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Incremental value of advanced cardiac imaging modalities for diagnosis and patient management : focus on real-time three-dimensional echocardiography and magnetic resonance imaging

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Citation

Marsan, N. A. (2011, November 7). *Incremental value of advanced cardiac imaging modalities for diagnosis and patient management : focus on real-time three-dimensional echocardiography and magnetic resonance imaging*. Retrieved from <https://hdl.handle.net/1887/18020>

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CHAPTER 20

Quantification of functional mitral regurgitation by real-time 3D echocardiography: comparison with 3D velocity-encoded cardiac magnetic resonance

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JACC Cardiovasc Imaging 2009;2:1245-52.

ABSTRACT

Objectives: Accurate grading of mitral regurgitation (MR) severity is crucial for appropriate patient management, but remains challenging. Velocity-encoded magnetic resonance imaging (MRI) with three-dimensional (3D) 3-directional acquisition has been recently proposed as the reference method. Aim of this study was to evaluate feasibility and accuracy of real-time 3D echocardiography for quantification of MR, in a head-to-head comparison with velocity-encoded MRI.

Methods: A total of 64 patients with functional MR were included. A 3D 3-directional velocity-encoded MRI acquisition was applied to quantify mitral regurgitant volume (Rvol). Color Doppler 3D-echocardiography was applied for direct measurement, in 'en face' view, of mitral effective regurgitant orifice area (EROA); Rvol was subsequently calculated as EROA multiplied by the velocity-time integral of the regurgitant jet on the continuous-wave Doppler. To assess the relative potential error of the conventional approach, color Doppler 2D-echocardiography was performed: vena contracta width was measured in the 4-chamber view and EROA calculated as circular (EROA-4CH); EROA was also calculated as elliptical (EROA-elliptical), measuring vena contracta also in the 2-chamber view. From these 2D measurements of EROA, the regurgitant volumes were also calculated.

Results: the EROA measured by 3D-echocardiography was significantly higher than EROA-4CH ($p < 0.001$) and EROA-elliptical ($p < 0.001$) with a significant bias between these measurements (0.10 cm² and 0.06 cm², respectively). Rvol measured by 3D-echocardiography showed excellent correlation with Rvol measured by MRI ($r = 0.94$) without a significant difference between these techniques (mean difference = -0.08 ml/beat). Conversely, 2D echocardiographic approach from the 4-chamber view significantly underestimated Rvol ($p = 0.006$) as compared to MRI (mean difference = 2.9 ml/beat). The 2D elliptical approach demonstrated a better agreement with MRI (mean difference = -1.6 ml/beat, $p = 0.04$).

Conclusions: Quantification of EROA and Rvol of functional MR using 3D-echocardiography is feasible and accurate as compared to 3D 3-directional velocity-encoded MRI; the currently recommended 2D-echocardiographic approach significantly underestimate both EROA and Rvol.

INTRODUCTION

Functional mitral regurgitation (MR) is a common and serious complication in patients with global and/or regional left ventricular (LV) dilatation and dysfunction, and is associated with relatively high morbidity and mortality¹⁻⁴. Consequently, timely diagnosis and accurate grading of MR severity are crucial for appropriate patient management and timing of surgical intervention^{2,5,6}. However, quantitative assessment of MR remains challenging, and different echocardiographic modalities or semiquantitative angiographic grading have been proposed, but a true gold standard technique is still lacking^{7,8}. Evaluation of the effective regurgitant orifice area (EROA) and regurgitant volume (Rvol) is currently recommended, applying 2-dimensional (2D) echocardiography with the proximal isovelocity surface area (PISA) or pulsed Doppler quantitative flow methods⁸. However, both methods have several limitations due to indirect measurements based on imprecise hemodynamic assumptions and multiple computational steps⁹⁻¹².

In addition, an accepted direct assessment of EROA is the vena contracta width (VCW), as the narrowest cross-section of the regurgitant jet^{8,13,14}. However, this method assumes the orifice as nearly circular and the exact shape and size may not be accurately assessed due to the limited scan plane orientation of 2D echocardiography. Real-time 3-dimensional echocardiography (RT3DE) is now available to overcome this limitation, which is particularly relevant in patients with functional MR, in whom EROA geometry is usually complex and asymmetric^{15,16}. In fact, RT3DE provides unlimited image plane orientation and, using color Doppler, allows for a direct EROA quantification^{15,17,18}.

Recently, velocity encoded magnetic resonance imaging (MRI) has been proposed as a reference method for transvalvular flow quantification^{19,20}; in particular, the use of a 3D 3-directional acquisition showed to be able to optimize the conventional 2D one-directional acquisition²¹⁻²⁴, providing independent MR flow quantification. Therefore, the aim of the current study was to explore in patients with functional MR, the feasibility and the accuracy of direct measurement of EROA and quantification of Rvol with RT3DE, in a head-to-head comparison with VE MRI. To assess the relative potential error of 2D echocardiography for these measurements, 2D echocardiography was also performed in the same patient cohort.

METHODS

Patient population and protocol

The patient population consisted of 70 consecutive patients who were clinically referred for cardiac MRI and had functional mild-to-severe MR on color Doppler echocardiography. Functional MR was defined as leaflet tethering and incomplete leaflet coaptation in the presence

of normal mitral valve anatomy and regional or global LV remodeling ²⁵.

Patients with atrial fibrillation, irregular heart rhythm or absolute contraindications (including cardiac devices) for MRI were excluded. The standard MRI protocol was applied to assess LV size and function. A 3D 3-directional velocity encoded MRI acquisition was added to quantify MR. On the same day, patients underwent also 2D color Doppler echocardiography and RT3DE to quantify MR and for comparison with MRI measurements. All patients gave informed consent and the protocol was approved by the institutional review board.

Magnetic resonance imaging

Data acquisition

Data acquisition was performed on a 1.5T MRI scanner equipped with Powertrack 6000 gradients (ACS-NT15 Intera, Philips Medical Systems, Best, The Netherlands; software release 11), using a 5-element cardiac coil placed on the chest for signal reception. LV volumes were determined by planimetry from a series of short-axis acquisitions covering the complete LV from apex to base, following a standardized protocol described previously ²⁶. The spatial resolution of the acquired images was $1.56 \times 1.56 \text{ mm}^2$.

For 3-directional velocity encoded MRI, a true free breathing 3D MRI acquisition was designed with velocity encoding in 3 orthogonal directions (field-of-view 370 mm, 3D volume scan with slab thickness 48 mm, reconstructed into 12 slices of 4 mm, TE 3.3 ms, TR 14 ms, α 10°, acquisition voxel size $2.9 \times 3.8 \times 4.0 \text{ mm}^3$, reconstructed into $1.4 \times 1.4 \times 4.0 \text{ mm}^3$, NSA 1, Venc 150 cm/s in all 3 directions) and with 30 phases reconstructed during one average cardiac cycle from the retrospectively gated acquisition (temporal resolution between 25 and 40ms, depending on the patient's heart rate). To reduce acquisition time, echo planar imaging was used with EPI factor 5. Scan time was less than 5 minutes, depending on the subject's heart rate.

LV volumes and function analysis

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. In the presence of significant mitral regurgitation, LV ejection fraction does not represent the true systolic stroke volume. To correct for this effect, the "forward LV ejection fraction" was calculated as the ratio of the forward stroke volume (obtained from aortic flow measurements derived from velocity encoded MRI) and LV end-diastolic volume ²⁷.

Mitral valve flow quantification

The 3D 3-directional velocity encoded MRI acquisitions were analyzed using in-house developed image processing software. The procedure was performed as previously described²⁴ and is schematically illustrated in Figure 1. In summary, from the MRI data, the 3 velocity vector components of blood flow at the level of the mitral valve plane needs to be reformatted, using the LV 4- and 2-chamber views; this procedure required 5 to 10 minutes. The velocities measured perpendicularly to the reconstructed mitral valve plane need to be corrected for the motion of the myocardium in basal/apical direction in order to obtain the true trans-valvular velocity of the blood flow²¹. Therefore, the through-plane velocity of the mitral valve annulus was determined in the lateral wall and subtracted from the through-plane MV flow velocities. The trans-valvular volume flow was obtained by integrating the resulting velocities over the annulus area. The regurgitant volume (Rvol-MRI) was obtained by calculating the Riemann sum of backward flow during systole in the flow graph. This analysis required approximately 5 minutes and its reproducibility was previously reported²⁴: intraobserver variation was less than 3%, while inter-observer variation was less than 6%.

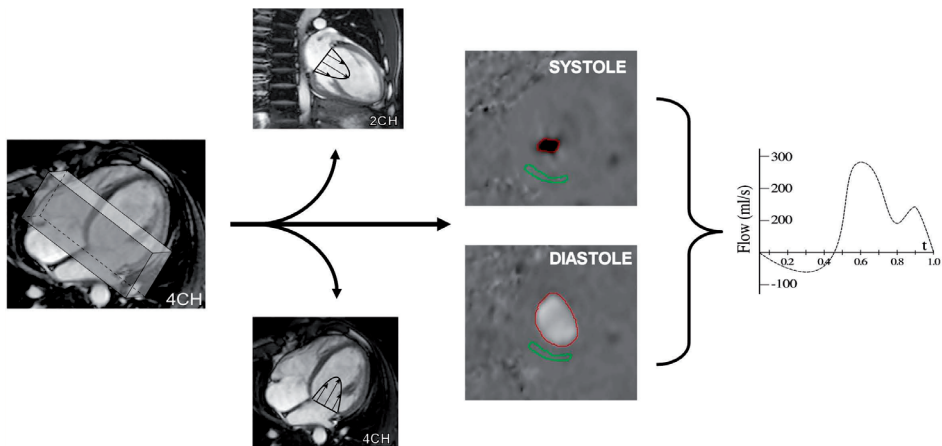


Figure 1. Reformat procedure of mitral valve flow from 3-dimensional (3D) 3-directional velocity encoded magnetic resonance imaging data. Schematic representation of reformat procedure of mitral valve flow from 3-dimensional (3D) 3-directional velocity encoded magnetic resonance imaging data. The acquisition is performed in a volume positioned at the basal level of the heart (left panel), covering the full excursion of the mitral valve during contraction and relaxation. From the 3D velocity vector field, the trans-mitral flow is retrospectively quantified by multi-planar reformatting of mitral valve in 2- and 4-chamber views (second panel). The through-plane velocity is constructed from the dot product with the normal vector (third panel). During systole, regurgitant flow can be identified and quantified. During diastole, mitral valve inflow is acquired. Through-plane motion correction is performed from the longitudinal velocity measured in the lateral wall (green lines). The regurgitant volume was obtained by calculating the Riemann sum of backward flow during systole in the flow graph (right panel).

Echocardiography

Standard 2D echocardiography

Patients were imaged in the left lateral decubitus position using a commercially available system (iE33, Philips Medical Systems, N.A., Bothell, Washington, USA) equipped with a 3.5-MHz transducer. VCW was measured as the narrowest portion of the MR color Doppler jet in a zoomed optimized apical 4-chamber (4CH) view. In addition, VCW was also measured in the apical 2-chamber (2CH) view to allow a more accurate calculation in case of asymmetric EROA. The systolic frame with the most relevant lesion size was selected for the measurement. Nyquist limits were always set between 30 and 50 cm/sec to avoid any over- or under-estimation and a color gain was used that just eliminates random color speckles from non-moving regions. From the VCW measurements, estimates of EROA were obtained as circular ($EROA\text{-}4CH = [\pi \times (VCW\text{-}4CH/2)]^2$) as well as biplane elliptical ($EROA\text{-}elliptical = [\pi \times (VCW\text{-}4CH/2) \times (VCW\text{-}2CH/2)]$)¹⁵. The Rvol can be estimated as EROA multiplied by the velocity time integral of the regurgitant jet on the continuous-wave Doppler.

Real-time 3-dimensional echocardiography

RT3DE was performed using the same ultrasound system and with an X3, fully sampled matrix transducer. Apical full-volume color Doppler datasets were obtained within 1 breath hold, combining 7 small real-time sub-volumes in a larger pyramidal volume (approximately 60 x 60 degrees). Nyquist limits (aliasing velocity) and color gain were set as for 2D echocardiography. Analysis of the 3D images was performed off-line (Q-Lab, version 6.0, Philips Medical Systems). To measure EROA (-3D), the 3D dataset was manually cropped by an image plane perpendicularly oriented to the jet direction until the narrowest cross-sectional area of the jet^{15,18} (Figure 2). EROA-3D was measured by manual planimetry of the color Doppler signal, tilting the image in an 'en face' view and selecting the systolic frame with the most relevant lesion size (Figure 2). The Rvol (-3D) was derived as for 2D echocardiography. On the cropped images, the ratio of the longest and shortest diameter of EROA (L/S) was also calculated as an index of orifice shape²⁸. The image post-processing required 3 to 5 minutes.

Twenty patients were randomly identified to evaluate the inter- and intra-observer agreement for the EROA-3D. According to the Bland-Altman analysis, inter-observer agreement was good: EROA-3D mean difference ($\pm 2SD$) = $0.06 \pm 0.04 \text{ cm}^2$ ($p = 0.43$). The intra-observer agreement was also good with a mean difference ($\pm 2SD$) of $0.04 \pm 0.04 \text{ cm}^2$ ($p = 0.55$).

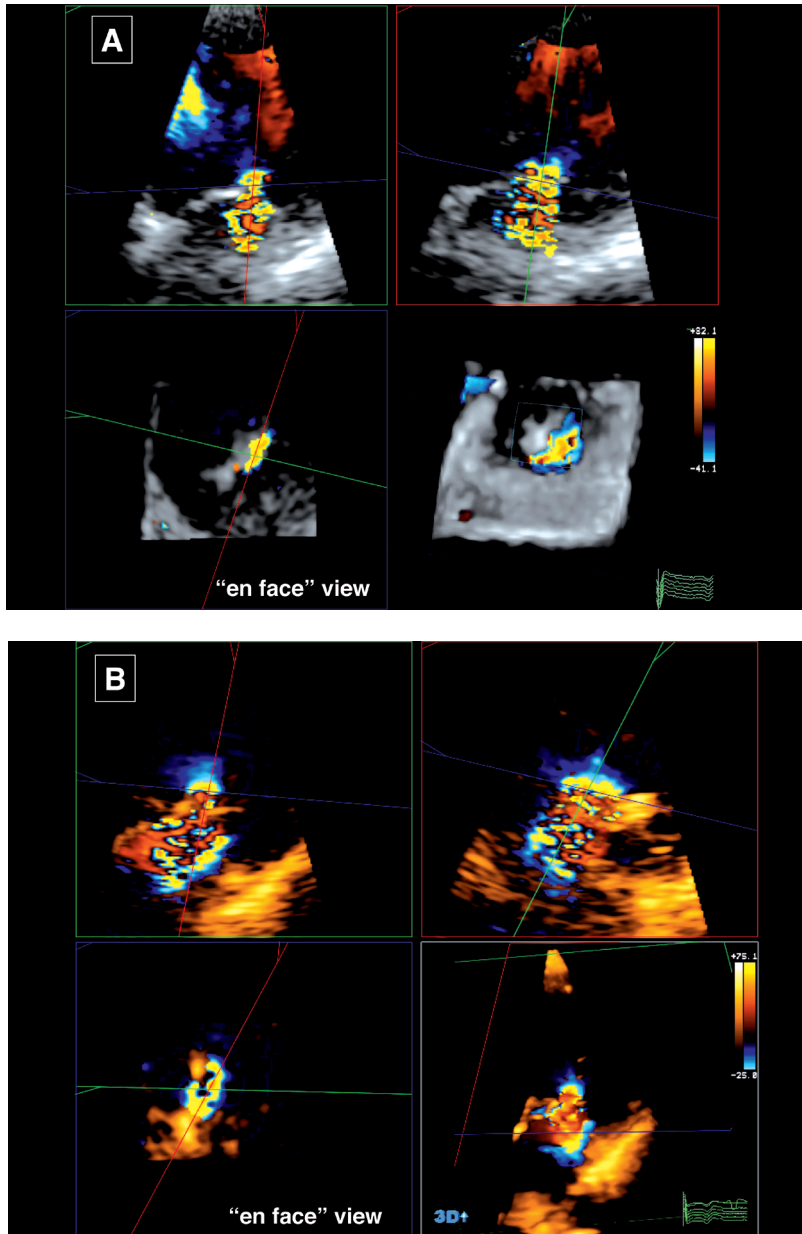


Figure 2. Real-time 3-dimensional (3D) echocardiographic technique for assessment of vena contracta area (EROA-3D). The 3D dataset is manually cropped by an image plane perpendicularly oriented to the jet direction until the narrowest cross-sectional area of the jet. EROA-3D is measured by manual planimetry of the color Doppler signal tilting the image in an 'en face' view. Panel A: example of a patient with moderate functional mitral regurgitation (MR) and asymmetric EROA-3D ($= 0.23 \text{ cm}^2$) elongated along the leaflet coaptation line. Panel B: example of a patient with severe functional MR and extremely irregular EROA-3D ($= 0.48 \text{ cm}^2$), for which geometric assumptions may not be applicable.

Statistical analysis

Continuous data are presented as mean $\pm$ standard deviation (the range, when of interest). Categorical data are presented as absolute numbers or percentages. T-test and χ^2 -test were used for appropriate comparisons. For Rvol and EROA, that were not normally distributed as evaluated by the Kolmogorov-Smirnov test, a log-transformation has been performed. Pearson's correlation analysis was performed to evaluate the relation between velocity encoded MRI, RT3DE and 2D echocardiographic measurements of EROA and Rvol. Bland-Altman analysis was performed to evaluate the differences in Rvol and EROA assessed with MRI, RT3DE and 2D echocardiography. The mean differences, trends and limits of agreement are reported. A p-value <0.05 was considered to be statistically significant. A statistical software program SPSS 16.0 (SPSS Inc, Chicago, IL, USA) was used for statistical analysis.

RESULTS

Six patients (8.5%) were excluded from further analysis because inadequate RT3DE color Doppler images. Among the remaining 64 patients (44 men, 60 $\pm$ 11 years), 48 (75%) were referred because of ischemic cardiomyopathy with a previous myocardial infarction (31 patients with anterior myocardial infarction and 17 with infero-posterior myocardial infarction) and 16 (25%) patients because of idiopathic dilated cardiomyopathy.

MRI analysis revealed severe LV dilatation (mean LV end-diastolic volume 273 $\pm$ 66 ml), with depressed LV systolic function (mean forward LV ejection fraction 29 $\pm$ 10%). From the 3-directional velocity encoded MRI analysis, the mean mitral Rvol was 12.9 $\pm$ 12.6 ml/beat, ranging from 2 to 63 ml/beat. No significant (more than mild) regurgitation of the other cardiac valves was detected by 3-directional velocity encoded MRI.

RT3DE versus 2D echocardiography

The mean values and the ranges of the EROA measurements with 2D echocardiography and RT3DE are displayed in Table 1. EROA-3D was significantly higher than EROA-4CH ($p < 0.001$) and EROA-elliptical ($p < 0.001$), and Bland-Altman analysis confirmed a significant systematic bias between these measurements (Table 2).

From the RT3DE analysis, EROA was considered significantly asymmetric when the L/S ratio was >1.5 ²⁸. In patients with an asymmetric orifice shape (18, 28%), 4CH was significantly smaller as compared to patients with L/S ≤ 1.5 ($p = 0.02$, Table 1), indicating a regurgitant orifice elongated along the leaflet coaptation line with the 4CH view representing the nar-

Table 1. Mean values and range (minimum-maximum) of EROA measured by 2 different 2D echocardiographic approaches (from the 4CH view and with the elliptical formula) and measured by RT3DE, in the total population and among patients with (L/S >1.5) and without (L/S ≤1.5) an asymmetrical regurgitant orifice.

	Total population (n = 64)	L/S >1.5 (n = 18)	L/S ≤1.5 (n = 46)
2D: EROA-4CH, cm ²			
Mean (±SD)	0.11±0.12†	0.06±0.06*	0.14±0.13
Range (min-max)	0.008-0.64	0.008-0.27	0.008-0.64
2D: EROA-elliptical, cm ²			
Mean (±SD)	0.14±0.15†	0.15±0.14	0.14±0.16
Range (max-min)	0.008-0.75	0.02-0.55	0.008-0.75
RT3DE: EROA-3D, cm ²			
Mean (±SD)	0.22±0.14	0.23±0.14	0.20±0.16
Range (max-min)	0.04-0.78	0.07-0.41	0.04-0.78

* = p <0.05 between patients with L/S >1.5 and with L/S ≤1.5.

† = p <0.001 between 2D echocardiography and RT3DE.

EROA: effective regurgitant orifice area; elliptical: elliptical formula; L/S: ratio of the longest and shortest diameter of EROA-3D; SD: standard deviation; 2D: 2-dimensional; 4CH: 4 chamber view; RT3DE: real-time 3-dimensional echocardiography

Table 2. Summary of the results of the Bland-Altman analysis applied for the EROA and Rvol measurements performed with 2D echocardiography (4CH view and elliptical approaches), RT3DE and 3D 3-directional velocity encoded MRI. The mean difference and the limits of agreements are reported.

	RT3DE: EROA-3D, cm ²
2D echo: EROA-4CH, cm ²	-0.10 (-0.26 to 0.08)*
2D echo: EROA-elliptical, cm ²	-0.06 (-0.17 to 0.04)*
	MRI: Rvol, ml/beat
2D echo: Rvol-4CH, ml/beat	-2.9 (-18.0 to 12.5)†
2D echo: Rvol-elliptical, ml/beat	-1.6 (-11.9 to 8.8)†
RT3DE: Rvol-3D, ml/beat	-0.08 (-7.7 to 7.6)

* = p <0.001

† = p <0.05

MRI: magnetic resonance imaging; Rvol: regurgitant volume. For other abbreviations see Table 1.

rowest and the 2CH view the widest VCW. EROA-elliptical and EROA-3D however, were not significantly different between patients with asymmetric or non-asymmetric EROA (Table 1).

RT3DE versus VE-MRI

The mean Rvol-3D was 12.8±12.7 ml/beat, ranging from 2 to 67 ml/beat. The mean Rvol-4CH was 10.1±11.9 ml/beat (from 1 to 51 ml/beat) and Rvol-elliptical was 11.3±12.1 ml/beat (from 1 to 55 ml/beat).

Rvol-3D showed an excellent correlation with Rvol-MRI (r = 0.94, Figure 3) and the Bland-Altman analysis revealed a non significant bias between these techniques (Figure 3): mean

difference (RT3DE – MRI) = -0.08 ml/beat ($p = 0.87$), limits of agreement from -7.7 to 7.6 ml/beat (Table 2).

Conversely, the 2D echocardiographic approach from the 4CH view (Rvol-4CH) significantly underestimated Rvol ($p = 0.006$) as compared to MRI (Rvol-MRI) (Table 2). However, the 2D elliptical approach demonstrated a better agreement with MRI: mean difference (Rvol-elliptical – Rvol-MRI) = -1.6 ml/beat ($p = 0.04$), limits of agreement from -11.9 to 8.8 ml/beat (Table 2).

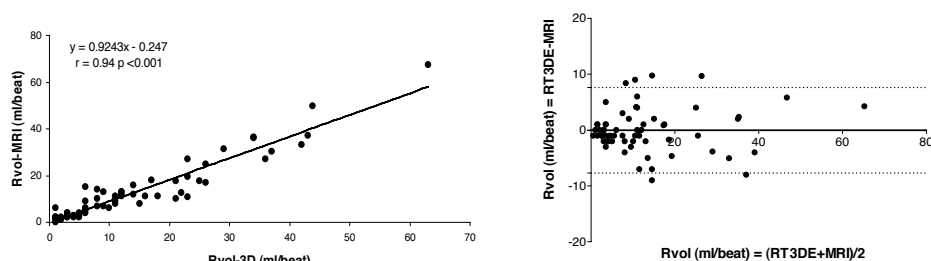


Figure 3. Comparison between mitral regurgitant volume (Rvol) assessed with real-time 3-dimensional echocardiography (RT3DE, Rvol-3D) and by 3-directional velocity encoded magnetic resonance imaging (MRI, Rvol-MRI). Left panel: correlation between mitral regurgitant volume (Rvol) assessed with real-time 3-dimensional echocardiography (RT3DE, Rvol-3D) and by 3-directional velocity encoded magnetic resonance imaging (MRI, Rvol-MRI). Right panel: Bland-Altman scatter plot of differences in Rvol between RT3DE and MRI and the average Rvol between the 2 techniques: Rvol-3D is 0.08 ml/beat lower than Rvol-MRI ($p = 0.87$), limits of agreement from -7.7 to 7.6 ml/beat.

DISCUSSION

The main findings of the current study can be summarized as follows: 1) in patients with functional MR direct assessment of EROA by RT3DE was feasible and reproducible; 2) 2D echocardiography systematically underestimated the EROA as compared to RT3DE and the difference between these 2 techniques was more accentuated in the presence of an asymmetric regurgitant orifice; 3) a strong correlation was observed between RT3DE and MRI for the measurement of Rvol, with no significant bias between these 2 techniques; conversely, 2D echocardiography significantly underestimated Rvol as compared to MRI.

Quantification of mitral regurgitation

RT3DE versus 2D echocardiography

Accurate grading of MR severity is an important but still controversial issue. Currently, conventional 2D echocardiography is the method of choice for the assessment of MR⁸, although

the limitations of this technique are well known. One of the most commonly used measures is the ratio between the regurgitant jet area and the left atrial area. However, this method is semiquantitative and rather subjective. In turn, quantitative approaches, such as PISA and pulsed Doppler quantitative flow methods, are limited by hemodynamic and geometric assumptions that introduce inaccuracies, and by complicated and time-consuming acquisitions and calculations^{8–11}. For estimation of MR severity, 2D echocardiographic measurement of VCW has also been proposed as a direct representation of the EROA^{8,13,14}. This approach assumes the EROA shape to be either circular or elliptical. However, these assumptions may not be applicable when mitral valve geometry is significantly altered²⁹ and the regurgitant orifice shows an irregular shape. Particularly in patients with functional MR, EROA is typically elongated along the semilunar-shaped leaflet coaptation line, which contributes to a significant underestimation of the regurgitant orifice when measured from the 4-chamber or parasternal long-axis views^{15,16}. In this group of patients, lower thresholds to define severe MR and to identify patients with poor prognosis have been proposed (EROA ≥ 0.2 cm² instead of 0.4 cm² and Rvol ≥ 30 ml/beat instead of ≥ 60 ml/beat)^{2,3,30}. This difference may be explained by the changes in LV and left atrium function and compliance^{2,3}, but the difference is probably also related to a significant underestimation of MR severity by conventional 2D echocardiographic methods in the presence of an asymmetric regurgitant orifice.

Color Doppler RT3DE, allowing for an unlimited plan orientation and in particular for an “en face” view of the mitral valve, provides a direct assessment of size and shape of regurgitant orifice, obviating the geometric assumptions applied by 2D echocardiography^{15,17,18,28}. Initial studies showed the incremental value of RT3DE measurements of EROA over 2D PISA and VCW. In particular, the studies by Iwakura et al²⁸ and Kahlert et al¹⁵ emphasized the importance of a 3D approach in patients with functional MR, in whom 2D echocardiography significantly underestimated the size of the regurgitant orifice. Similarly, in the current study a significant difference in the measurement of EROA was observed between RT3DE and 2D echocardiography (-0.10 cm² for EROA-4CH and -0.06 cm² for EROA-elliptical); also, 2D echocardiography underestimated EROA particularly in patients with an asymmetric regurgitant orifice (L/S > 1.5). Thus far, a true validation study of RT3DE measurement of EROA is lacking, since previous studies were limited to comparisons between different echocardiographic techniques or used semiquantitative angiographic grading as a reference^{15,18,28}. The present study is the first systematic comparison between RT3DE and velocity encoded MRI, which has been recently proposed as the reference method for quantification of MR.

RT3DE versus VE MRI

Velocity encoded MRI is particularly suitable for determining trans-valvular blood flow, providing quantitative information on moving spins³¹, and has been recently proposed as a ref-

erence method^{19,20}. However, conventional single-slice one-directional velocity encoded MRI showed some limitations²¹, in particular due to the fact that the acquisition plane can not be adapted to the motion of the valve, and currently the most accurate approach is considered the 3D 3-directional velocity encoded MRI with retrospective valve tracking. This technique is able to cover the complete velocity vector field of the blood flow and to correct for the through-plane myocardial motion in the apical-basal direction^{22,23}. Furthermore, it has been validated in vitro with flow phantoms and in vivo, and showed excellent reproducibility²⁴.

In the current study, RT3DE measurement of Rvol was compared against 3D 3-directional velocity encoded MRI. An excellent correlation between the 2 techniques was found without a significant bias. The residual non-significant difference between RT3DE and MRI may be explained by 2 sources of errors: the fixed position and the eventual misalignment of the continuous-wave Doppler ultrasound beam to the flow direction. Furthermore, imaging the region of interest with RT3DE can be complicated by acoustic attenuation from cardiac and thoracic structures.

The currently recommended 2D approach, providing a less accurate measurement of the EROA and presenting the same limitations of the Doppler acquisitions, showed a significant underestimation of the Rvol when compared to 3D 3-directional velocity encoded MRI. In particular, a mean bias between these 2 techniques of -2.9 ml/beat ($p < 0.05$, limits of agreement from -18.0 to 12.5 ml/beat) may easily lead to a misdiagnosis of the severity of MR (mild instead of moderate or moderate instead of mild).

Clinical implications

The presence of functional MR has important prognostic value and accurate assessment of its severity is crucial for risk stratification and clinical decision making¹⁻⁶. In the present study, quantification of Rvol by RT3DE demonstrated to be feasible and highly accurate compared to 3D 3-directional velocity encoded MRI and, consequently, may be proposed as a better alternative to conventional 2D echocardiographic measurements. In addition, RT3DE will probably overcome the need for 2 different cut-off values to define severity of organic and functional MR, providing direct and accurate quantification of the EROA. Further multi-center studies are needed to confirm the present results and follow-up data are necessary to explore the prognostic implications of these measures.

Of note, RT3DE technology is in continuous progress and will lead to further improvement in the image quality (allowing for a direct assessment of the regurgitant orifice without Color Doppler) and in the temporal resolution (higher frame rate).

CONCLUSIONS

Quantification of the regurgitant orifice and volume of functional MR using RT3DE is feasible and accurate and demonstrated to be superior to the currently recommended 2D echocardiographic approach in a head-to-head comparison with 3D 3-directional velocity encoded MRI.

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