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Magnetic Resonance to Assess the Aortic Valve Area in Aortic Stenosis

How Does it Compare to Current Diagnostic Standards?

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OBJECTIVES The purpose of the present study was to evaluate whether magnetic resonance (MR) planimetry of the aortic valve area (AVA) may prove to be a reliable, non-invasive diagnostic tool in the assessment of aortic valve stenosis, and how the results compare with current diagnostic standards.

BACKGROUND Current standard techniques for assessing the severity of aortic stenosis include transthoracic and transesophageal echocardiography (TEE) as well as transvalvular pressure measurements during cardiac catheterization.

METHODS Forty consecutive patients underwent cardiac catheterization, TEE, and MR. The AVA was estimated by direct planimetry (MR, TEE) or calculated indirectly via the peak systolic transvalvular gradient (catheter). Pressure gradients from cardiac catheterization and Doppler echocardiography were also compared.

RESULTS By MR, the mean AVA_{max} was 0.91 ± 0.25 cm^2; by TEE, AVA_{max} was 0.89 ± 0.28 cm^2; and by catheter, the AVA was calculated as 0.64 ± 0.26 cm^2. Mean absolute differences in AVA were 0.02 cm^2 for MR versus TEE, 0.27 cm^2 for MR versus catheter, and 0.25 cm^2 for TEE versus catheter. Correlations for AVA_{max} were r = 0.96 between MR and TEE, r = 0.47 between TEE and catheter, and r = 0.44 between MR and catheter. The correlation between Doppler and catheter gradients was r = 0.71.

CONCLUSIONS Magnetic resonance planimetry of the AVA correlates well with TEE and less well with the catheter-derived AVA. Invasive and Doppler pressure correlated less well than those obtained from planimetric techniques. Magnetic resonance planimetry of the AVA may provide an accurate, non-invasive, well-tolerated alternative to invasive techniques and transthoracic echocardiography in the assessment of aortic stenosis. (J Am Coll Cardiol 2003;42:519–26)

Aortic stenosis (AS) is the most common valve disease resulting in valve replacement (1). Thorough assessment of the severity of stenosis is necessary before valve replacement is considered, particularly because AS is a disease mainly of the elderly, in whom the risk of surgical intervention may be high. Although transthoracic echocardiography (TTE), including transvalvular Doppler, is a useful method for diagnosing AS, it may not provide sufficient information on the degree of stenosis (2). The transvalvular gradient determined by continuous-wave Doppler may be misleading, as it is dependent on many factors, including left ventricular (LV) preload and afterload, LV contractility, and concomitant aortic regurgitation. In addition, the peak aortic velocity may be significantly underestimated if the angle between the ultrasound beam and the jet direction exceeds 20°. As a result, a mean transvalvular gradient of approximately 50 mm Hg, usually classifying moderate AS, may be associated with mild, moderate, or even severe AS (3). Calculation of the aortic valve area (AVA) from Doppler echocardiographic data, using the continuity equation, may underestimate the AVA (4). Additional poor transthoracic image quality may make the acquisition of valid data difficult in some patients. Therefore, it is important to determine the AVA by using a flow-independent technique such as planimetry of the valve area. Some authors consider the AVA to be the gold standard for assessing the severity of AS (3,5).

Cardiac catheterization with selective coronary angiography is indicated in all patients above 35 years of age in whom valve replacement is considered and in those suspected to have coronary artery disease (6). Cardiac catheterization allows invasive measurement of the transvalvular gradient, which may also be used to calculate a functional (i.e., hemodynamic) AVA. However, the use of the Gorlin equation to estimate the AVA is associated with several sources of error. It is directly related to cardiac output, blood viscosity, and turbulent flow (7).

Our aim was to validate magnetic resonance (MR) planimetry of the AVA as a non-invasive tool in the assessment of aortic valve stenosis against transesophageal echocardiography (TEE) planimetric results and hemodynamic data obtained in Doppler and invasive studies.

METHODS

Patients. Forty consecutive patients were included in the study (25 males; mean age 70 ± 8.8 years [range 44 to 86

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Abbreviations and Acronyms

ACC/AHA	= American College of Cardiology/ American Heart Association
AF	= atrial fibrillation
AS	= aortic stenosis
TTE	= transthoracic echocardiography
LV	= left ventricle/ventricular
AVA	= aortic valve area
MR	= magnetic resonance
TEE	= transesophageal echocardiography

years]). Patients were referred to our institution for evaluation of AS. All were symptomatic with either dyspnea on exertion, syncope, dizziness, angina, or a history of congestive cardiac failure.

Exclusion criteria were indwelling pacemakers or implantable defibrillators, intracranial vascular clips, intra-auricular or intra-ocular implants, severe claustrophobia, intolerance to lying supine, cardiac rhythm other than sinus or rate-controlled atrial fibrillation (AF), aortic regurgitation, and previous aortic valve surgery. Eight patients were excluded: two had permanent pacemakers, one could not tolerate lying supine, and five had concomitant aortic regurgitation. Informed consent was obtained in all patients.

MR. Magnetic resonance scans were performed on a 1.5-T Magnetom Vision (Siemens Medical Systems, Erlangen, Germany), using flash two-dimensional cine-segmented gradient-echo sequences, repetition time = 60 to 80 ms, echo time = 4.8 ms, flip angle 20°, virtual time resolution 30 to 40 ms, spatial resolution 1.24 to 2.91 × 1.17 to 1.56 mm, and slice thickness 4 mm. Cine series of the LV outflow tract in two orthogonal planes (oblique transverse and oblique coronal; Figs. 1A and 1B) were obtained in all patients to visualize the systolic jet originating from the stenotic valve. Imaging planes for planimetry were chosen perpendicular to the stenotic jet, as deduced from the area of signal loss due to turbulent flow at valve orifice level. In the cross-sectional planes, planimetry of the AVA was performed in all systolic images to determine the maximum AVA and amplitude (i.e., range of AVA during systole) (Figs. 1B and 1C). Planimetry of the aortic valve was performed independently by two observers blinded to the results of TEE and cardiac catheterization and was repeated two months later to determine intra-observer variability. The area of signal void in severely calcified valves or in areas of turbulent flow was counted as part of the valve leaflet.

Transthoracic Doppler echocardiography. Patients underwent a complete two-dimensional and Doppler transthoracic study (Hewlett-Packard Sonos 4500 or 5500, Andover, Massachusetts). Continuous-wave Doppler spectra of AS were traced from multiple transducer positions to obtain the maximum velocity. The three highest velocity beats were averaged to assess the peak and mean gradients (8).

TEE. Transesophageal echocardiography was performed with a multiplane probe capable of mechanically changing the imaging plane orientation from 0° to 180°. To define the optimal level of the transducer location, the leaflet tips were initially positioned in the center of the two-dimensional sector in the long-axis view of the aortic valve and ascending aorta. With the transducer position held stable, the imaging plane was then rotated to obtain a short-axis view of the aortic valve. Minimal probe manipulation was performed to ensure that the smallest orifice of the aortic valve at the leaflet tips was identified. Special care was taken to optimize gain settings and gray scale. The view was considered adequate for planimetry if the aorta had a circular shape and all cusps were visualized simultaneously. The AVA was defined as the orifice area between the cusps at the time of maximal opening in systole. At least three consecutive measurements (at least 6 if the patient was in AF) were averaged (9).

Cardiac catheterization. A standard cardiac catheterization procedure was performed via the percutaneous femoral approach, including right and left heart pressure measurements. A 6F pigtail catheter was used for retrograde approach of the LV. Transvalvular pressure gradients were obtained by catheter pullback; cardiac output was calculated by employing the Fick principle; the valvular area was then estimated using the Gorlin equation (10). Left ventricular and aortic root angiography in the two planes was performed to assess LV function and aortic valve performance.

According to the American College of Cardiology/American Heart Association (ACC/AHA) guidelines, AS with a valve area >1.5 cm^2 was considered as mild, 1.0 to 1.5 cm^2 as moderate, 0.75 to 1.0 cm^2 as severe, and <0.75 cm^2 as critical (11). Patients with an AVA <1.0 cm^2 and AS-related symptoms were recommended for aortic valve replacement.

Statistical analysis. Data are expressed as estimated mean ± SD. Linear regression analysis was performed to describe correlations between the different techniques, and confidence intervals were set at 95% (Figs. 2A and 2B). Agreement between the different techniques was assessed as described by Bland and Altman (Figs. 3A and 3B) (12).

RESULTS

There were no complications during any of the investigations. The average time delay between cardiac catheterization and MR scan was 16 ± 12 days and between TEE and MR scanning 3 ± 1 day. Four patients were in rate-controlled AF, and 36 in sinus rhythm, at the time of study.

MR. All studies were diagnostic and well tolerated by all patients. The mean AVA was 0.91 ± 0.25 cm^2 (range 0.5 to 1.6). On MR, 27 patients (68%) had severe or very severe AS (AVA <1.0 cm^2), eight of whom had critical AS with an AVA <0.75 cm^2, and 19 of whom had severe AS, and 13 of whom had moderate AS. The mean amplitude in AVA change over systole was 0.23 ± 0.16 cm^2 for severe and

critical lesions, as opposed to 0.39 ± 0.21 cm^2 in the mild and moderate AS groups. Inter-observer variability was 0.07 ± 0.06 cm^2. Intra-observer variability was 0.05 ± 0.04 cm^2. Images of severely calcified valves were more difficult to interpret than less calcified ones, due to signal void at the edges of the valve leaflets. One aortic valve was bicuspid.

TEE. Mean AVA on TEE was 0.89 ± 0.28 cm^2 (range 0.5 to 1.6 cm^2). On TEE, AS was classified as very severe in 9 patients, severe in 20, and moderate in 11 (i.e., 72% of the study population was diagnosed with severe or very severe AS). One aortic valve was bicuspid. In the presence of heavy calcification, planimetry was more difficult to perform due to the irregularity of the valve orifice; however, TEE planimetry of the AVA was possible in all patients. Of those 27 patients classified as having severe or very severe AS on MR, 25 (92%) were classified as severe or very severe by TEE. The other two had AVAs of 1.0 cm^2 on TEE.

TTE. Pressure gradients obtained by Doppler TTE are displayed in Table 1. The mean Doppler pressure gradient was 50 ± 23 mm Hg (range 12 to 88 mm Hg). According to ACC/AHA guidelines, 18 (45%) of 40 lesions would have been considered severe or critical, as defined by the Doppler transvalvular gradient. Fourteen of these had been labeled severe or very severe by MR-determined AVA. Twelve (44%) of those 27 labeled severe or very severe by MR had a pressure gradient <50 mm Hg by Doppler. Two patients with a gradient >50 mm Hg by Doppler had an MR-determined AVA >1 cm^2.

Cardiac catheterization. Transvalvular pressure gradients and derived AVAs are shown in Table 1. The mean pullback gradient was 48 ± 20 mm Hg (range 17 to 82 mm Hg), and the mean AVA derived was 0.56 ± 0.26 cm^2 (range 0.23 to 1.4 cm^2). In severely calcified valves, the retrograde passage of the pigtail catheter across the aortic valve was technically more difficult than in less calcified valves. In one patient, no catheter pullback was attempted, and hence, no AVA was calculated. In another patient, the AVA was not calculated. Coronary artery disease was present in 14 patients, and coronary artery sclerosis without hemodynamically relevant coronary stenoses was detected in 11 patients. During LV angiography, LV function was graded as normal in 26 patients, mildly impaired in 8 and severely impaired in 6. According to the ACC/AHA guidelines, 20 (51%) of 39 aortic stenoses would have been considered severe or very severe as defined by the transvalvular gradient measured invasively; 32 of 38 would have been classified as severe or very severe as defined by the calculated AVA. Of those 27 classified as severe or very severe by MR, 25 (92%) were consistently identified by catheter-derived AVA (in the other 2, AVA was not available), and 16 of the 27 were identified by the invasively measured pressure gradient (59%). By comparison with MR, eight patients were classified as severe or very severe by catheter-derived AVA, and two patients, as defined by the pressure gradient, had an AVA >1 cm^2 by MR. Only 11 (29%) of 38 patients in whom data from all methods were available were unanimously classified as having severe or very severe AS.

The correlation between AVA by MR and TEE was $r = 0.96$ ($p < 0.000001$); between MR and catheter, $r = 0.64$ ($p < 0.00001$); and between TEE and catheter, $r = 0.58$ ($p < 0.0001$). There was an inverse correlation of AVA between MR and Doppler pressure gradient of −0.63 and between MR and catheter gradient of −0.44. The inverse correlation of AVA between TEE and Doppler pressure gradient was −0.64, and between TEE and catheter gradient it was −0.47. The correlation between mean gradients assessed by Doppler and catheter was 0.71 ($p < 0.0001$). Linear regression between MR and TEE and between Doppler and catheter gradients is shown in Figure 2.

Of those six patients with severely impaired LV function, pullback gradients were available in five. The mean AVA_{max} by MR in those five was measured at 0.98 cm^2 and by TEE at 0.93 cm^2; the mean AVA derived from catheter pressure measurements was calculated at 0.85 cm^2.

On Bland-Altman analysis, the limits of agreement between MR and TEE were calculated as follows: $d_{mean} - 2s = -0.17$ cm^2, $d_{mean} + 2s = 0.13$ cm^2, placing 38 of 40 patients within the limits of agreement. Figure 3A shows the corresponding graph. No significant bias can be found between MR and TEE. For Doppler versus catheter, the limits of agreement were $d_{mean} - 2s = -43.62$ mm Hg and $d_{mean} + 2s = 44.12$ mm Hg. All results for Doppler versus catheter gradients were within the limits of agreement. The spread of data points shows that there is no significant bias toward higher or lower pressure gradients. Both MR versus TEE and Doppler versus catheter measurements show good agreement.

DISCUSSION

Measurements of the AVA by MR and TEE correlated very well ($r = 0.96$). Both techniques assess the "anatomic" AVA independent of LV function, jet direction, and velocities. Bland-Altman analysis shows good agreement between MR and TEE AVA measurements and no significant bias. Correlation of AVA as measured by MR and TEE with catheter- and Doppler-derived estimations of severity was expectedly less good but still highly significant. Classification of the severity of AS is a parameter of crucial importance, in addition to clinical findings, in deciding whether to recommend aortic valve replacement.

Limitations of catheter and Doppler. The severity of stenosis may be overestimated or underestimated by both Doppler and catheter techniques. During catheter pullback, in critical stenoses, the volume of the catheter itself may lead to underestimation of the orifice area. Discrepancies between pressure gradients assessed by Doppler and catheter may be explained through the fact that Doppler measures peak velocities and, thereby, the maximum pressure drop across the valve. Via the pressure recovery phenomenon, the catheter measures the "actual" pressure drop (i.e., the

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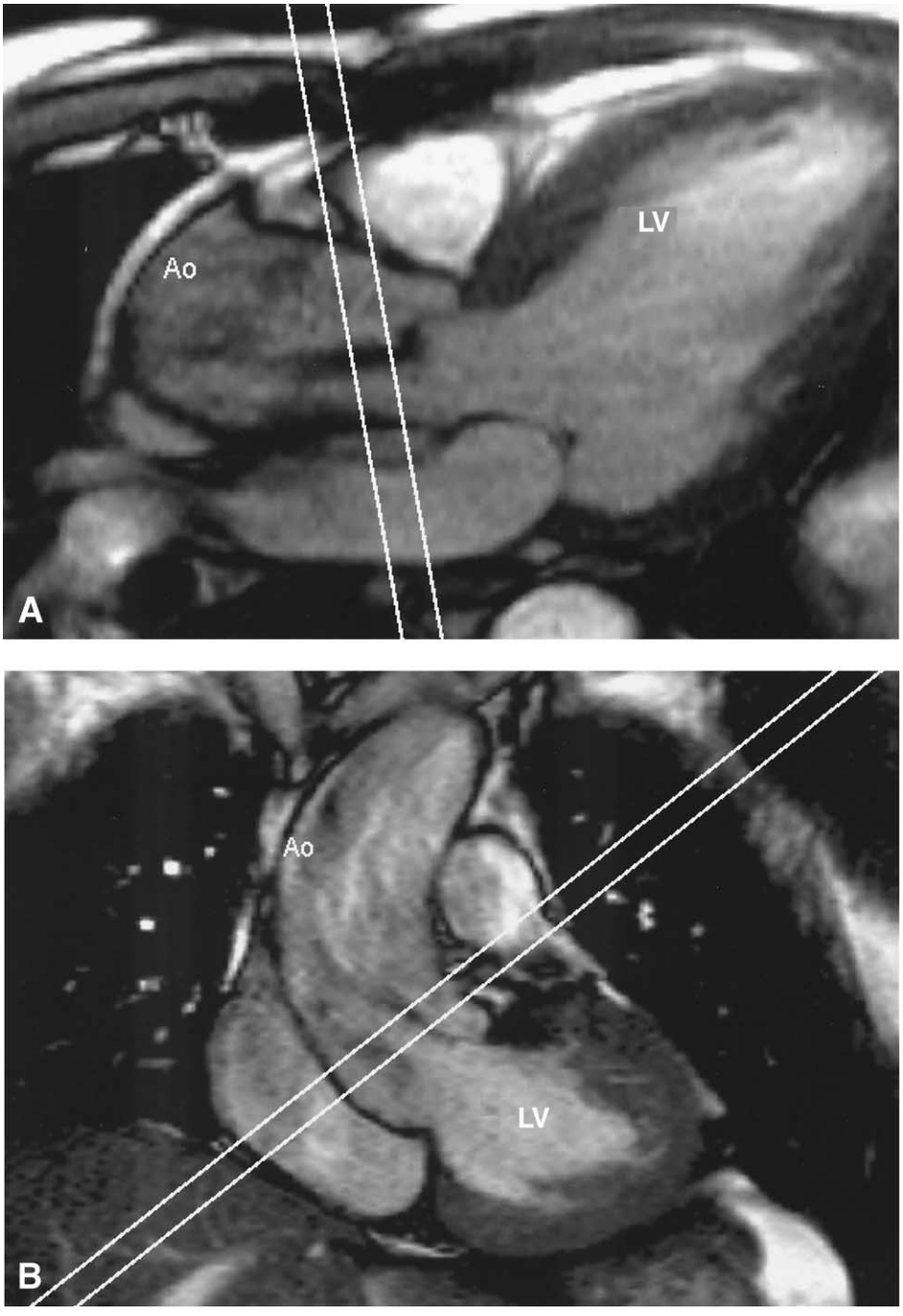

Figure 1. Slice positioning for planimetry of the aortic valve. **(A)** Oblique transaxial view of the aortic outflow tract, with the magnetic resonance (MR) slice position indicated by **two white lines**. **(B)** Oblique sagittal view of the aortic outflow tract, with the MR slice position indicated by **two white lines** orthogonal to the stenotic jet. *Continued on next page.*

"relevant" pressure drop as it represents actual pressure in the ascending aorta).

With TEE, on the other hand, in our series it was possible to obtain diagnostic information on valve morphology and function irrespective of the degree of stenosis or valve morphology and calcification in all cases. Magnetic resonance also allowed assessment of the valve, but in an even less invasive fashion, without the need for sedation or the use of ionizing radiation. Magnetic resonance planimetry has been shown to be highly reproducible and well tolerated, and the results correlate very well with TEE results. By obtaining multiple images during systole as well as diastole, it is also possible to judge valve performance at any time in the cardiac cycle. Lester et al. (13) have shown that the rate of change in AVA during systole can predict the rate of progression of AS. Therefore, estimating the amplitude of change in AVA by MR is an additional measure of the severity of AS. This implies that in two

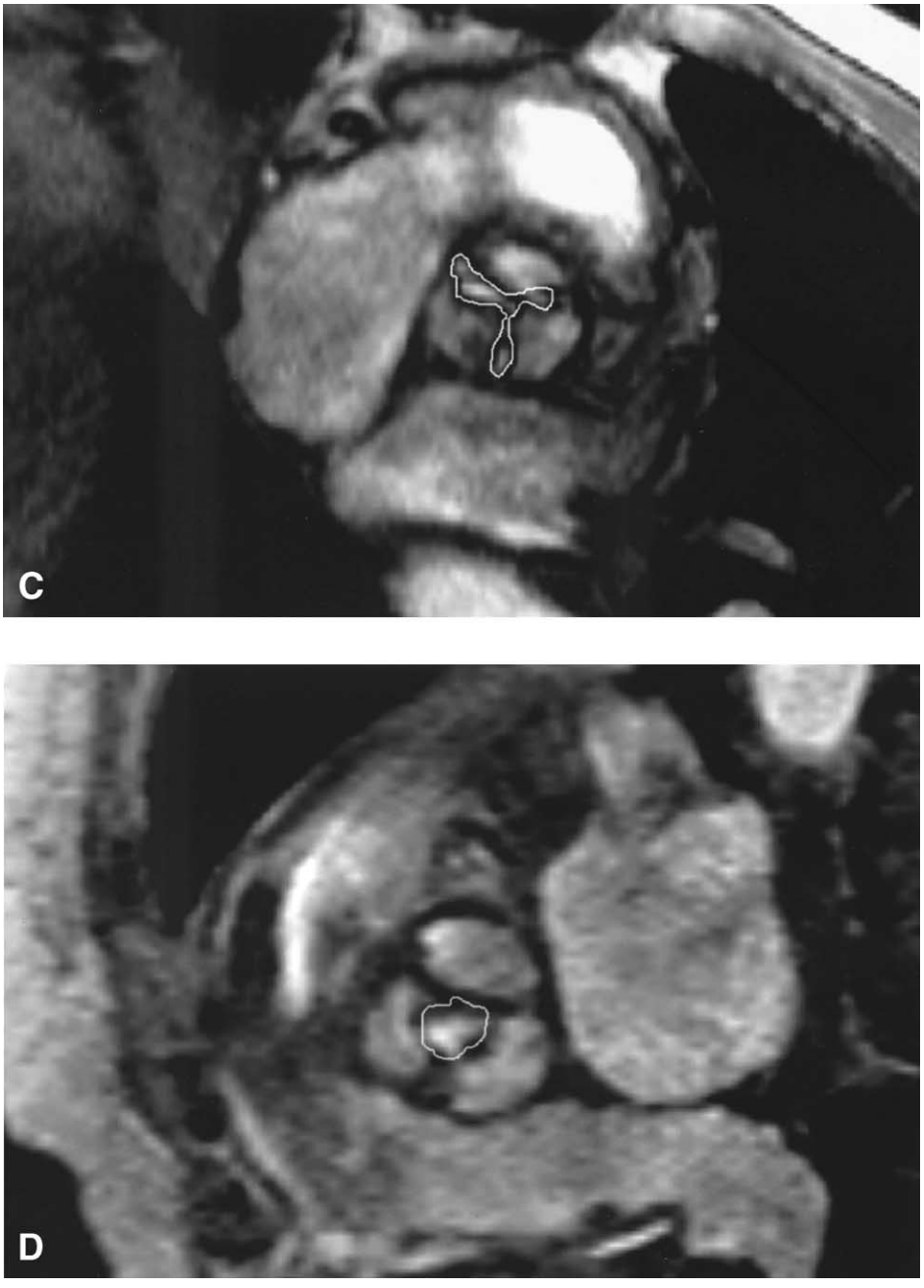

Figure 1 Continued. (C) Cross-sectional view of a moderately stenotic aortic valve; the gray line denotes the aortic valve area (AVA). **(D)** Cross-sectional view of a severely stenotic aortic valve; the **white line** denotes the AVA. Ao = ascending aorta; LV = left ventricle.

patients with a maximum AVA of 1.0 cm^2, one may have a very small amplitude associated with severe disease, the other one may have a wider range of AVA during systole indicating less severe disease. Thus, it may be useful not only for assessing the maximum AVA but also the AVA amplitude, and consequently mean AVA, during systole, and MR can achieve this.

Planimetric techniques provide a more reproducible estimate of the severity of aortic valve stenosis than flow-dependent methods. Burwash et al. (14) demonstrated that the AVA calculated from Doppler measurements and the continuity equation was systematically larger than the AVA calculated from an invasively measured gradient and the Gorlin equation in low-flow states. Our series is too small to draw conclusions on the statistical significance, but there seems to be a trend for catheter measurements to underestimate the AVA, by comparison with "anatomical" techniques, in patients with severely impaired LV function.

Limitations of TEE and MR planimetry. Generally, a limitation of assessing the planimetric (anatomic) orifice area is that an LV with poor systolic function and a low stroke volume may not be able to generate the pressures necessary to open the valve leaflets to the full extent and may hence lead to an underestimation of the AVA. However, a

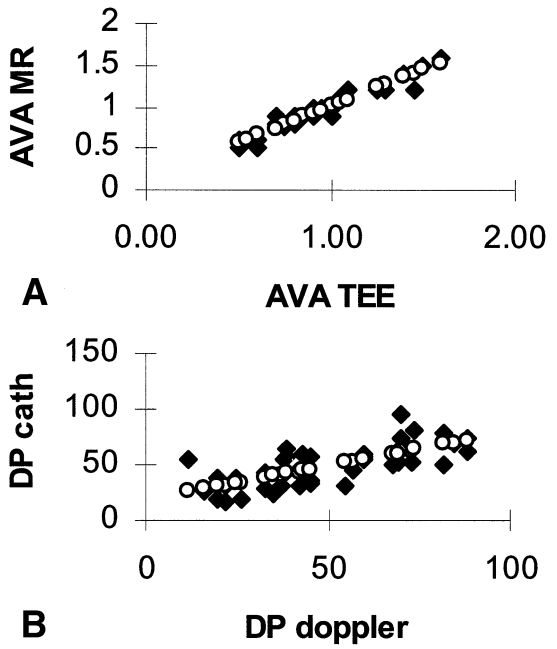

Figure 2. (A) Linear regression between MR-derived and transesophageal echocardiography (TEE)-derived aortic valve areas (AVAs). There is a good correlation between AVA by magnetic resonance (MR) and that by TEE, as indicated by the proximity of data points. **Solid diamonds** = actual AVA by MR; **open circles** = predicted AVA by MR. **(B)** Linear regression plot between Doppler- and catheter-derived pressure gradients. The data points are less close; however, there is still a good correlation, although less than that between MR and TEE AVAs. **Solid diamonds** = pressure gradient (DP) by cardiac catheterization (cath); **open circles** = predicted pressure gradient by cardiac catheterization.

study by Tardif et al. (15) suggests that an increase in transvalvular flow does not result in significant changes of the anatomic valve area measured by direct TEE planimetry.

TEE PLANIMETRY. Limitations to the use of TEE are contraindications, such as esophageal varices or diverticula, and also patient discomfort, as it is a semi-invasive technique often requiring sedation. In some cases, heavy calcification may make assessment of the actual orifice area difficult; however, in our series, this did not occur.

MR PLANIMETRY. Severe cardiac arrhythmia may cause trigger problems resulting in reduced image quality and less accurate planimetric results. In our series, rate-controlled AF did not affect image quality and the accuracy of the measurement. Calcification as well as turbulent flow across the valve can cause signal void, which can make edge discrimination of the valve leaflets difficult. For reasons of consistency, areas of signal void around the orifice area were treated as part of the leaflet, which in some cases may have been a misinterpretation. However, the good agreement between TEE and MR planimetric results suggests that the error caused by possible misinterpretation of signal void due to turbulence, as calcification or fibrosis may be negligible. In a few patients, severe claustrophobia may be a limitation, but in most cases, this can be overcome by light sedation if necessary.

MR VELOCITY MAPPING. Because of the numerous assumptions that are necessary to calculate the AVA from velocity measurement and the error associated with it, we did not perform MR velocity mapping of the aortic valve as proposed previously (16). Limitations of MR velocity mapping in AS include turbulent flow and aliasing. Choosing the correct plane for maximum velocity measurement can be difficult.

Study limitations. Forty patients is a small number of patients; however, this study indicates that MR planimetry of the AVA is feasible and safe. A further limitation of this study is that patients with MR contraindications were excluded. Patients with concomitant aortic regurgitation and certain rhythm disturbances were also excluded, as this was beyond the scope of this feasibility study. Further studies are necessary to assess the usefulness and accuracy of MR planimetry in patients who have more severe cardiac arrhythmias and concomitant aortic regurgitation.

In the assessment of the aortic valve lesion, other factors such as LV hypertrophy, also play an important role. Magnetic resonance has been shown to be accurate and reproducible in measuring LV mass and function (17). This can be done in the same imaging session with only little extra time.

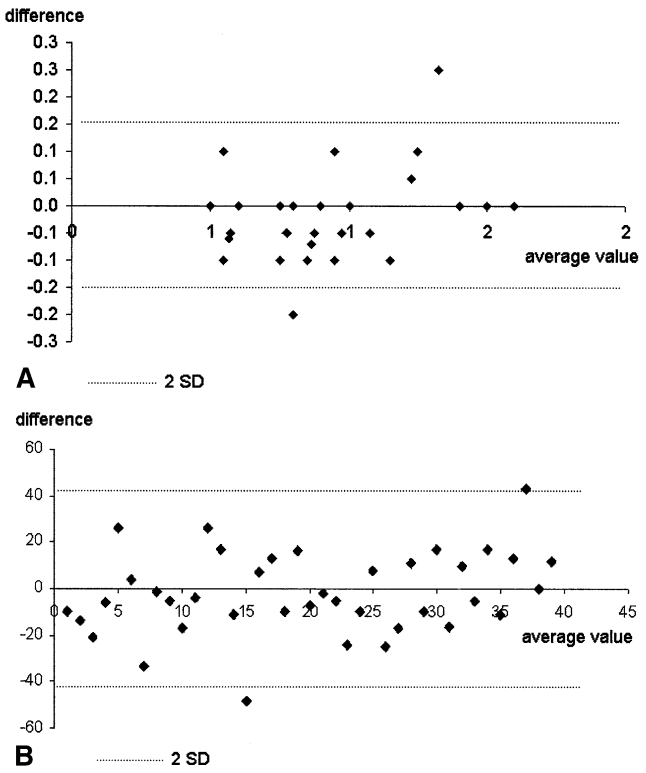

Figure 3. (A) Bland-Altman plot of magnetic resonance-derived versus transesophageal echocardiography-derived aortic valve area, showing no difference in the variability depending on the magnitude of the measurement and no significant bias. **(B)** Bland-Altman plot of the Doppler gradient versus catheter gradient, showing no significant bias between Doppler- and catheter-derived pressure gradients. Variability between the two is independent of the magnitude of the data. SD = standard deviation.

Table 1. Results

Patient No.	Mean AVA by MR (cm^2)	AVA by MR (cm^2)	AVA by TEE (cm^2)	AVA by CC (cm^2)	PG by CC (mm Hg)	PG by Doppler (mm Hg)	LV Function (%)
1	0.50	0.50	0.60	0.45	32	42	40
2	0.49	0.50	0.50	0.50	74	88	50
3	0.60	0.60	0.50	0.50	52	73	45
4	0.59	0.60	0.55	0.30	20	26	25
5	0.50	0.60	0.60	0.35	96	70	50
6	0.60	0.60	0.54	0.67	74	70	55
7	0.60	0.60	0.60	0.40	49	82	45
8	0.60	0.60	0.55	0.23	59	60	50
9	0.75	0.75	0.75	0.68	55	60	40
10	0.74	0.80	0.75	0.50	68	85	55
11	0.51	0.80	0.80	0.40	78	82	60
12	0.58	0.80	0.75	0.50	65	39	50
13	0.76	0.80	0.75	0.64	60	43	45
14	0.79	0.80	0.80	0.56	46	57	55
15	0.72	0.80	0.75			48	30
16	0.69	0.80	0.70	0.30	81	74	40
17	0.66	0.80	0.75	0.71	58	45	55
18	0.80	0.90	1.00	0.65	35	45	65
19	0.70	0.90	1.00	0.70	54	38	55
20	0.87	0.90	0.85	0.70	30	37	60
21	0.90	0.90	0.85	0.70	58	60	55
22	0.90	0.90	0.83	0.95	28	33	25
23	0.88	0.90	0.90	0.80	31	55	50
24	0.79	0.90	0.85	0.42	25	35	40
25	0.90	0.90	0.80	1.13	30	22	35
26	0.65	0.90	0.90	0.51	63	88	55
27	0.61	0.90	0.70	0.29	82		60
28	1.00	1.00	0.90		51	68	60
29	0.64	1.00	1.00	0.80	44	33	35
30	0.88	1.00	1.00	0.78	25	35	65
31	0.73	1.00	0.95	0.80	56	39	45
32	1.10	1.10	1.05	0.68	53	69	65
33	0.97	1.20	1.30	0.60	26	16	65
34	1.12	1.20	1.10	1.10	17	22	55
35	1.03	1.20	1.45	0.60	37	20	50
36	0.94	1.20	1.25	0.60	34	45	55
37	0.76	1.40	1.40	1.10	38	25	55
38	0.91	1.40	1.40	0.42	55	12	60
39	1.39	1.50	1.50	1.08	20	20	30
40	1.6 bic	1.60 bic	1.60 bic	1.40 bic	32	20	65

AVA = aortic valve area; bic = bicuspid; CC = cardiac catheterization; LV = left ventricular; MR = magnetic resonance; PG = pressure gradient; TEE = transesophageal echocardiography.

Conclusions. This series shows that MR planimetry of the AVA is well tolerated, reproducible, and observer-independent and correlates well with TEE measurements. It may therefore become a non-invasive, radiation-free alternative to current diagnostic standards.

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