murana, M.D.,* Giuseppina Novo, M.D.,† Giuseppa Caccamo, M.D.,† Emanuela C. Bertolino, M.D.† Roberta Sampognaro, M.D.,‡ Salvatore Novo, M.D.,† Giovanni Ruvolo, M.D.,† and Patrizio Lancellotti, M.D., Ph.D.§

*Department of Cardiac Surgery and †Department of Cardiology, University of Palermo, Palermo, Italy; ‡GVM Care and Research, Maria Eleonora Hospital, Palermo, Italy; and §Department of Cardiology, Heart Valve Clinic, University of Liège, CHU Sart Tilman, Liège, Belgium

Objectives: Intraoperative three-dimensional (3D) transesophageal echocardiography (TEE) has been suggested to be a valuable technique for the evaluation of the mechanisms of ischemic mitral regurgitation (IMR). Studies comparing multiplane two-dimensional (2D) with 3D TEE reconstruction of the mitral valve using the new mitral valve quantification (MVQ) software are lacking. We undertook a prospective comparison between multiplane 2D and 3D TEE for the assessment of IMR. Methods: We evaluated echocardiographically 45 patients with IMR who underwent mitral valve surgery in our institution. 2D and 3D TEE examinations followed by a 3D offline assessment of the mitral valve apparatus were performed in all patients. Offline analysis of mitral valve apparatus was conducted with QLAB–MVQ. Results: 3D TEE image acquisitions were performed in a short period of time and were feasible in all patients. Real time 3D TEE imaging was superior to 2D in identifying specific mitral scallops (A1, A3, P1, P3) and commissures. When compared with 2D TEE, 3D offline reconstruction of the mitral valve allows an accurate quantification of the shape and diameters of the mitral annulus. Both approaches provide almost similar values for the tenting area and the coaptation depth. The 3D approach gave the advantage of direct calculation of the leaflets angles, tenting volume, and surface of the leaflets. The interpapillary muscles distance at the level of the papillary muscle head was greater in 2D than in 3D. Conclusions: 3D TEE imaging provides valuable and complementary information to multiplane 2D TEE for the assessment of patients with IMR. (Echocardiography 2011;28:1125-1132)

Key words: real time 3D echocardiography, ischemic mitral regurgitation, transesophageal echocardiography

An ischemic myocardial damage represents the initiating event for ischemic mitral regurgitation (IMR), a valve dysfunction due to an uncoordinated three-dimensional (3D) interconnection between the left ventricle (LV), the mitral annulus, the mitral leaflets, and the subvalvular apparatus. The ischemic insult results in a regional and/or global remodeling process of the LV, characterized by the acquisition of a more spherical shape and wall-motion abnormalities. These changes progressively lead to mitral annular dilatation and flatness and subvalvular apparatus distortion and displacement.[1–3] Thanks to the development and widespread use of advanced techniques for surgical valve reconstruction, which in comparison with valve replacement has shown to improve survival and outcome, the demand for assessing the feasibility of mitral valve repair by echocardiography has increased considerably. Although 2D transesophageal echocardiography (TEE) can provide precise information regarding mitral valve anatomy, 3D TEE can potentially increase the understanding of more complex abnormalities of mitral valve apparatus.[4–6] 3D-echocardiography has been shown to be a valuable technique for the preoperative assessment of patients undergoing mitral repair surgery, especially in the setting of organic mitral regurgitation (MR). In ischemic disease, 3D-echocardiography has contributed most to our knowledge of the mechanism of IMR.[7] 3D mitral valve tethering geometry and altered annular shape and motion have been described as major contributors to IMR in both animal models and patients using sophisticated and time-consuming mathematical software.[8,9] The main limitation of such 3D approaches is the inability to perform direct measurement from 3D sections. Recently, new dedicated software for advanced

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Address for correspondence and reprint requests: Prof. Khalil Fattouch, M.D., Ph.D., Via Liborio Giuffré, 5, Department of Cardiac Surgery, University of Palermo, 90100 Palermo, Italy. E-mail: khalilfattouch@hotmail.com

3D analysis of the mitral valve has been developed to be incorporated into clinical practice.[10,11] This mitral valve quantification (MVQ) software provides a 3D realistic model of the mitral valve, which is constructed by the echocardiographer interactively with MVQ program. Hence, the program allows the calculation of a range of parameters (annulus, anterior and posterior leaflet (PL), leaflet segmentation, coaptation line and potential coaptation defects, mitral valve spatial relationship with the papillary muscles, and aortic valve) for quantitative assessment of the 3D mitral valve structure. Hitherto, whether the 3D measurements obtained with the MVQ program are comparable to the 2D representations of the mitral valve is unknown. In this study, we undertook a prospective comparison of multiplane 2D versus 3D TEE for the assessment of IMR.

Methods:

Population:

Between December 2008 and September 2010, we studied 45 patients (35 men, mean age 65 ± 8 years) with IMR referred to our institute to undergo mitral valve surgery. A comprehensive 2D and 3D TEE examinations followed by a 3D offline assessment of the mitral valve apparatus was performed in all patients. To permit the analysis of 3D mitral valve geometry, we included subjects with structurally normal mitral valve, technically adequate real time 3D echocardiographic imaging of LV and mitral apparatus (annulus, leaflets, and subvalvular apparatus). Patients with acute myocardial infarction (MI), structural mitral valve, or subvalvular lesions (e.g., mitral valve prolapse or rheumatic disease) and other cardiac diseases (pericardial and congenital) were excluded from the study.

Echocardiographic Protocol:

All echocardiographic examinations were performed using a recently introduced fully sampled matrix array TEE transducer (X7–2t) capable of acquiring images in both 2D and 3D dimensions (iE 33 echocardiographic, Philips Medical Systems, Veenpluis, The Netherlands). Full-volume datasets were obtained using electrocardiographic gating over seven consecutive heart beats to combine seven small real time subvolumes into a larger pyramidal volume. Accuracy was made to avoid imaging artifacts. Offline analysis of mitral valve apparatus was conducted with QLAB–MVQ and QLAB3DQ Adv (Philips Medical Systems) using the same echocardiographer utilized for the images acquisition.

A three-point scoring protocol was applied to all eight mitral valve scallops according to Carpentier's classification.[12] We evaluated the ease of recognition and confidence of interpretation of segmental function with 2D and 3D TEE,[13]

0: Inadequate for analysis (not clearly identified),
1: Adequate for analysis (could be identified),
2: Good for analysis (well identified with excellent image quality).

To accurately quantify the degree of mitral leaflets tethering we also investigated the difference between the two methods regarding to annulus structure, leaflets area, angles between leaflets and annulus plane, coaptation depth, tenting area and volume, interpappilary muscle distance, and LV volumes.

Two-Dimensional Echocardiographic Approach:

The 2D images were acquired by level III–trained echocardiographers.[14] Multiplane 2D TEE evaluation included a standardized approach. This evaluation was performed as previously described using the Carpentier's nomenclature. The mitral valve was examined in multiple image projections. At 0°, three positions were used: Anterior five chamber (P1 and A1), middle or four chamber (P2 and A2), and posterior (A3 and P3). Between 45° and 90°, with clockwise and counter clockwise rotation and with drawl 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. Particular emphasis was placed on attempting to visualize the commissural zones, with vertical pullback of the probe from the five-chamber 0° view for the anterolaterale commissure and clockwise rotation from the two-chamber 90° view for the posteromediale commissure. The transgastric 0° view was also used to visualize the valve closure line and commissures, and at 60°–90° to visualize the subvalvular apparatus (papillary muscles and chordae).

The posterior and the anterior leaflet angles were calculated according to the following formulas described by Magne et al.[15]: $PLA = \sin^{-1}$ (CD/PLL) and $ALA = \sin^{-1}$ (BD/ALBD), where PLA is the posterior leaflet angle, CD is the coaptation distance, and PLL is the PL length (i.e., the distance between the posterior annulus and the PL tip). In the second formula, ALA is the anterior leaflet angle, BD is the bending distance (i.e., the distance between the anterior leaflet bending and annular line), and ALBD is the anterior leaflet bending distance (i.e., the distance between anterior annulus and anterior leaflet bending point).

The valvular tenting area was measured by the area enclosed between the annular plane and the mitral leaflets from the transesophageal 120° view at early systole. The coaptation depth considered as the distance between leaflets coaptation and the mitral annulus plane was measured from the same view at early systole.

Three-Dimensional Echocardiographic Approach:
As the 2D TEE study was being completed, another operator was paged and performed the live 3D TEE imaging, blinded to the 2D results. The 3D TEE operator was level III–trained echocardiographers with additional training in 3D echo. The 3D echo examination was started in the real time mode to obtain a first orientation of the mitral valve and LV. A live 3D zoom mode was then performed in the middle transesophageal or four-chamber view, throughout the cardiac cycle, to provide an "en face" surgical view of the mitral valve from the left atrial (LA) perspective[5] (Fig. 1). Finally, from the four-chamber view 3D zoom mode, we switched to the full-volume mode using electrocardiographic gating over seven consecutive heart beats to combine seven small real time subvolumes into a larger pyramidal volume. Care was taken to include the entire LV inside the echocardiographic window to avoid any imaging artifacts.

Offline Analysis of 3D Images:
Recorded 2D and 3D TEE images were analyzed off line separately. The 2D TEE operator, blinded to the 3D TEE information, evaluated all 2D TEE images. The expert in 3D echocardiography blinded to the 2D TEE information, analyzed the recorded 3D TEE images. Subsequently, after 1–4-month interval, on the basis of images recorded in the echocardiographic system, one observer (trained QLAB software echocardiographer), blinded to both 2D and 3D results obtained previously, repeated all the offline measurements. The intraobserver variability was calculated from repeated offline measurements on recorded images within 24 hours after the first analysis. Strength of agreement was good for the interobserver analysis ($r = 0.81$–0.87) and excellent for the intraobserver analysis ($r = 0.85$–0.92) for all the parameters evaluated. Full-volume 3D datasets were digitally stored and transferred to a workstation with Q-Laboratory MVQ Software (Version 6.0, Philips Medical Systems) for offline analysis. Three orthogonal mitral annulus images were displayed and subsequently modified to optimize visualization of the entire annulus. Mitral annular measurements were performed six times during the cardiac cycle in early, middle, and late systole and diastole. First, we marked four annular key reference points (anterolateral and posteromedial hinge points of leaflet insertion, anterior, and posterior points). Second, with three key orthogonal planes locked in, seven rotational planes allowed marking of 14 markers around the annulus at leaflets insertion, thereby completing 18 total discretely marked points. Finally, we marked anterior and posterior papillary tips. With complete 3D delineation of the annulus and papillary muscles, the software build a 3D model and estimate the tenting and annulus parameters in 3D space, with precise calculation of annular area and circumference, intercommissural diameter, septolateral distance (or antero-posterior distance), anterior and posterior leaflets areas, posterior and anterior leaflets angles, coaptation depth, tenting area and volume, and interpapillary muscles distance.

Statistical Analysis:
Statistical analysis was performed using MedCalc Program (version 11.3.8.0, MedCalc Software, Broekstraat, Belgium) Results are expressed as mean ± SD. Differences in continuous variables between groups were assessed by a one-way analysis of variance. Categorical variables were analyzed by the χ^2 test or Fisher's Exact test, as appropriate. A one-way analysis of variance with subsequent 2-tailed *t*-tests was used to compare differences between groups. $P < 0.05$ were considered statistically significant. Linear regression analysis was performed and Pearson coefficients were calculated for 2D/3D correlations. Agreement was assessed using the Bland-Altman method.

Results:

All patients were in III and IV New York Heart Association (NYHA) functional (NYHA) class more than II. Mean LV ejection fraction (EF) was 40 ± 6%. All patients have severe mitral valve regurgitation caused by restrictive systolic leaflets motion (Carpentier's type IIIb) and/or annular dilation (Carpentier's type I). Mitral regurgitation (MR) was defined as ischemic when caused by coronary artery disease (CAD) in patients who had a previous MI, 2 weeks or more before hospital admission for CABG and exhibited normal valve apparatus anatomy.

Interpretable 2D and 3D TEE acquisitions were obtainable in all patients. All patients had good 3D images quality suitable for offline analysis of the mitral valve anatomy. Real time 3D TEE imaging was superior compared with 2D in identifying specific mitral scallops and commissures, particularly A1 ($P = 0.002$), A3 ($P = 0.002$), P1 ($P = 0.026$), P3 ($P = 0.03$), and anterior and posterior commissures ($P < 0.001$). The two methods appeared to be equivalent for evaluation of A2 and P2 scallops (P = ns; Fig. 2).

All data regarding the mitral valve deformation are illustrated in Table I. The flatness and the circumference dilatation of the mitral annulus were

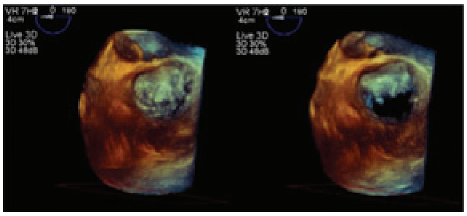

Figure 1. Left atrial view (an "en face" surgical view) in zoom 3D acquisition mode of mitral leaflet in systolo-diastolic phase.

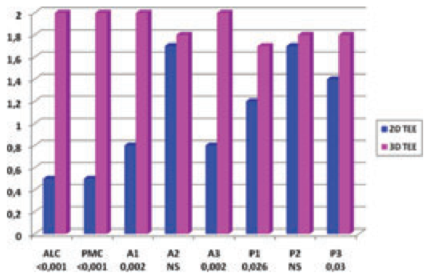

Figure 2. Segmental recognition scores (according to Carpentier's classification[15]) for 3D compared with 2D echo images. P-values represent statistical differences between the rates of accuracy obtained for each component of the mitral valve by both modalities.

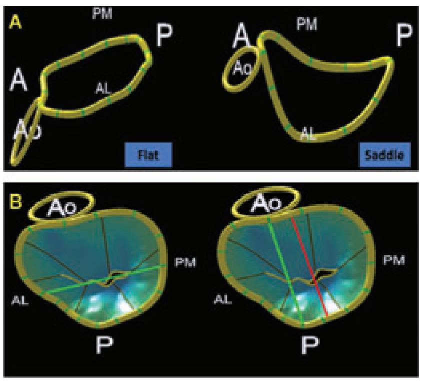

Figure 3. A. 3D annulus reconstruction: A flat dilated mitral annulus (left side) compared with the normal saddle-shaped mitral annulus (right side). **B.** The figure shows the automatic calculation of the intercommissural (left side) and septo-lateral (right side) distances in a 3D mitral valve reconstruction.

well shown on 3D echocardiography (Fig. 3). Regarding the assessment of the mitral annulus, the 3D septo-lateral distance was superior to the 2D value ($P = 0.01$). No statistical significant difference was found between the two methods for the estimation of the intercommissural distance (Table I). In the calculation of the angles between the plane of the annulus and mitral leaflets, we found a significant difference between both approaches. The 2D approach tended to overestimate the value of the angle and the 3D approach was more accurate and less time-consuming because the 3D reconstruction allows a snapshot of these data (Table I, Fig. 4A and -B). With 3D, the leaflet area, a parameter not available with 2D, was easily measured (Fig. 4C and -D). The 3D approach gave the advantage of direct 3D

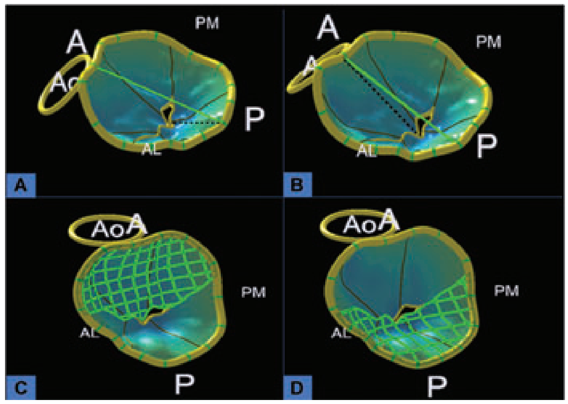

Figure 4. The angles between the plane of the annulus and **A.** posterior and **B.** anterior mitral leaflets. The **C.** anterior and the **D.** posterior leaflets surface.

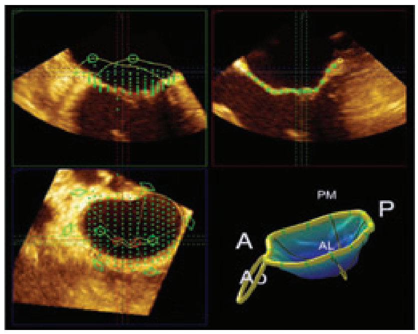

Figure 5. The figure shows each step required to reconstruct the final 3D mitral annular shape and tenting volume model using the QLAB-MVQ software.

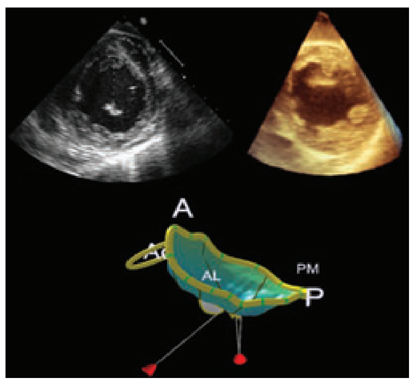

Figure 6. Interpapillary muscle distance in a transgastric 0° view using 2D and 3D acquisitions. At the bottom, the 3D mitral valve reconstruction evidences the heads of papillary muscles that allow an accurate measurement of interpapillary distance.

TABLE I

Comparison between 2D and 3D TEE for All Variables

Mitral Parameters	2D TEE	3D TEE	P Value
Annulus			
Intercommissural distance (mm)	31.7 ± 0.6	31.8 ± 0.6	NS
Septo-lateral distance (mm)	32.5 ± 0.3	34.8 ± 0.7	0.01
Leaflets			
Anterior leaflet area (mm^2)	–	757.6 ± 56.2	–
Posterior leaflet area(mm^2)	–	460.5 ± 62.4	–
Ventricule			
Interpapillary distance (mm):			
PPM tip*	2.4 ± 0.3	2.1 ± 0.2	0.003
PPM body*	2.56 ± 0.3	2.6 ± 0.3	NS
LVEDV (mL)	110.9 ± 7.6	130.9 ± 7.3	<0.001
LVESV (mL)	68.7 ± 7.3	85.7 ± 4.1	<0.001
Leaflet angle			
Posterior leaflet angle (°)	51.4 ± 1.1	47.8 ± 1, 4	0.006
Anterior leaflet angle (°)	37.9 ± 0.5	35.5 ± 0.9	0.01
Coaptation			
Coaptation depth (mm)	9.8 ± 0.5	9.8 ± 0.4	NS
Tethering			
Tenting area (mm^2)	27.2 ± 0.6	27.10 ± 0.6	NS
Tenting volume (mL)	–	8.9 ± 1.7	–

*NS = not significant.

visualization (tenting site and regurgitant orifice) and volume calculation of the tenting area (Fig. 5).

A significant difference was found between both echocardiographic approaches for the evaluation of interpapillary distance and LV volumes (Fig. 6). The interpapillary muscles distance (at the level of the papillary muscle head) was greater with the 2D approach as compared with the 3D approach ($P = 0.003$). Conversely, no statistical difference was found between the two methods regarding the interpapillary muscles distance measured at the level of the papillary muscles body. When compared with 3D, 2D TEE underestimated LV volumes.

There was a significant correlation between 2D and 3D measurements for the intercommissural distance ($r = 0.89$), the papillary muscles separation ($r = 0.86$), the coaptation depth ($r = 0.93$), and the tenting area ($r = 0.94$) (Fig. 7). In contrast, no linear correlation was found for the septo-lateral distance ($r = 0.10$), the distance between papillary muscle tips ($r = -0.03$), the LV volumes ($r = -0.04$), the ALA ($r = -0.21$), and the PLA ($r = -0.04$) (Fig. 8).

Discussion:

In ischemic disease, the mitral valve architecture is sharply modified. In patients referred for surgical correction of IMR, TEE is the reference intraoperative technique for the examination of the mitral valve apparatus complexity. In this study, we showed that the analysis of the mitral valve using the 3D TEE is feasible and provides additional information to multiplane 2D TEE. 3D TEE has the advantage to better define the mechanisms of IMR.

In practice, a better understanding of mechanisms of IMR can help surgeons in decision making, with the goal of improving long-term valve repair results. Multiplane 2D TEE plays an important role in assessing the feasibility of repair but demands specialist skill and experience.[16,17] Conversely, real time 3D echocardiography imaging allows visualization of the entire LV in multiple planes by simply cropping the volumetric 3D dataset. The recent application of 3D TEE to the study of the mitral valve has brought new understanding into the mechanism of IMR. The results of the present study confirm and extend previous findings. 3D TEE imaging is superior to 2D TEE for identifying specific mitral scallops and commissures, particularly A1, A3, P1, P3, and anterior and posterior commissures. Conversely, both techniques are equivalent for the evaluation of A2 and P2 scallops.

The mitral annulus has a complex geometry, including an asymmetric elliptical shape with a saddle-shaped 3D structure.[18] The incorporation of the QLAB-MVQ software into latest 3D echo machines allows the accurate quantification of the 3D shape and dynamic of the mitral annulus, which remain difficult with conventional 2D TEE.[19] In IMR, the mitral valve annulus is often dilated and flattened, the distortion being greater

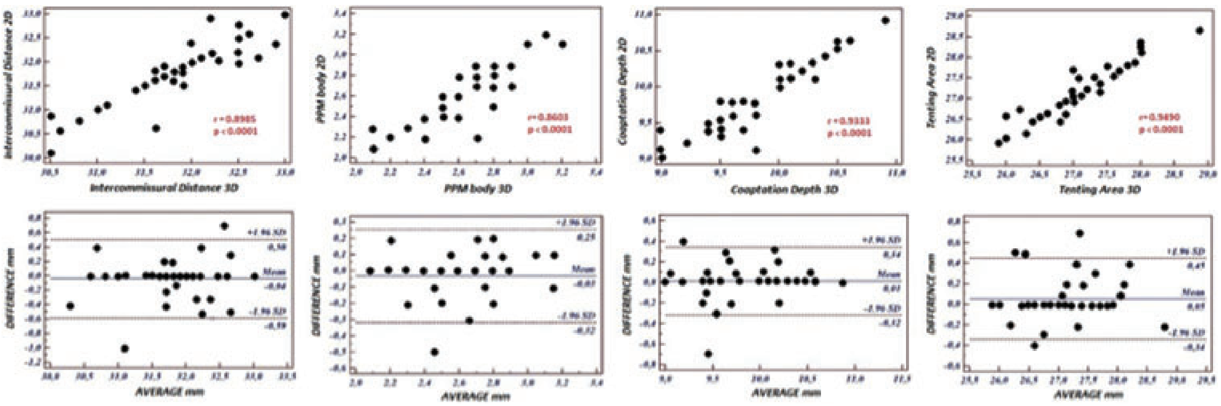

Figure 7. Linear regression and Bland-Altman plots for intercommissural distance, PPM body, coaptation depth, and tenting area as assessed with multiplane 2D and 3D TEE imaging.

in anterior MI.[20] In this study, the mitral annulus dimensions specifically in the posterior region and the site of maximum dilatation were larger in 3D echo than in 2D. On the contrary, the intercommissural distance was found to be equal with both techniques. Magne et al.[15] found that the preoperative PLA predicts outcome after restrictive annuloplasty and its determination may be useful in preoperative planning of surgery. Posterior displacement of the coaptation and verticalization of the PL after restrictive annuloplasty can be explained as a result of restricted PL motion and may lead to recurrent MR.[21] The calculation of the angle between the PL and the plane of the annulus is feasible by 2D echo but, on the contrary of 3D echo, it is more time-consuming and may be subject to error. However, the 2D and 3D measurements of the leaflet angles are not similar; it appears greater with 2D TEE. Conversely, both approaches provide similar value for the tenting area and the coaptation depth. The calculation of the surface of the leaflets and specifically the anterior leaflet is only feasible with 3D echo. Although such a measurement may be helpful in the choice of the ring size during mitral valve annuloplasty, specific studies are required to examine its clinical usefulness.

The displacement of the papillary muscle heads was better revealed by the 3D approach. Such a measurement can be useful at the time of mitral valve repair when additional subvalvular techniques are used. Of note, with 2D, the transgastric (0° and 90°) view is not well aligned with the papillary muscles head while the 3D reconstruction can easily draw a line between the heads of both papillary muscles. In our study, when compared with 3D, 2D TEE underestimated LV volumes. Of note, the approach used to quantify LV volumes from 3D dataset was based on semiautomated detection of LV endocardium surface, followed by calculation of the volume inside this surface either for selected phases such as

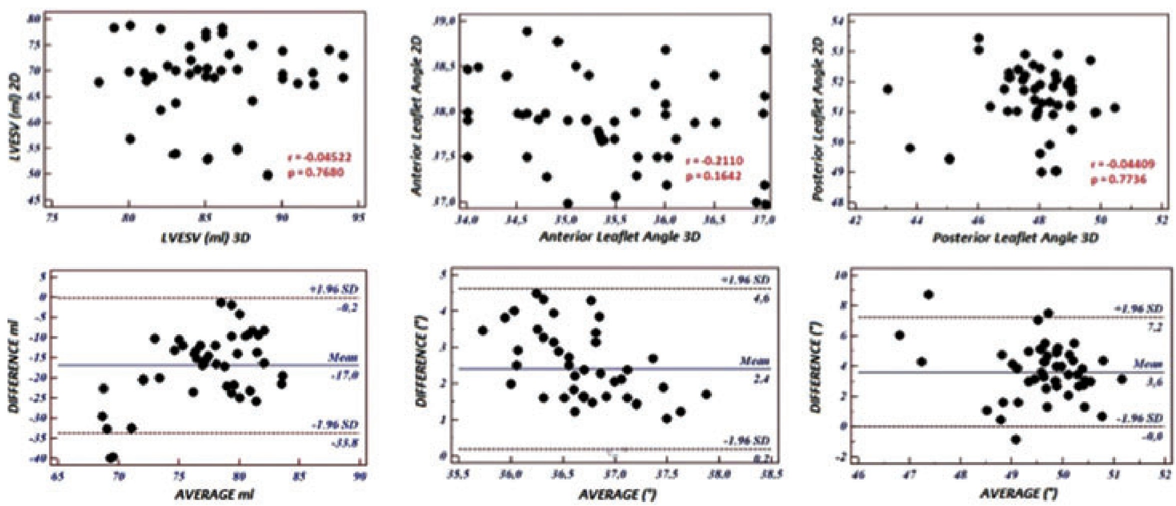

Figure 8. Linear regression and Bland-Altman plots for LVESV, anterior leaflet angle, and posterior leaflet angle as assessed with multiplane 2D and 3D TEE imaging.

end-systole and end-diastole or throughout the cardiac cycle. Because this approach uses direct volumetric quantification, it is not affected by LV foreshortening and does not rely on geometric modeling. As previously shown, 3D TEE better quantitates the LV remodeling.[22]

This study concerned a relatively small number of patients. Further investigation with more patients is thus required. As is the case with 2D TEE imaging, 3D TEE imaging is an operator-dependent technique, and training in this modality is required. However, the MVQ program (only available with the Philips Medical Systems) is easy-to-use and friendly intuitive. Although the acquisition of the full 3D dataset takes no additional time, the time dedicated for analysing the 3D data remains by far long. Furthermore, the recently developed transthoracic matrix probe X5–1 by Philips Medical Systems seems very promising in overcoming some of these limitations.

Conclusions:

Both 2D and 3D imaging modalities provide valuable information for the evaluation of patients with IMR. 3D TEE is superior to 2D TEE in the description of the mechanisms of IMR. Particularly, 3D echo approach provides new insights for the assessment of mitral annulus shape and mitral apparatus deformation with accurate visualization of specific mitral scallops, leaflets angles, and tenting volume. Moreover, 3D echo improves the quality of subvalvular apparatus visualization (papillary muscles displacement) and is more accurate in evaluation of the LV volume. 3D TEE should thus be regarded as an important adjunct to standard 2D TEE examination in decisions regarding mitral valve repair. Whether the additional morphologic information revealed by 3D TEE might improve the surgical repair approach for IMR needs to be addressed in further studies.

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Supporting Information

The following supplementary material is available for this article online:

Movie clip S1: 3D volume rending of the mitral valve.

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