Assessment of the anatomic regurgitant orifice in aortic regurgitation: a clinical magnetic resonance imaging study

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ABSTRACT

Background: The aim of our study was to determine whether planimetry of the anatomic regurgitant orifice (ARO) in patients with aortic regurgitation (AR) by magnetic resonance imaging (MRI) is feasible and whether ARO by MRI correlates with the severity of AR.
Methods and results: Planimetry of ARO by MRI was performed on a clinical magnetic resonance system (1.5 T Sonata, Siemens Medical Solutions) in 45 patients and correlated with the regurgitant fraction (RgF) and regurgitant volume (RgV) determined by MRI phase velocity mapping (PVM; MRI-RgF, MRI-RgV, n = 45) and with invasively quantified AR by supravalvular aortography (n = 32) and RgF upon cardiac catheterisation (CATH-RgF, n = 15). Determination of ARO was possible in 98% (44/45) of the patients with adequate image quality. MRI-RgF and CATH-RgF were modestly correlated (n = 15, r = 0.71, $p<0.01$). ARO was closely correlated with MRI-RgF (n = 44, r = 0.88, $p<0.001$) and was modestly correlated with CATH-RgF (n = 14, r = 0.66, p = 0.01). Sensitivity and specificity of ARO to detect moderately severe and severe aortic regurgitation (defined as MRI-RgF ⩾40%) were 96% and 95% at a threshold of 0.28 cm^2 (AUC = 0.99). Of note, sensitivity and specificity of ARO to detect moderately severe and severe AR at catheterisation (defined as CATH-RgF ⩾40% or supravalvular aortography ⩾3+) were 90% and 91% at a similar threshold of 0.28 cm^2 (AUC = 0.95). Lastly, sensitivity and specificity of ARO to detect severe aortic regurgitation (defined as MRI-RgF ⩾50% and/or regurgitant volume ⩾60 ml) were 83% and 97% at a threshold of 0.48 cm^2 (AUC = 0.97).
Conclusions: Visualisation and planimetry of the ARO in patients with AR are feasible by MRI. There is a strong correlation of ARO with RgV and RgF assessed by PVM and with invasively graded AR at catheterisation. Therefore, determination of ARO by MRI is a new non-invasive measure for assessing the severity of AR.

Quantification of the severity of regurgitation and assessment of left ventricular (LV) size and function are crucial in the management of patients with aortic regurgitation (AR).[1] The severity of AR can be estimated non-invasively by echocardiography and invasively at catheterisation. At catheterisation, supravalvular aortography provides a semiquantitative approach to the severity of AR by visual grading of the amount of contrast that appears in the LV after aortography. Additionally, the regurgitant fraction can be estimated invasively through comparison of the angiographic LV stroke volume and cardiac output at thermodilution.[2]

Upon Doppler echocardiography, jet width on colour-flow imaging, jet velocity deceleration and width of vena contracta allow semiquantitative estimation of the severity of AR.[3] Additionally, quantitative measurements such as the effective regurgitant orifice (ERO) can be performed by Doppler echocardiography.[4] Recently, measurement of the vena contracta area has been reported as a new promising method for quantitative grading of AR.[5–8] Nevertheless, echocardiographic quantification of AR remains a challenge, and current guidelines suggest an integrative approach.[9]

Magnetic resonance phase velocity mapping (PVM) allows accurate antegrade and retrograde blood flow measurement in the ascending aorta[10] and quantitative assessment of the severity of AR is possible by calculation of regurgitant volume (RgV) and regurgitant fraction (RgF).[11 12] Additionally, new cine magnetic resonance imaging (MRI) sequences, such as steady-state precession techniques (SSFP), allow visualisation of the aortic valve in a chosen plane with an excellent image quality. Additionally, planimetry of the aortic valve area by MRI in aortic stenosis has recently been demonstrated as a reliable tool for assessment of the severity of aortic stenosis.[13–16]

We therefore hypothesised that the anatomic regurgitant orifice (ARO) could as well be visualised and quantified by planimetry in AR, analogous to planimetry of stenotic orifices in aortic stenosis. To address this hypothesis, we evaluated ARO planimetry for assessment of the severity of AR in comparison with PVM in the ascending aorta. Additionally, the value of MRI (ARO, PVM) in the quantification AR was compared with invasively derived data at catheterisation.

METHODS

Patients

Forty-five consecutive patients with known or suspected aortic regurgitation were enrolled in our study. All patients gave informed consent to participate. RgV and RgF were calculated by PVM in the ascending aorta by MRI in all patients. Visualisation of the aortic valve and planimetry of the ARO were possible in 44/45 patients (98%). In 32 patients, an invasive quantification of the severity of AR was performed (supravalvular aortography in all 32 patients, calculation of RgF by additional right heart catheterisation in 15 patients). All studies were performed within 2 weeks.

Cardiac catheterisation

Severity of AR was semiquantitatively estimated by supravalvular aortography based on the amount of contrast that appears in the LV after aortography (mild or 1+ AR: contrast appearing in the LV but clearing with each beat; moderate or 2+ AR: faint opacification of the entire LV over several cardiac cycles; moderately severe or 3+ AR: opacification of the entire LV with the same intensity as in the aorta; severe or 4+ AR: opacification of the entire LV on the first heart beat with an intensity higher than in the aorta). RgF was calculated through LV angiographic stroke volume by left ventriculography (SV) and cardiac output by thermodilution (CO, average of at least three measurements) as: RgF = (SV – (CO/HR))/SV

Magnetic resonance imaging studies

Magnetic resonance imaging studies were performed on a 1.5 T scanner (Sonata, Siemens Medical Solutions). Cine images were acquired in multiple short-axis and long-axis views with fast imaging with steady-state precession (SSFP, slice thickness 8 mm, echo time 1.53 ms, pixel bandwidth 1.085 Hz, repetition time 3.14 ms, matrix 256×202). The number of Fourier lines per heart beat was adjusted to allow the acquisition of 20 cardiac phases covering systole and diastole within a cardiac cycle. The field of view was 340 mm on average and adapted to the size of the patient. Calculation of LV volumes, mass and ejection fraction was performed in the serial short-axis slices. The imaging plane of the aortic valve was defined by acquiring a systolic five-chamber view parallel to the long axis of the LV outflow tract and a long-axis view of the LV outflow tract and the proximal aorta, perpendicular to the five-chamber view, as described previously.[16] The subsequent slices (slice thickness 5 mm) were defined parallel to the valvular plane and additionally, especially in cases of orifices with an eccentric regurgitant jet, perpendicular to the direction of the jet.

At least four slices (range 4–7) at subsequent levels of the aortic valve, starting at the tips of the cusps, were acquired and the imaging plane with the smallest diastolic regurgitant orifice was chosen by visual assessment. Planimetry of the regurgitant orifice during diastole (usually mid diastole) was then performed in the SSFP studies. At least three measurements were averaged for calculating the ARO. Additionally, through plane breath-hold PVM was performed in the same slice positions (flash 2D; slice thickness 5 mm, echo time 3.2 ms, pixel bandwidth 391 Hz, repetition time 55 ms, matrix 256×125). Aortic regurgitant volume and antegrade stroke volume were quantified by through plane PVM in a retrospective gating technique during normal respiration to cover the whole cardiac cycle (flash 2D; slice thickness 5 mm, echo time 3.2 ms, pixel bandwidth 391 Hz, repetition time 41 ms, matrix 256×192). Slice position was perpendicular to the ascending aorta as close as possible above the aortic valve (usually at the level of the coronary ostia).[11] For the calculation of flow volumes, the cross sectional area of the ascending aorta was drawn manually for each time frame on the magnitude images and transferred to the corresponding phase image. RgF was then calculated as: RgF = RgV/SV

Statistical analysis

Results are shown as mean (SD). The correlation between the methods of quantification of AR was assessed by univariate regression analysis. The agreement between the two methods of quantification of the regurgitant fraction was assessed by univariate regression analysis and by the Bland–Altman method. Differences in mean values between two groups were analysed by Student t test. χ^2 test was performed to compare frequencies between groups. ROC analysis was carried out to determine the predictive values of MRI to detect moderately severe and severe AR. A level of significance of below 0.05 was defined as statistically significant. SPSS version 12.0.1 was used for statistical analysis.

RESULTS

Patients

Patient characteristics are depicted in table 1 according to AR severity by PVM. Among all 44 patients, 35 patients were symptomatic with dyspnoea and three with angina. Five patients had coronary artery disease (lumen reduction >50%) and 15 had impaired left ventricular function (EF <50%). No differences in the prevalence of bicuspid and tricuspid aortic valve disease and concomitant aortic stenosis (aortic valve area $\leqslant$1.5 cm²) were observed. Three patients had a history of endocarditis and one patient revealed severe annuloaortic ectasia. Prevalence of NYHA functional class III/IV tended to be higher in patients with more severe aortic regurgitation. Among patients with more severe aortic regurgitation, systolic and diastolic blood pressures were significantly lower than among patients with less severe regurgitation. No significant differences in LV ejection fraction and prevalence of coronary artery disease were observed.

Anatomic regurgitant orifice for assessment of the severity of aortic regurgitation

Planimetry of ARO could be performed in 44 patients (fig 1). In one patient, planimetry was not possible due to impaired image quality. Planimetry of ARO was possible using SSFP-sequences in 40/44 patients with adequate image quality. In a further four patients, where planimetry in the SSFP-sequences was not possible, planimetry of ARO could be performed in the phase-encoding breath-hold PVM images in the aortic valve position. Mean ARO was 0.35 (SD 0.19) cm². Interobserver and intraobserver variabilities (coefficient of variation) were 0.01 (SD 0.02) cm² and 0.02 (SD 0.02) cm², respectively. ARO was

Table 1 Patient characteristics

	AR I/II (n = 19)	AR III/IV (n = 26)
Age (years)	63.3 (9.0)	44.5 (13.4)*
Gender (% male)	69	81
Aortic valve characteristics (n)		
Bicuspid	9	16
Tricuspid	10	10
History of endocarditis	–	3
Severe annuloaortic ectasia	–	1
Aortic stenosis ($\leqslant$1.5 cm²)	6	5
NYHA functional class (%)		
I/II	63	54
III/IV	21	46
Sinus rhythm (%)	79	96
BP sys. (mm Hg)	140.3 (20.1)	126.5 (16.4)†
BP dia. (mm Hg)	69.4 (9.9)	61.2 (9.5)†
EF (%)	50.5 (17.4)	50.7 (12.1)
CAD (%)	16	8

AR, aortic regurgitation (graded by MRI; AR III, defined as regurgitant fraction $\geqslant$40%; AR IV, defined as regurgitant fraction $\geqslant$50% and/or regurgitant volume $\geqslant$60 ml); CAD, coronary artery disease (>50% lumen diameter reduction); BP, blood pressure; EF, ejection fraction;
*p<0.01 vs AR I/II
†p<0.05 vs AR I/II.

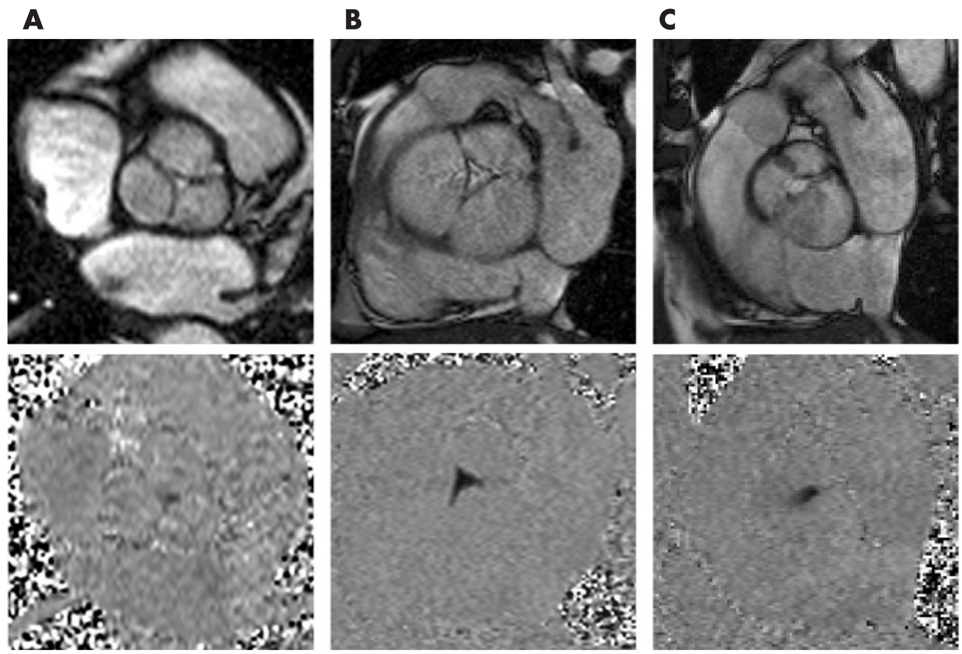

Figure 1 SSFP and phase encoding PVM images of the anatomic regurgitant orifice (ARO) in A, moderate aortic regurgitation (AR), B, severe AR in annuloaortic ectasia and C, severe AR in a bicuspid aortic valve.

closely correlated with MRI-RgV (n = 44, r = 0.90, p<0.001) and MRI-RgF (n = 44, r = 0.88, p<0.001) and was modestly correlated with CATH-RgF (n = 14, r = 0.66, p = 0.01) (figs 2 and 3).

Comparison of non-invasive and invasive regurgitant fractions

In the 15 patients who underwent right and left heart catheterisation, mean MRI-RgF was 39.9 (SD 9.0)% and mean CATH-RgF was 42.3 (SD 15.3)% (p = 0.41). MRI-RgF and CATH-RgF were modestly correlated (r = 0.71, p<0.01). As shown in the Bland–Altman analysis, there was a good agreement between both methods (figs 4 and 5). Patient

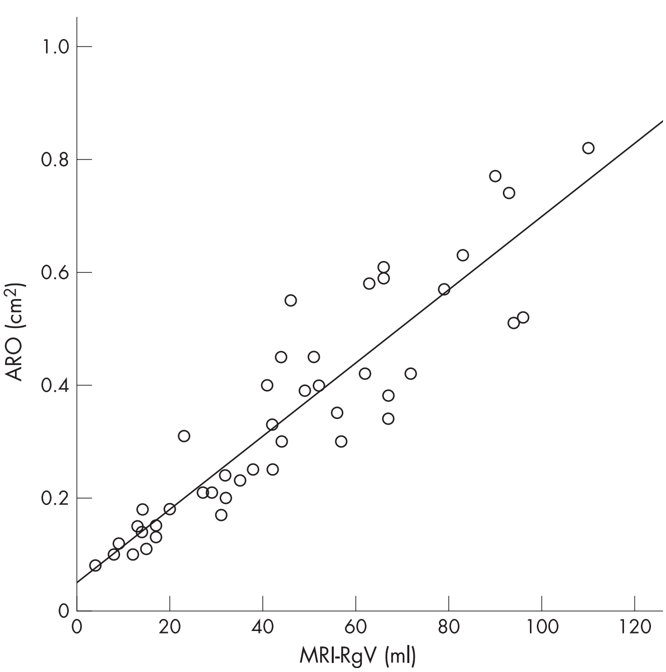

Figure 2 Scattergram of the regurgitant volume (MRI-RgV) and anatomic regurgitant orifice (ARO) determined by MRI in 44 patients.

characteristics and results of the 15 patients who had both cardiac catheterisation and MRI assessment of RgF are shown in table 2.

Predictive values of ARO for aortic regurgitation severity

Sensitivity and specificity of ARO to detect moderately severe and severe AR (defined as MRI-RgF ⩾40%) were 96% and 95% at a threshold of 0.28 cm^2 (AUC = 0.99). Sensitivity and specificity of ARO to detect moderately severe and severe AR at catheterisation (defined as CATH-RgF ⩾40% or supravalvular aortography ⩾3+) were 90% and 91% at a similar threshold of 0.28 cm^2 (AUC = 0.95). Sensitivity and specificity of ARO to detect severe AR (defined as MRI-RgF ⩾50% and/or MRI-RgV ⩾60 ml) were 83% and 97% at a threshold of 0.48 cm^2 (AUC = 0.97) (table 3).

DISCUSSION

To the best of our knowledge, the current study is the first to apply planimetry of ARO by MRI in a large number of patients with various degrees of AR. Planimetry of ARO by MRI is feasible in a high proportion of patients and there is a close correlation with PVM in the ascending aorta by MRI as well as with AR grading at catheterisation.

The concept of effective and anatomic regurgitant orifice

Quantification of AR by echocardiography is challenging and an integrative approach of different echocardiographic modalities is recommended.[9] Colour Doppler imaging of the vena contracta width is usually applied as a simple measure of the severity of AR.[3 5] However, vena contracta width is a unidimensional measure that may not truly reflect lesion severity if the regurgitant orifice is complex in shape. Therefore, calculation of the effective regurgitant orifice (ERO) by different echocardiographic modalities (PISA, quantitative Doppler and quantitative two-dimensional echocardiography) has been suggested.[4 17] ERO is less dependent on haemodynamic variables in comparison with RgV and RgF and is not dependent on heart rate.[18–20] Thus, ERO provides a quantitative (although indirect) measure of lesion severity reflecting the effective regurgitant

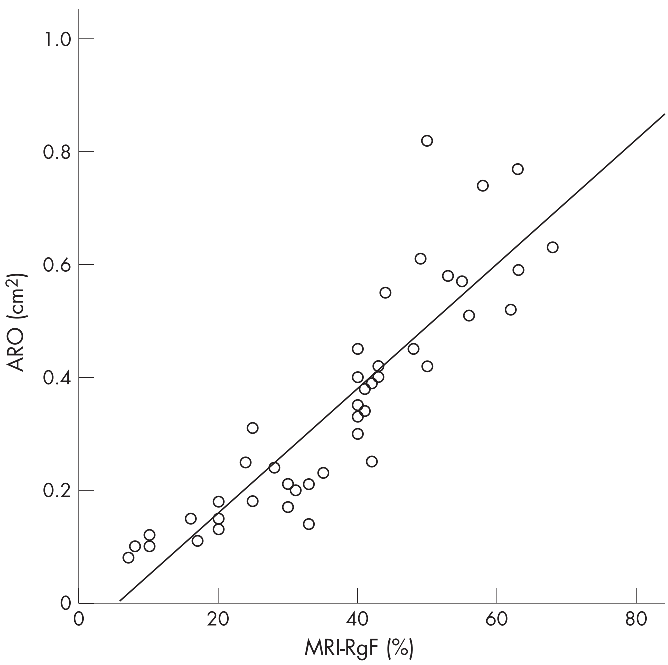

Figure 3 Scattergram of the regurgitant fraction (MRI-RgF) and anatomic regurgitant orifice (ARO) determined by MRI in 44 patients.

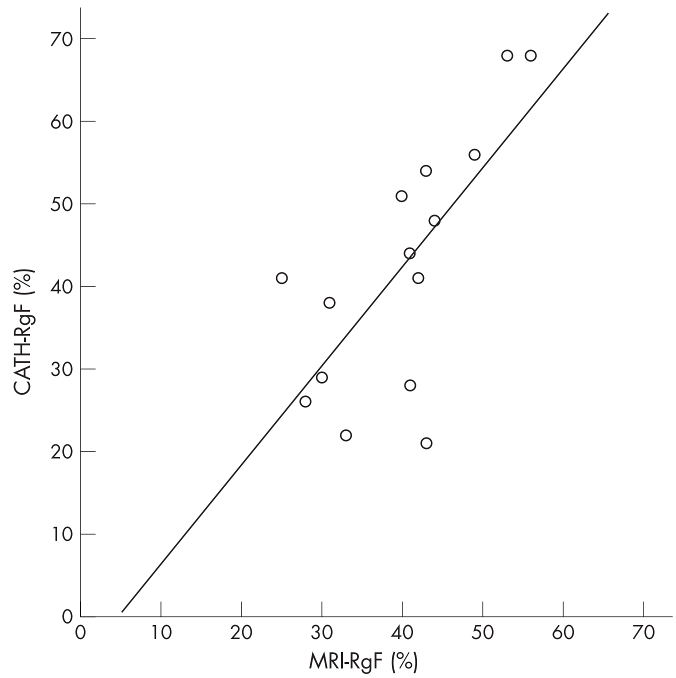

Figure 4 Scattergram of the regurgitant fraction determined by MRI (MRI-RgF) and catheterisation (CATH-RgF) in 15 patients.

"hole" in the aortic orifice. Interestingly, direct planimetry of the vena contracta area, representing the "anatomical" hole (anatomical regurgitant orifice, ARO), as a measure of lesion severity has recently also been attempted.[5–8]

Feasibility and predictive values of ARO

In the current study, planimetry of ARO using steady state free precession sequences (SSFP) was possible in 40/44 patients with adequate image quality, and regurgitant area delineation was improved by additionally performed breath-hold PVM images at the same levels as the SSFP-sequences. In a further four patients, where planimetry in the SSFP-sequences was not possible, planimetry of ARO could be performed only in the breath-hold PVM images in the aortic valve area. We therefore recommend this approach for an optimised visualisation of the regurgitant orifice.

There was a strong correlation of ARO with RgV and RgF assessed by PVM and with invasively graded AR at catheterisation. In our study, an ARO $\geqslant$0.28 cm^2 and $\geqslant$0.48 cm^2 indicated an AR grade 3 and 4, respectively, with high sensitivity and specificity. Interestingly, specific cut-off values of vena contracta areas during echocardiography range from $\geqslant$0.3 cm^2 to $>$0.75 cm^2 for AR grade 4.[5,8] Therefore, our current results confirm and extend these echocardiographic results and we suggest an ARO $\geqslant$0.3 cm^2 as an indicator of moderately severe and an ARO $\geqslant$0.5 cm^2 as an indicator of severe AR upon MRI for practical purposes. Regarding potential differences between the imaging modalities, it has to be noted that the areas of ERO and vena contracta during echocardiography may tend to be smaller than anatomic orifices because of blood flow contraction through the regurgitant orifice.[21] Furthermore, potential differences of vena contracta area by Doppler colour flow mapping and ARO planimetry by MRI may be related to valve motion and slice orientation. Specifically, transplanar valve motion during diastole might lead to overestimation of valve area when the imaging plane misses the smallest ARO. Nevertheless, we addressed this problem by acquiring at least four slices at different levels of the aortic valve and highly recommend this approach to minimise the potential of aortic regurgitant orifice overestimation because of imprecise localisation. With respect to slice orientation, image acquisition was adjusted parallel to the valvular plane and, additionally, perpendicular to the direction of the jet. This approach again reduces potential imprecision in cases with eccentric regurgitant orifices.

Clinical relevance

With respect to the clinical work-up of patients with AR, transthoracic and transoesophageal echocardiography is often adequate

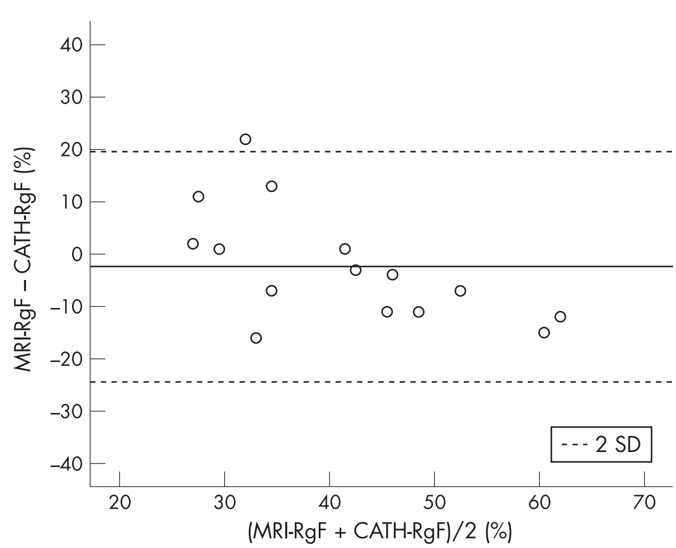

Figure 5 Bland–Altman plot of the average mean versus the differences between regurgitant fraction determined by MRI (MRI-RgF) and catheterisation (CATH-RgF) in 15 patients. The solid line is the mean difference, the dotted lines mark standard deviations of the differences.

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Table 2 Patient characteristics and severity of aortic regurgitation of the 15 patients who had both cardiac catheterisation and MRI assessment of regurgitant fraction.

Patient	Age (years)	Sex	MRI-ARO (cm^2)	MRI-RgF (%)	CATH-RgF (%)	Aortography (grade I–IV)	Echocardiography (grade I–IV)
1	61	F	0.25	26	28	II	II
2	76	M	0.21	33	22	II	II
3	61	M	0.20	31	38	II	II
4	53	M	0.42	43	54	III	III
5	43	M	0.58	53	68	IV	IV
6	64	M	0.38	41	28	III	III
7	33	M	0.55	44	48	III	III
8	63	M	not possible	49	56	III	IV
9	49	M	0.39	42	41	III	III
10	52	M	0.40	43	21	II	III
11	51	M	0.33	40	51	III	III
12	74	M	0.29	25	41	III	III
13	30	M	0.51	56	68	IV	IV
14	24	M	0.34	41	44	III	III
15	53	M	0.17	30	29	II	II

CATH-RgF, regurgitant fraction assessed by cardiac catheterisation; F, female; M, male; MRI-RgF, regurgitant fraction assessed by MRI.

Table 3 MRI-planimetry of ARO, predictive values

	Cases/total (n)	ARO-cutoff (cm^2)	ROC-area (95% CI)	Sensitivity/ specificity (%)
MRI-AR ⩾III	26/45	0.28	0.99 (0.99 to 1.0)	96/95
CATH-AR ⩾III	21/32	0.28	0.95 (0.85 to 1.0)	90/91
MRI-AR IV	13/45	0.48	0.97 (0.90 to 1.0)	83/97

MRI-AR and CATH-AR denote severity of aortic regurgitation by MRI and catheterisation, respectively.
ARO-Cutoff, optimal cutoff for anatomic regurgitant orifice to detect the given MRI-AR and CATH-AR; ROC, receiver operator characteristic; CI, confidence interval.

to determine the severity of the disease by semiquantitative and quantitative modalities. In cases of impaired image quality, however, and in cases with eccentric regurgitant jets, quantification of AR might be difficult. In patients with unclear echocardiographic findings, MRI might be a reliable tool for assessment of the severity of AR. PVM in the ascending aorta close to the aortic valve is already an established technique for calculation of RgF and RgV. Additionally, direct planimetry of the regurgitant "hole" in the aortic orifice by MRI incorporates the full geometry of the valvular lesion, which is independent of load conditions. Together, these methods provide a comprehensive picture of anatomical and functional lesion severity and an optimal basis for a clinical decision for either surgical or medical therapy. Since ERO has been demonstrated as an important prognosis parameter in mitral regurgitation,[22] ARO in AR might also offer prognostic information that has to be investigated in further studies.

In conclusion, we have demonstrated that visualisation and planimetry of the ARO in AR are feasible by MRI. There is a strong correlation of ARO with RgV and RgF assessed by PVM and with invasively graded AR at catheterisation. Therefore, determination of ARO by MRI could be used as a new non-invasive measure for assessing the severity of AR.

Competing interests: None declared.

K Debl and B Djavidani contributed equally to the article.

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Heart

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