Quantitative Assessment of Mitral Regurgitation: Comparison Between Three-dimensional Transesophageal Echocardiography and Magnetic Resonance Imaging

Running Title: Shanks et al: Mitral regurgitation quantification: 3D TEE vs. MRI

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ABSTRACT

**Background**—Quantification of mitral regurgitation severity with 2-dimensional (2D) imaging techniques remains challenging. The present study compared the accuracy of 2D transesophageal echocardiography (TEE) and 3-dimensional (3D) TEE for quantification of mitral regurgitation, using magnetic resonance imaging (MRI) as reference method.

**Methods and Results**—2D and 3D TEE and cardiac MRI were performed in 30 patients with mitral regurgitation. Mitral effective regurgitant orifice area (EROA) and regurgitant volume (Rvol) were estimated with 2D and 3D TEE. With 3D TEE, EROA was calculated using planimetry of the color Doppler flow from “en face” views and Rvol was derived by multiplying the EROA by the velocity time integral of the regurgitant jet. Finally, using MRI mitral Rvol was quantified by subtracting the aortic flow volume from left ventricular stroke volume. Compared to 3D TEE, 2D TEE underestimated the EROA by a mean of 0.13 cm². In addition, 2D TEE underestimated the Rvol by 21.6% when compared to 3D TEE and by 21.3% when compared to MRI. In contrast, 3D TEE underestimated the Rvol by only 1.2% when compared to MRI. Finally, one third of the patients in grade 1 and ≥50% of the patients in grade 2 and 3, as assessed with 2D TEE, would have been upgraded to a more severe grade based on the 3D TEE and MRI measurements.

**Conclusions**—Quantification of mitral EROA and Rvol with 3D TEE is feasible and accurate as compared to MRI and results in less underestimation of the Rvol as compared to 2D TEE.

**Key Words:** mitral regurgitation; real-time 3-dimensional transesophageal echocardiography; magnetic resonance imaging
INTRODUCTION

The clinical relevance of quantitative assessment of mitral regurgitation has been demonstrated in several studies.\textsuperscript{1, 2} In patients with isolated, asymptomatic organic mitral regurgitation, the effective regurgitant orifice area (EROA) as assessed with echocardiographic Doppler techniques is one of the strongest determinants of long-term outcome.\textsuperscript{1} In addition, EROA and regurgitant volume (Rvol) are independent predictors of excess mortality in asymptomatic and symptomatic patients with functional mitral regurgitation.\textsuperscript{2} In light of this evidence, current recommendations of the American Society of Echocardiography underscore the use of quantitative methods to grade mitral regurgitation, including the Rvol as a marker of volume overload and the EROA as a descriptor of lesion severity.\textsuperscript{3}

Quantitative evaluation of mitral regurgitation remains challenging. Two-dimensional (2D) color flow and Doppler echocardiography with the use of the proximal isovelocity surface area (PISA) method is the standard approach to estimate the EROA and Rvol. However, the presence of ellipsoid regurgitant orifices or the presence of eccentric regurgitant jets limits the accuracy of 2D echocardiographic PISA method to quantify mitral regurgitation.\textsuperscript{4} Recent advances in 3-dimensional (3D) echocardiography have allowed direct visualization and measurement of even highly asymmetric EROA. Validation studies have demonstrated good correlation between EROA-3D echocardiography (EROA-3D) measurements and angiographic,\textsuperscript{5, 6} and magnetic resonance imaging (MRI) measurements.\textsuperscript{4, 7, 8} In addition, several recent studies using transthoracic echocardiography (TTE) have demonstrated less underestimation of EROA-3D compared to 2D vena contracta width (VCW-2D) and 2D PISA derived measurements suggesting improved accuracy in the estimation of mitral regurgitation severity.\textsuperscript{9, 4}

The advent of a 3D fully-sampled matrix array transesophageal echocardiography (TEE) probe allowing real-time acquisition of 3D images has constituted a step forward in the evaluation of patients with mitral regurgitation. The superb image quality obtained with real-time 3D TEE has led to an increasing implementation of this technique in the daily clinical practice to evaluate mitral valve anatomy and to localize the coaptation leaflet failure. More important, the improved visualization of the vena
contracta with 3D TEE may result in more accurate quantitative evaluation of mitral regurgitation and, consequently, in an improved risk stratification of patients with mitral regurgitation. The present study aimed to compare the accuracy of 2D TEE and 3D TEE for quantification of the severity of mitral regurgitation using MRI as method of reference.

METHODS

Study population and protocols

The study population consisted of 30 patients who were clinically referred for a TEE and cardiac MRI for assessment of mitral regurgitation. Patients with irregular heart rhythm (including atrial fibrillation), a history of mitral valve replacement, significant aortic or tricuspid valve regurgitation or absolute contraindications to TEE and MRI were excluded. The standard MRI protocol was applied to assess left ventricular (LV) size and LV function, and aortic flow. The MRI study was performed on the same day as TEE. The standard volumetric and flow measurements were subsequently used for quantification of mitral regurgitation. The severity of mitral regurgitation on TEE was quantified from 2D and 3D color Doppler data sets and compared, using MRI as a reference. Functional mitral regurgitation was defined on TEE as leaflet tethering and incomplete leaflet coaptation in the presence of normal mitral valve anatomy and regional or global LV remodeling, while organic mitral regurgitation was a result of intrinsic valve lesions.

2D and 3D TEE data acquisition and analysis

Transesophageal echocardiography was performed using the iE33 ultrasound imaging system (Philips Medical Systems, Andover, MA, USA) equipped with the fully sampled matrix-array TEE transducer (X7-2t) capable of displaying both 2D and live 3D images. Complete 2D, color, pulsed- and continuous-wave Doppler images were obtained for assessment of cardiac structures and function. Mitral regurgitation severity was determined quantitatively from the 4-chamber views obtained at mid esophageal level with 0 degree tilt. The systolic frame with the most relevant lesion size was selected for
the measurement. Nyquist limit (aliasing velocity) and color gain were adjusted to eliminate random color speckle from non-moving regions, as recommended. The vena contracta was identified and the VCW-2D was measured as the narrowest portion of the regurgitant jet that occurs at or just downstream from the regurgitant orifice. By using PISA method, the 2D EROA (EROA-2D) and 2D Rvol (Rvol-2D) were quantified as previously described. The severity of mitral regurgitation was graded on a 4-point scale based on Rvol-2D (grade 1 (mild) < 30 ml, grade 2 (mild to moderate) = 30-44 ml, grade 3 (moderate to severe) = 45-59 ml, and grade 4 (severe) ≥ 60 ml). Vena contracta width-2D was measured as the narrowest portion of the mitral regurgitation color Doppler jet, with VCW-2D < 0.30 cm indicating grade 1, VCW-2D 0.30 – 0.69 cm grade 2 or 3, and VCW-2D ≥ 0.70 cm grade 4 mitral regurgitation based on current recommendations.

Three-dimensional color Doppler datasets of the mitral regurgitation jets were acquired from the views that provided the visualization of the entire vena contracta area. Full-volume datasets were obtained using ECG-gating over 7 consecutive heart beats to combine 7 small real-time sub-volumes into a larger pyramidal volume. To avoid stitch artifacts, the images were acquired during a brief suspension of breathing and special care was taken to stabilize the probe during data acquisition. All images were digitally stored for offline analysis (QLAB cardiac 3DQ, Philips Medical System, Andover, MA, USA). Using multiplanar reconstruction of the 3D TEE volume data set, a cross-sectional plane through the vena contracta perpendicular to the jet direction was selected and the EROA-3D was determined using manual planimetry of the color Doppler flow signal from an en face view (Figures 1 and 2). The Rvol by 3D TEE (Rvol-3D) was calculated as EROA-3D multiplied by the velocity time integral of the regurgitant jet on the continuous-wave Doppler.

MRI data acquisition and analysis

Data acquisition was performed on a 1.5-T Gyroscan ACS-NT/Intera MRI scanner (Philips Medical Systems, Eindhoven, The Netherlands) equipped with a 5-element cardiac synergy coil. Images were acquired during breath-holds of approximately 15 seconds using vector electrocardiographic gating.
The heart was imaged from the apex to the base, with 10 to 12 imaging levels (dependent on the heart size) in the short-axis view using a balanced turbo-field echo sequence with parallel imaging (sensitivity encoding [SENSE], acceleration factor 2). Typical parameters were a field of view of 400 x 320 mm2, matrix of 256 x 206 pixels, slice thickness of 10 mm, no slice gap, flip angle of 35°, time to echo of 1.67 ms, and time to repeat of 3.3 ms. The temporal resolution was 25 to 39 ms. Quantification of LV end-systolic and end-diastolic volumes and ejection fraction was performed on the short-axis series using MASS analytical software (Medis, Leiden, the Netherlands) and manual contour segmentation of the epicardial and endocardial borders.\textsuperscript{12, 13} Left ventricular stroke volume was obtained by subtracting LV end-systolic volume from LV end-diastolic volume.\textsuperscript{14, 15} In addition, aortic flow was obtained using phase-contrast velocity maps. Multislice spin echo images oriented in the coronal plane were obtained to identify the orientation and course of the aortic arch. At a position 2-5 cm above the aortic valve, where the aorta was nearly parallel to the caudal cranial axis of the patient, a velocity map was acquired in the axial orientation using velocity-encoded cine MRI as described previously.\textsuperscript{16} Retrospective gating was applied to acquire images evenly spaced over a complete cardiac cycle, resulting in 20 cardiac phases. By semiautomatic drawing regions of interest over the appropriate flow areas, phase-contrast velocity maps were acquired, integrated over time, and subtracted using FLOW analytical software (Medis, Leiden, the Netherlands).\textsuperscript{16} To determine mitral valve Rvol by MRI (Rvol-MRI), aortic flow volume was subtracted from LV stroke volume.\textsuperscript{12, 15}

**Statistical analysis**

Continuous data are presented as mean ± standard deviation. Categorical data are presented as absolute numbers or percentages. The Student’s t test and Mann-Whitney U test were used to compare 2 groups of unpaired data of Gaussian and non-Gaussian distribution respectively. Linear regression analysis (Pearson correlation) for continuous variables was performed to evaluate the relation between VCW-2D and 2D PISA-derived measurements. Kendall’s tau-b test for categorical variables was used to evaluate the relation between the etiology of mitral regurgitation and direction of mitral regurgitation jet.
Bland-Altman plots were used to evaluate differences in Rvol and EROA assessments by 2D TEE, 3D TEE and MRI. The mean differences and limits of agreement are reported. The percentage of under- or over-estimation by 2D and 3D TEE versus MRI was calculated as the mean of the percentage difference observed in each of the studied patients. The inter- and intra-observer reproducibility of the EROA-3D measurements were evaluated in the 30 study patients. To test the intra-observer reproducibility, one experienced observer repeated the measurements at two different time points. To evaluate the inter-observer reproducibility, a second experienced observer blinded to the measurements of the observer 1 performed the measurements at a different time point. The intra-class correlation coefficients were calculated and the mean bias and 95% limits of agreement were calculated with Bland-Altman analysis. Good correlation was defined as intra-class correlation coefficient > 0.8. All statistical analyses were performed using SPSS for Windows (SPSS Inc, Chicago), version 16. A p-value < 0.05 was considered to be statistically significant.

RESULTS

The study population consisted of 20 men and 10 women, mean age 63.3 ± 11.6 years. Table 1 describes the clinical characteristics of the patients. Functional mitral regurgitation was present in 16 (53.3%) patients and organic mitral regurgitation in 14 (46.7%), with mitral valve prolapse in 12 (30.0%), infective endocarditis in 1 (3.3%) and chordal rupture in 1 (3.3%) patient. Mitral regurgitation was directed anteriorly in 11 (36.7%) patients and posteriorly in 2 (6.7%). Central or eccentric mitral regurgitant jets were observed in 17 (57%) and 13 (43%) patients respectively. Mean LV end-diastolic volume and end-systolic volume as measured with MRI were 257.9 ± 88.1 ml and 117.1 ± 64.6 ml, respectively. Mean LV ejection fraction was 56.1 ± 15.0%.

Vena contracta, mitral valve effective regurgitant orifice area and regurgitant volume

The mean VCW-2D of the mitral regurgitant jet was 5.71 ± 2.58 mm. There was a significant, although modest correlation between VCW-2D and EROA-2D ($r = 0.624; p < 0.001$), and Rvol-2D ($r = 0.8$).
The mean EROA-2D was 0.35 ± 0.34 cm² and EROA-3D was 0.47 ± 0.37 cm². Two-dimensional TEE underestimated the EROA by a mean of 0.13 cm² (95% limits of agreement -0.55 cm²; 0.29 cm²) without significant trend. The mean Rvol-2D was 53.2 ± 35.3 ml/beat, Rvol-3D was 63.2 ± 41.3 ml/beat, and Rvol-MRI was 65.1 ± 42.7 ml/beat. The mean differences in the Rvol between 2D TEE, 3D TEE and MRI are described in Figure 3. Two-dimensional TEE underestimated the Rvol by 21.6% when compared to 3D TEE and by 21.3% when compared to MRI. In addition, 3D TEE underestimated the Rvol by 1.2% when compared to MRI.

The intra- and inter-observer reproducibility for the EROA-3D measurements were evaluated in the 30 study patients using Bland-Altman and intraclass correlation coefficient analyses. There was a good intra-observer reproducibility (mean difference = 0.011 ± 0.16 cm²; intraclass correlation coefficient = 0.98), as well as inter-observer reproducibility (mean difference = 0.013 ± 0.14 cm²; intraclass correlation coefficient = 0.98).

Mitral valve regurgitation severity grade

Based on Rvol-2D, 6 (20%) patients had grade 1, 7 (23%) patients grade 2, 6 (20%) patients grade 3, and 11 (37%) patients grade 4 mitral regurgitation. Based on VCW-2D, 3 (10%) patients had grade 1, 20 (63%) patients grade 2 or 3, and 8 (27%) patients grade 4 mitral regurgitation. Compared to Rvol-2D, VCW-2D underestimated the severity of mitral regurgitation by 1 grade in 5 (17%) patients. On the other hand, 4 (14%) patients were classified as having more severe mitral regurgitation by 1 grade using VCW-2D, compared to Rvol-2D.

Compared to 3D TEE and MRI, mitral regurgitation severity using Rvol-2D was underestimated in 9 (30%) patients, and overestimated in 1 (3.4%) patient. More specifically, 2 (33%) patients in grade 1, 4 (57%) patients in grade 2 and 3 (50%) patients in grade 3 by Rvol-2D would be upgraded to a higher mitral regurgitation grade by quantifying mitral Rvol with 3D TEE and MRI. Figure 4 shows the number of the patients classified into the same versus different mitral regurgitation severity grades after applying the currently used Rvol-2D mitral regurgitation grading criteria to all three imaging techniques. Similar
results were seen with VCW-2D, where 9 (30%) patients graded as having moderate (grade 2-3) mitral regurgitation would be upgraded to severe (grade 4) regurgitation with 3D TEE, while the same upgrade would apply to 8 (27%) patients if MRI was used. On the other hand, 2 (7%) patients had their severity of mitral regurgitation underestimated by at least 1 grade by VCW-2D, when compared to 3D TEE and MRI.

**Eiology and direction of mitral regurgitation**

There was a significant, although only modest correlation between the etiology and direction of the mitral regurgitation jet (tau-b = 0.605, p < 0.001). Two (13%) patients with functional mitral regurgitation had eccentric regurgitant jets, while 4 (29%) patients with organic mitral regurgitation had central regurgitant jets. Compared to both 3D TEE and MRI, there was no significant difference in underestimation of the Rvol by 2D TEE between the organic and central mitral regurgitation. On the other hand, a more significant underestimation of Rvol by 2D TEE was seen in the eccentric mitral regurgitation jets, compared to centrally directed jets. The amount of the Rvol overestimation by 3D TEE compared to MRI was not different between the central and eccentric mitral regurgitation (Table 2).

**DISCUSSION**

The main findings of the study include: 1) 2D TEE underestimates the mitral valve EROA and Rvol compared to 3D TEE and MRI; 2) compared to 3D TEE and MRI, 2D TEE underestimated the Rvol significantly more in the eccentric than in the central mitral regurgitation; 3) using the current grading system for the severity of mitral regurgitation based on Rvol-2D, one third of the patients in grade 1 and over half of the patients in grade 2 and 3 would have been upgraded into a more severe grade based on the 3D TEE and MRI measurements.

**Quantification of mitral regurgitation using 2D vs. 3D TEE**

Accurate quantitative assessment of mitral regurgitation has been shown to be crucial in risk stratification and clinical management of patients with mitral regurgitation. Currently, the PISA method
with 2D echocardiography is one of the most commonly used quantitative methods to grade mitral regurgitation severity, providing information on lesion severity (EROA) and volume overload (Rvol). However, the accuracy of the PISA method to quantify EROA and Rvol may be limited by the presence of hemi-elliptic shape of the flow convergence region or by the presence of eccentric regurgitant jets. Differences of EROA asymmetry among different etiologies of mitral regurgitation have been demonstrated, with a noncircular shape observed in the majority of the patients. In particular, the patients with functional mitral regurgitation often show typical elongation of EROA along the semilunar-shaped line of incomplete mitral leaflet closure caused by leaflet tethering. On the other hand, a broad spectrum of irregularly shaped EROA is often found in patients with organic mitral valve disease. Considering the ability of 3D color Doppler echocardiography to directly image the EROA without the assumption of rotational symmetry, this technique may be more accurate than 2D echocardiography for quantification of mitral regurgitation. Several in vitro and in vivo studies have compared the accuracy of 2D and 3D color Doppler techniques to quantify mitral regurgitant volume against reference methods (flow-meter standard and MRI). Three-dimensional color Doppler echocardiography resulted in less regurgitant volume underestimation for all orifice shapes tested compared to 2D flow-convergence method. Similar results were obtained in clinical studies where the assumption of an hemispherical shape of the regurgitant orifice by 2D echocardiography significantly underestimated the flow rate by 35-44%. Accordingly, the use of formulas that assume a hemi-elliptical shape of the flow convergence region even in circular orifices have been proposed to improve the accuracy of the PISA method in mitral regurgitation quantification, although this may further increase the complexity of the measurements. In addition, PISA method is less reliable in eccentric than central regurgitation, as demonstrated in the present study. Similarly to PISA measurements, disagreement in the assessment of the severity of mitral regurgitation was also observed between VCW-2D and 3D TEE and MRI. Moreover, disagreement was observed between the 2D TEE techniques themselves (VCW-2D and Rvol-2D). This could be related to some of the limitations of VCW-2D technique, including the small values of
the width of the vena contracta, with small errors potentially leading to a large percent error and misclassification of the severity of regurgitation. Relatively large number (43%) of our patient population had eccentric mitral regurgitation, which further limited the assessment of its severity due to a potential for underestimation of the mitral regurgitation jet area on color Doppler, or due to incomplete continuous wave Doppler signal potentially affecting the density of the mitral regurgitant jet. Some of these limitations may be resolved by direct en face visualization of the vena contracta area. In this regard, real-time 3D echocardiography has provided meaningful insights into the quantitative assessment of mitral regurgitation.

Real-time 3D echocardiography permits direct visualization of the vena contracta. With the use of multiplanar reformatting planes, the exact cross-sectional view of the regurgitant orifice can be obtained. Several studies have demonstrated the superior accuracy of real-time 3D echocardiography over 2D echocardiography to assess the EROA. For example, in 57 patients with significant mitral regurgitation of different etiologies, Kahlert et al. demonstrated good correlation between the direct measurement of the vena contracta with real-time 3D TTE and the measurement of EROA by hemispheric PISA method. In contrast, in non-circular regions, the hemispheric PISA method resulted in significant underestimation of the EROA. Similarly, in a recent series including 64 patients with functional mitral regurgitation, 2D echocardiography significantly underestimated the EROA as compared to real-time 3D TTE, with a mean difference ranging between 0.06-0.10 cm² (p<0.001). The present study confirms and extends previous findings by demonstrating the superior accuracy of real-time 3D TEE over 2D TEE in the quantitative evaluation of mitral regurgitation. Two-dimensional TEE PISA method significantly underestimated the EROA as compared to real-time 3D TEE. This resulted in up to half of the patients being classified into the lower mitral regurgitation severity grade by 2D TEE. In addition, compared to 3D TEE, the underestimation of EROA and Rvol by 2D TEE was more pronounced in the eccentric jets than in the central regurgitant jets. On the other hand, no differences were observed in underestimation of the mitral regurgitation severity in different etiologies of mitral
regurgitation. This could be related to the fact that there was only a modest correlation between the etiology and direction of mitral regurgitation in our study. This finding further highlights the usefulness of 3D imaging to directly visualize the EROA in any given mitral regurgitant jet, by allowing free orientation of the imaging planes.

Quantification of mitral regurgitation using 3D TEE vs. MRI

The majority of the studies comparing different methods to quantify mitral regurgitation have relied on echocardiographic techniques and only few studies have evaluated the accuracy of 3D echocardiography to estimate mitral Rvol using MRI as reference method. MRI measures directly flow through an image slice and avoids the use of complex equations to calculate it. The accuracy of flow measurement with MRI has been demonstrated in several in vitro studies and invasive in vivo measurements. Therefore, although it may be debatable, MRI may be considered one of the reference methods to evaluate the accuracy of other imaging techniques in the assessment of regurgitant valvular lesions.

The introduction of 3D echocardiography permitted the en face visualization of the mitral regurgitant orifice. The measurement of the EROA-3D by planimetry yielded more accurate quantification of Rvol using TTE approach. Therefore, the agreement between 3D echocardiography and MRI may be superior to the agreement observed between 2D echocardiography and MRI for Rvol quantification. Indeed, this has been demonstrated in several studies comparing the accuracy of 2D and 3D TTE in mitral Rvol quantification and using MRI as a reference method. Regardless the MRI method used as a reference (phase velocity mapping or volumetric assessment), different techniques based on 3D TTE have demonstrated superior accuracy to quantify mitral Rvol as compared to conventional 2D PISA method. Similarly, the present study extends previous results and demonstrates the feasibility and accuracy of 3D TEE to quantify mitral regurgitation by providing comprehensive information on EROA and Rvol. In addition, 3D TEE shows comparable accuracy to quantify mitral Rvol in central and eccentric regurgitant jets with minimal underestimation as compared to MRI. In contrast,
2D TEE significantly underestimates the Rvol in eccentric jets and underscores the need of 3D imaging techniques that permit accurate quantification of mitral regurgitation severity by correct alignment of the imaging planes.

**Study limitations**

In the present study, quantification of mitral regurgitation based on 2D TEE data was performed only with the PISA method. The inclusion of other methods such as volumetric quantification could help define the accuracy of this methodology to quantify mitral regurgitation severity using MRI as reference method.

**CONCLUSIONS**

The present study demonstrated that 3D TEE is feasible, and is more accurate in the quantitative assessment of both functional and organic mitral regurgitation when compared to 2D TEE. Given the potential strengths of 3D echocardiography, prospective studies to determine the importance of the 3D data for the clinical outcome may be needed.
DISCLOSURES

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REFERENCES


Table 1. Clinical characteristics of the patients.

<table>
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<tr>
<th>Variable</th>
<th>Patients (n = 30)</th>
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<tr>
<td>Age (years)</td>
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<td>Male / female (%)</td>
<td>33.3 / 66.7</td>
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<td>New York Heart Association Class (%)</td>
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<tr>
<td>I</td>
<td>44.8</td>
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<tr>
<td>II</td>
<td>31.1</td>
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<td>III</td>
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<td>Medical history (%)</td>
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<tr>
<td>Coronary artery disease</td>
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<tr>
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<td>Hyperlipidemia</td>
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<tr>
<td>Medications (%)</td>
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<td>Beta blockers</td>
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<td>Calcium channel blockers</td>
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<td>Spironolactone</td>
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<tr>
<td>Anticoagulation</td>
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Abbreviations: ACEI = angiotensin converting enzyme inhibitor; ARB-II = angiotensin receptor blocker-II
Table 2. Etiology and direction of mitral regurgitation: comparison between 2D TEE, 3D TEE and MRI

<table>
<thead>
<tr>
<th>Etiology and direction</th>
<th>Mean difference in Rvol (ml/beat)</th>
<th>Functional mitral regurgitation (n = 16)</th>
<th>Organic mitral regurgitation (n = 14)</th>
<th>p-value</th>
<th>Central jet (n = 17)</th>
<th>Eccentric jet (n = 13)</th>
<th>p-value</th>
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<td>2D TEE vs. 3D TEE</td>
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<td>-12.45 ± 9.0</td>
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<td>2D TEE vs. MRI</td>
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<td>-8.0 ± 6.56</td>
<td>18.2 ± 22.7</td>
<td>0.105</td>
<td>-5.8 ± 10.1</td>
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<td>3D TEE vs. MRI</td>
<td></td>
<td>-4.5 ± 8.1</td>
<td>-4.3 ± 8.06</td>
<td>0.963</td>
<td>-1.5 ± 5.3</td>
<td>-3.4 ± 11.3</td>
<td>0.950</td>
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</table>

Abbreviations: 2D TEE = two-dimensional transesophageal echocardiography; 3D TEE = three-dimensional transesophageal echocardiography; MRI = magnetic resonance imaging.
FIGURE LEGENDS

Figure 1. Three-dimensional (3D) echocardiography for assessment of the effective regurgitant orifice area (EROA-3D).

The 3D color Doppler dataset is manually cropped using the plane perpendicular to the jet direction until the narrowest cross-sectional area of the jet is reached (panel A). In an ‘en face’ view (panel B), the EROA-3D is measured by manual planimetry of the color Doppler signal. An example of an asymmetric EROA-3D elongated along the leaflet coaptation line is provided, for which hemispherical convergence method using geometric assumptions may not be applicable.

Figure 2. An example of a patient with central functional mitral regurgitation.

Multiplanar processing of the 3-dimensional Doppler data sets revealed an asymmetric circular EROA-3D demonstrated in an ‘en face’ view (right panel).

EROA-3D = effective regurgitant orifice area by three-dimensional echocardiography

Figure 3. Bland-Altman plots demonstrating the agreements in the measurements of the mitral valve Rvol obtained by 2D TEE and 3D TEE and using MRI as gold standard. The Rvol were underestimated by 2D TEE compared to 3D TEE (-10.0 ml/beat; 95% limits of agreement -46.7 ml/beat; 26.6 ml/beat; plot A) and to MRI (-12.4 ml/beat; 95% limits of agreement -45.6 ml/beat; 20.8 ml/beat; plot B). Finally, 3D TEE showed better agreement with MRI and Rvol was slightly underestimated by 3D TEE (-2.32 ml/beat; 95% limits of agreement -18.6 ml/beat; 13.9 ml/beat; plot C). 2D TEE = two-dimensional transesophageal echocardiography; 3D TEE = three-dimensional transesophageal echocardiography; MRI = magnetic resonance imaging; ml = milliliters
Figure 4. The number of the patients classified in the same vs. different mitral regurgitation severity grade: comparison between 2D TEE, 3D TEE and MRI.

2D TEE = two-dimensional transesophageal echocardiography; 3D TEE = three-dimensional transesophageal echocardiography; MR = mitral regurgitation; MRI = magnetic resonance imaging
Number of patients

- 2D TEE vs. 3D TEE: 20
- 2D TEE vs. MRI: 20
- 3D TEE vs. MRI: 29

Legend:
- ■ Agreement in the MR severity grade between techniques
- □ Disagreement in the MR severity grade between techniques
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