Journal of Cardiovascular Magnetic Resonance (2007) **9,** 799–805

ISSN: 1097-6647 print / 1532-429X online
DOI: 10.1080/10976640701545479

informa
healthcare

Correlation of Aortic Valve Area Obtained by the Velocity-Encoded Phase Contrast Continuity Method to Direct Planimetry using Cardiovascular Magnetic Resonance

Kaoru Tanaka, MD, PhD, Amgad N. Makaryus, MD, and **Steven D. Wolff, MD, PhD**

Division of Cardiology, Columbia University College of Physicians and Surgeons, Columbia University Medical Center, New York City, New York, USA

ABSTRACT

***Background*: Aortic stenosis (AS) is the most common valvular heart disease resulting in surgical intervention. Transthoracic echocardiography (TTE) utilizing the continuity equation is commonly used to determine aortic valve area (AVA). However, sometimes TTE can be limited by poor acoustic windows, heavy valvular calcification, or eccentric jet morphology. Cardiovascular magnetic resonance (CMR) provides an alternative non-invasive method for the evaluation of AVA using direct planimetry. Prior studies have shown good correlation between CMR and other modalities, such as TTE, TEE, and cardiac catheterization. CMR can also assess AVA by using the continuity equation employing velocity-encoded phase contrast (VEPC) imaging. We sought to assess whether velocity-encoded phase-contrast MRI can provide an alternate means of quantifying AVA by CMR. *Methods*: Twenty-two consecutive AS patients were imaged with CMR. AVA was determined by VEPC imaging and by direct planimetry. *Results*: Mean AVA by planimetry was $1.05 \pm 0.41 cm^2$ and $1.00 \pm 0.4\ cm^2$ by VEPC, with a strong correlation ($R^2 = 0.86$, $p < 0.0001$) between the two methods. The mean difference of AVA was 0.05 ± 0.15 (95% CI $= [0.02 - 0.08]$), and the limits of agreement were -0.26 to $0.36\ cm^2$. The mean difference between 2 observers for planimetry was 0.030 ± 0.07 (95% CI $= [0.02 - 0.04]$) with limits of agreement of -0.11 to $0.16\ cm^2$ and for VEPC was 0.008 ± 0.085 (95% CI $= [-0.01 - 0.026]$) with limits of agreement of -0.16 to $0.18\ cm^2$. *Conclusions*: VEPC CMR is an alternative method to direct planimetry for accurately determining AVA. Both techniques can be easily incorporated into a single CMR exam to increase the confidence of AVA determination utilizing cardiac magnetic resonance imaging.**

INTRODUCTION

With the aging of the population, aortic stenosis (AS) has become the most common valvular heart disease resulting in surgical intervention, and its prevalence will continue to increase. The latest percutaneous techniques, such as aortic valvuloplasty or balloon-mounted valve implantation, enable the treatment of inoperable patients with end-stage AS, leading to hemodynamic and clinical improvement. Non-invasive techniques for evaluation of AS severity avoid the complications associated with cardiac catheterization. As the clinical decision to perform invasive correction depends in large part on quantification of valve area, the accurate and reproducible evaluation is necessary for the adequate selection of the optimal candidates to undergo AS valve procedures (1).

The conventional assessment of AS severity has been undertaken by echocardiography. Aortic valve area (AVA) is calculated by transthoracic Doppler-derived calculations using the continuity equation (2, 3). Certain patients, however, may have a suboptimal evaluation because of poor acoustic windows, heavy calcification of the aortic valve, or significant flow acceleration

Received 15 March 2007; accepted 27 June 2007.
Keywords: Aortic Valve Area, Cardiovascular Magnetic Resonance Imaging, Planimetry, Velocity-encoded Phase Contrast, Continuity Equation
Correspondence to:
Steven D. Wolff, MD, PhD
Advanced Cardiovascular Imaging
62 East 88th Street
New York, NY 10128
tel: (212) 369-9200
email: sdwolff@mrict.com

in the left ventricular outflow tract (LVOT), which may obscure accurate assessment. In this population, transesophageal echocardiography (TEE) is an alternative; however, it is relatively invasive and can have similar pitfalls as transthoracic echocardiography (TTE).

Cardiovascular magnetic resonance (CMR) is a noninvasive alternative, which, with new software and hardware advancements can perform quantitative assessment of cardiac valvular disease. Two ways to assess AS with CMR include direct planimetry and velocity-encoded phase contrast (VEPC) imaging utilizing both diameter derived LVOT area and planimetry derived LVOT area measurements in the continuity equation. The aim of this study was to compare AVA measurements by CMR using planimetry and VEPC CMR methods.

METHODS

Patient population

Twenty-two consecutive patients who had undergone CMR for the evaluation of AS between December 1, 2005 and September 1, 2006 were evaluated. The majority of these patients had been diagnosed with AS by TTE and were referred to CMR for further evaluation of the AS prior to planned surgical procedures. Patients in a rhythm other than sinus rhythm (ie, atrial fibrillation) or who were determined to have more than mild aortic regurgitation were excluded. Patients with significant AR were excluded in order to maintain a pure sample population without introducing any confounding factors that may affect flow hemodynamics and alter VEPC measurements. Analysis was performed retrospectively, and this protocol was approved by the Columbia University Medical Center institutional review board.

CMR methods

Patients were imaged with a 1.5-Tesla MRI scanner using an 8 element, phased-array cardiac coil (GE Signa, EXCITE, GE Medical Systems, Milwaukee, Wisconsin, USA). Imaging was ECG gated, and all images were acquired during breath holds. All patients were imaged by an experienced technologist without complication. The image interpretation was performed by two different observers that were blinded to the presenting data. CMR data was analyzed at a work station utilizing Report Card 3.0 software (GE Medical Systems).

CMR protocol for planimetry measurements

Images parallel to the aortic annulus were acquired employing the steady-state free precession (FIESTA, GE Medical Systems, Milwaukee, WI) CMR protocol (Fig. 1). Repetition time (TR) was 3.5 ms; echo time (TE) was 1.5 ms; the flip angle was 60°; views per segment (VPS) were 12; field of view (FOV) was 350 × 350 mm; matrix size was 192 × 160; nominal temporal resolution was 42 ms; breath hold time range was 12–20 s; slice thickness was 5.0 mm, and nominal spatial resolution (voxel size) was 5 × 1.8 × 2.2 mm. Manual planimetry of the AVA was measured at peak systole, where the valve was the most open at the level of the leaflet tips. Dark signal was not planimetered as these dark areas likely represent calcium. Figures 2A and B show examples of two of our patients. Figure 2A is an example of a single orifice, and Fig. 2B shows an example of multiple orifices due to fused commissures. Two observers made the necessary measurements, and interobserver variability was assessed. We also examined intra-observer variation.

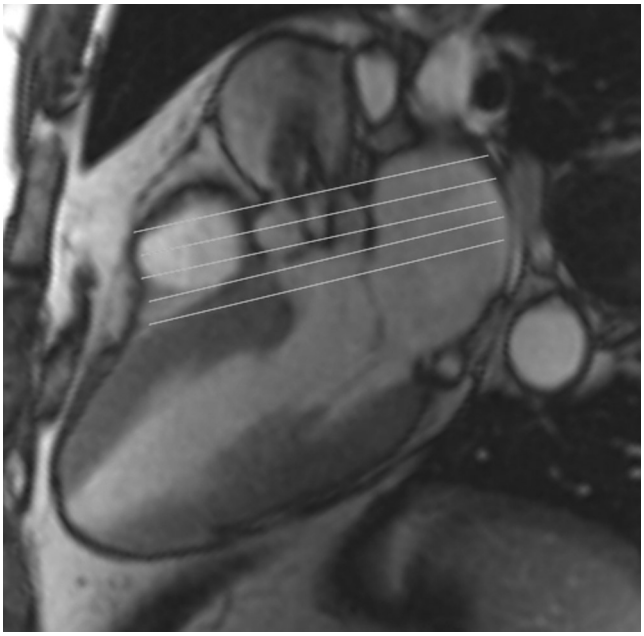
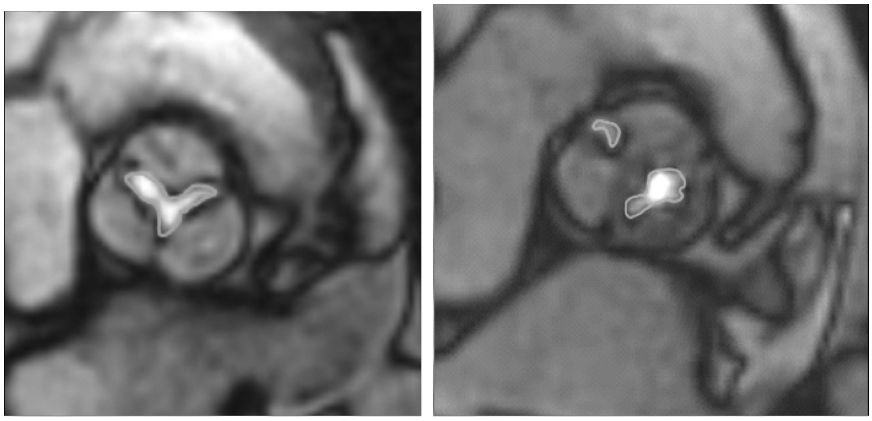


Figure 1. The aortic localizer view showing a turbulent AS jet and imaging slice planes perpendicular to the jet.

CMR protocol for velocity-encoded phase contrast imaging continuity measurements

To ensure velocity measurements were perpendicular to the plane of flow, a cine localizer was first obtained parallel to the direction of flow. From this localizer, perpendicular (to the jet flow) phase-contrast images were obtained from the LVOT through the aortic root. TR was 7.6 ms; TE was 3.8 ms; the flip angle was 20°; VPS was 8; FOV was 480 × 360 mm; matrix size was 512 × 224; nominal temporal resolution was 121 ms; breath hold time range was 18–30 seconds; maximum encoded velocity ($V_{ENC\,max}$) was 550 cm/s; slice thickness was 7.0 mm; and nominal spatial resolution (voxel size) was 7 × 0.94 × 2.1 mm. Phase contrast images were interpolated so that thirty image time points were acquired per cardiac cycle.

Aortic valve area was calculated using the continuity equation: AVA = (peak LVOT velocity × LVOT area)/peak aortic valve velocity. Each of these parameters was measured from the paired magnitude/phase contrast images (Fig. 3). The LVOT area was determined in two ways. One way used planimetry of the LVOT at peak systole from the magnitude image (Fig. 3A), and the other way employed a measurement of the LVOT diameter from the 3-chamber view (not shown), and a calculation of the LVOT area using the area = πr^2 formula. The peak velocity at



(A) (B)

Figure 2A, B. Examples of stenotic aortic valves and the measurement of the AVA with a single orifice (2A) and with multiple orifices (2B) by planimetry.

the level of the LVOT was obtained by drawing a small region of interest (typical ROI size: 6×6 mm^2; Fig. 3B). A small ROI was used instead of a single pixel value so as to minimize the effect of noise. Figure 4 shows the magnitude (4A) and phase (4B) images of the stenotic aortic valve. Peak aortic valve velocity was measured by interrogating individual pixels in the phase contrast images and the highest peak velocity value obtained was used. Spurious values due to low signal-to-noise or edge pixels were excluded. Both observers made the necessary measurements, and interobserver and intraobserver variability was again assessed.

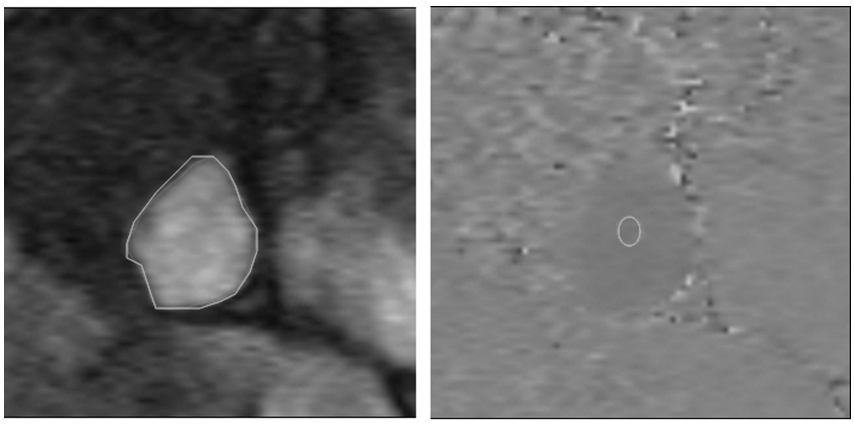
Statistical analysis

Statistical analysis was performed using Analyse-It (Analyse-It Software, Ltd., Leeds, United Kingdom), and QuattroPro10 (Corel; Ottawa, Canada). Continuous data are expressed as mean $\pm$ standard deviation. Correlation between the two methods (VEPC and planimetry) was tested by regression analysis. Agreement in terms of how closely the two techniques produced the same result with respect to AVA was assessed by the Bland-Altman method (4).

RESULTS

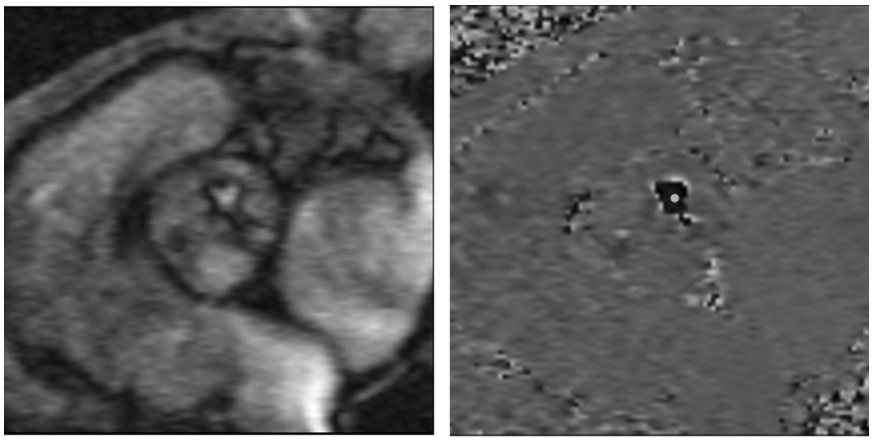
Patient characteristics and CMR results

Patient characteristics and CMR measurements of each patient are shown in Table 1. The mean age of the patient population was 72 $\pm$ 14 years (range 30–87 years). All patients were in sinus rhythm at the time of the study. Two patients had a bicuspid aortic valve. The mean ejection fraction (EF) was 57 $\pm$ 11% (range 26.4–72.2%), and low EF, which was considered under 40%, was observed in 2 patients. Concomitant aortic



(A) (B)

Figure 3. The magnitude (3A) and phase (3B) images of a left ventricular outflow tract (LVOT).



(A) (B)

Figure 4. The magnitude (4A) and phase (4B) images of a stenotic aortic valve. The velocity at the aortic valve from the sampled voxels was used for the area calculation.

regurgitation was present in 11 (50%) patients. Regurgitation in these patients was mild with a regurgitant fractions of $<10\%$.

Severity of AS and valve area comparison

Planimetry of AVA was possible in all patients, and the mean AVA measured by planimetry was 1.05 ± 0.4 cm^2. According to the AVA by planimetry, 12 patients (55%) had severe AS (AVA $<$ 1.0 cm^2), 8 (36%) had moderate AS (AVA range 1.0–1.5 cm^2), and 2 (9%) had mild AS (AVA $>$ 1.5 cm^2). AVA calculation by phase-contrast CMR was also possible in all patients, and the mean AVA measured by employing the planimetered LVOT area in the continuity equation was 1.00 ± 0.4 cm^2. Mean AVA measured by employing the LVOT diameter derived area in the continuity equation was 0.89 ± 0.38 cm^2.

AVA measured by planimetry and phase-contrast CMR employing the planimetered LVOT area shows a strong linear correlation ($R^2 = 0.86$) (Fig. 5). The mean difference of AVA by these two methods was 0.05 ± 0.15 cm^2 (95% CI = [0.02 − 0.08]), and the limits of agreement were -0.26 to 0.36 cm^2 (Fig. 6). The mean difference between the 2 observers for the planimetry method was 0.030 ± 0.07 cm^2 (95% CI = [0.03 − 0.04]), and the limits of agreement were -0.11 to 0.16 cm^2. The mean difference was 0.008 ± 0.083 (95% CI = [$-0.01 - 0.025$]) and the limits of agreement were -0.16 to 0.17 cm^2 for the continuity method. Despite a trend towards underestimation of AVA when employing the LVOT diameter in the continuity equation (0.89 ± 0.38 cm^2 vs. 1.00 ± 0.4 cm^2), this measurement still showed good correlation with planimetry of the AVA ($R^2 = 0.80$, $p < 0.001$). The intra-observer difference (one week of time between the 2 measurements) for the planimetry method was 0.001 ± 0.05 cm^2 (95% CI = [$-0.01 - 0.01$]), and the limits of agreement were -0.10 to 0.10 cm^2 and for the continuity method the mean difference was 0.003 ± 0.07 (95% CI = [$-0.02 - 0.01$]), and the limits of agreement were -0.14 to 0.13 cm^2.

DISCUSSION

Kilner et al (5) were among the earliest investigators to show the potential for quantitative assessment of aortic valve stenosis with CMR velocity mapping. Sondergaard et al (6) used velocity-encoded CMR to estimate the orifice area and illustrated good correlation with invasive catheterization. Other researchers have also demonstrated excellent correlation between valve area by CMR velocity mapping and invasive hemodynamic measurements (7–9). Other investigators have also shown that CMR planimetry correlates well with other established techniques, including echocardiography and invasive catheterization (7, 10–14).

In the present study, we have shown a strong linear correlation between AVA as measured by CMR VEPC imaging and by planimetry. The agreement between the two methods indicates that these two methods can be used interchangeably. In our study, the 95% confidence limit of the difference between the two techniques is -0.26 to $+0.36$ cm^2 by the Bland-Altman analysis (Fig. 6). The mean difference of AVA by these two methods was 0.05 ± 0.15 cm^2 (95% CI = [$0.02 - 0.08$]), suggesting no significant systematic bias towards over/underestimation in one technique relative to the other. The interobserver and intraobserver differences in both methods also showed good reproducibility to prove the robustness of the measurements. It has been suggested by prior investigators that planimetry by CMR underestimates the valve area in severe AS cases due to severe calcification, artifacts from intravoxel dephasing from turbulent flow, and partial volume averaging (7, 10). However, our data showed an excellent correlation even among severe AS cases. We attempted to minimize limitations from severe calcification, artifacts from intravoxel dephasing, and partial volume averaging by not including the signal void created by the calcification. This edge discrimination, however, may cause difficulty during planimetry measurements and may make VEPC techniques more favorable in these circumstances.

Table 1. Patient Characteristics and CMR Results

Patient	HR(/min)	LV EF (%)	Aortic Regurgitation	LVOT area (cm^2)	LVOT velocity (m/s)	AV velocity (m/s)	AVA by Continuity (cm^2)	AVA by Planimetry (cm^2)
1	91	64.8	Mild	5.3	0.8	4.4	1	0.8
2	57	62.2	None	5	0.74	3.8	1.3	1.2
3	88	63.4	None	4.2	0.56	1.9	1	1.2
4	102	62.5	None	3.8	0.7	4.2	0.6	0.75
5	55	62.9	Mild	4	0.75	3.5	0.9	1.1
6	50	60.5	Mild	3.9	0.8	4.8	0.6	0.6
7	61	64.9	Mild	4.6	1	4.4	1	1
8	77	73.6	None	3.1	1.1	3	1.1	1.1
9	49	48.1	None	5.5	0.5	3.2	0.9	1
10	101	26.4	Mild	3.1	0.8	3.1	0.8	0.75
11	68	59.2	None	4.5	0.57	2	1.4	1.1
12	77	57.1	None	4	0.8	4.6	0.7	0.6
13	69	34.4	None	5.7	0.34	3.3	0.6	0.6
14	55	72.2	Mild	2.3	1.5	3.3	0.9	1
15	62	53.9	Mild	4.7	0.9	3	1.4	1.4
16	76	56.2	Mild	7.3	0.9	4.1	1.6	1.6
17	80	56.4	Mild	4.3	0.75	4.4	0.8	1
18	73	57.2	Mild	3.7	0.67	4	0.6	0.75
19	50	58.2	Mild	5.9	0.8	2.3	2.1	2.4
20	81	59	None	4.9	0.43	2.6	0.8	1.1
21	64	52.2	None	5	0.59	2.3	1.3	1.3
22	61	74.2	Mild	3.7	0.97	4.5	0.8	0.8

Echocardiography has long been the standard non-invasive diagnostic technique for assessing AS. However, poor sonographic windows may compromise image quality, and unusual anatomic configurations that do not allow parallel positioning of the sample volume may preclude exact determination of maximal velocity. In patients with suboptimal transthoracic imaging, CMR is a feasible non-invasive alternative. As we showed in our study, planimetry is possible in most of the cases with severe calcification. Furthermore, in echocardiography, there are certain assumptions which are not always accurate. For example, the

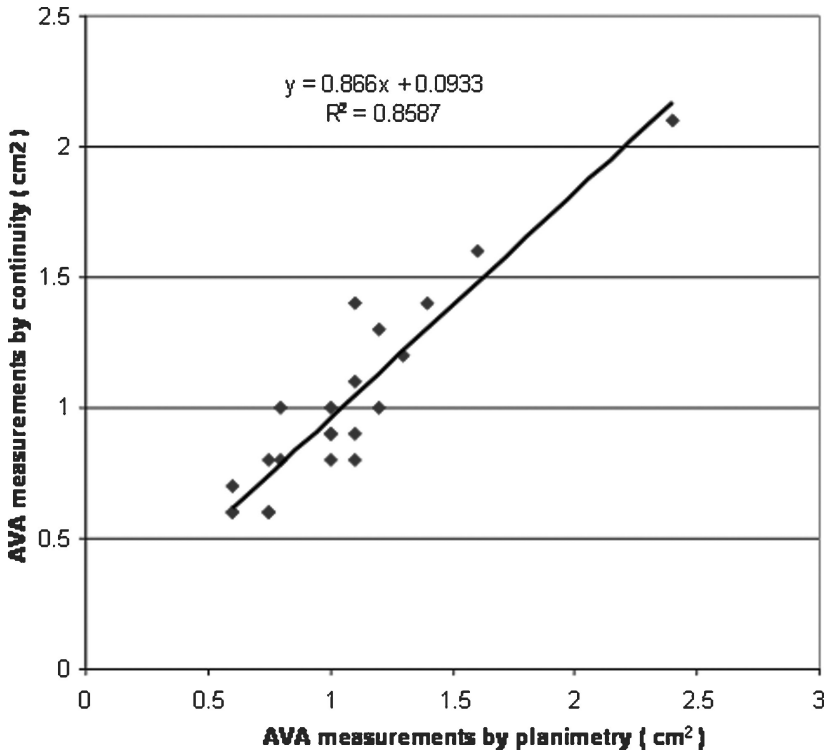


Figure 5. AVA measured by planimetry and phase-contrast CMR shows a strong linear correlation.

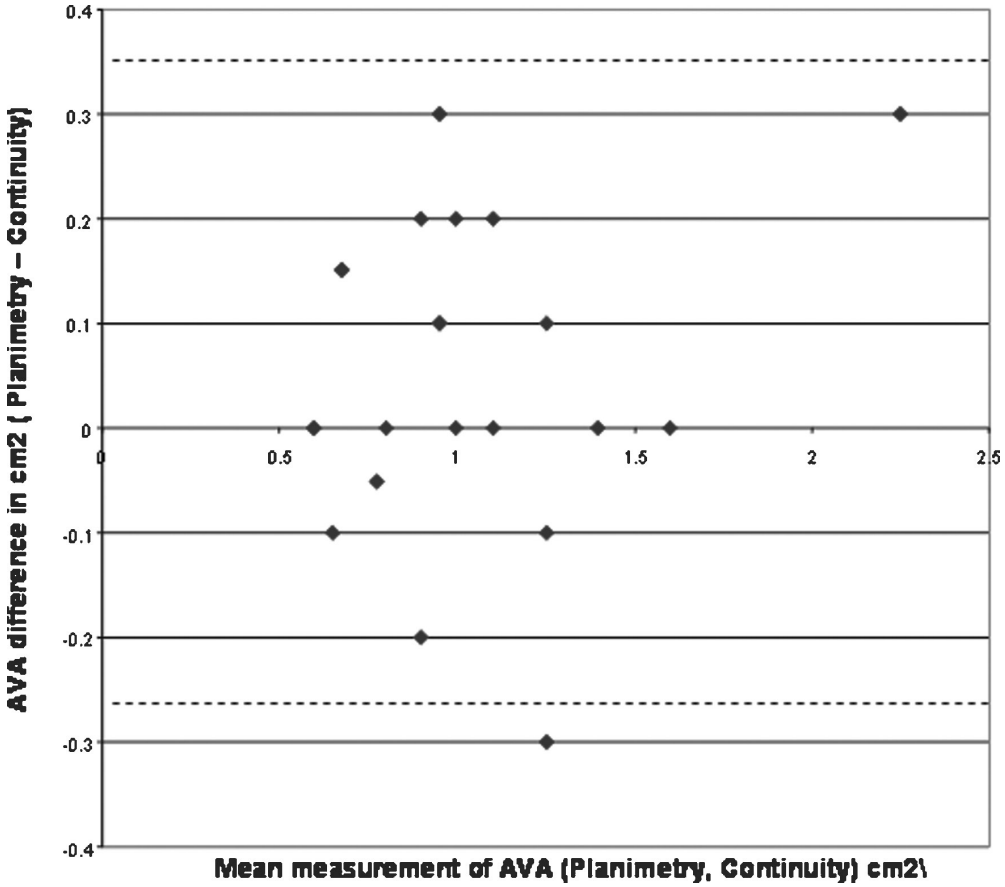


Figure 6. The mean difference of AVA by planimetry and phase-contrast CMR.

diameter of the LVOT is used to calculate the LVOT area on the basic assumption that the LVOT is circular. As our CMR images show, this is rarely the case, and the LVOT is generally ellipsoid in shape (Fig. 3A). We assessed the difference in AVA continuity calculations by using both the planimetered LVOT area and the diameter-derived LVOT area as is used in echocardiography. Despite a trend towards underestimation of AVA when employing the LVOT diameter in the continuity equation (0.89 ± 0.38 cm^2 vs. 1.00 ± 0.4 cm^2), this measurement still had a good correlation with planimetry of the AVA ($R^2 = 0.80$, $p < 0.001$). The assumption applied, however, is now no longer necessary as CMR planes are clearly delineated prior to sequence acquisition from the localizer and no assumptions are made with respect to area assessment. Additionally, in the future, more advanced and accurate techniques utilizing complete 3D velocity encoding data, which then allows correction of the angle of acquisition to assure acquisition of the maximal velocity, will be applied clinically.

Although planimetry and VEPC continuity measurements each have their own advantages and pitfalls, they provide an excellent internal check on each other while performing CMR for the assessment of AVA. This being said, it is in the experience of the authors that planimetry measurements are generally the preferred and recommended assessment method for AVA, because planimetry images can be obtained with shorter breath holding time and, therefore, a shorter total acquisition time. VEPC imaging takes longer breath holds (18–30 seconds vs. 12–20 seconds with planimetry) and requires a more precise prescription (as described in the methods section) to obtain the optimal images. In patients with severe calcification at the leaflet tips, however, artifacts from intravoxel dephasing and partial volume averaging make edge discrimination for planimetry difficult. This makes VEPC techniques more favorable in these circumstances.

Study limitations

Limitations to CMR including the contraindications to MRI in general—pacemaker/defibrillator or metallic implants, severe claustrophobia, and severe cardiac arrhythmias, still exist. According to a prior investigation (10), however, rate-controlled atrial fibrillation does not preclude the evaluation of the AVA by planimetry. Also, calcification of the aortic valve as well as turbulent flow caused by aortic regurgitation can cause signal void, which makes edge discrimination of the valve leaflets during planimetry difficult (10, 15). We minimized this error by not including the signal void created by the calcification.

Another limitation is in the case of LVOT obstructions, in which, VEPC derived valve area may be inaccurate as the

LVOT flow will be accelerated. This can be avoided by being vigilant to high turbulence flow jets in the LVOT. Patients with decreased systolic left ventricular function (so-called "low output aortic stenosis") can have the severity of their aortic stenosis overestimated due to the inability of the left ventricle to generate enough force to open the aortic valve. Similar to echocardiography, velocity measurements with VEPC can be affected in this way. In our study, however, the two patients (patients 10 and 13) (Table 1) with decreased left ventricular ejection fraction (26% and 34%, respectively) were still able to generate adequate stroke volumes (46.8 mL and 51.8 mL, respectively) that this effect of over-estimation of aortic stenosis severity was not seen and the VEPC-derived AVA correlated well with the planimetry-derived AVA. The last limitation of our study is that we did not directly compare our data with the other imaging modalities. However, prior studies have found excellent correlation between planimetry derived CMR methods and other modalities, and our correlation between the newer technique applying VEPC CMR imaging to the already validated planimetry CMR further extends the utility of CMR.

CONCLUSION

CMR VEPC imaging correlates well with CMR planimetry and is a highly reliable and reproducible technique. Therefore, CMR techniques using planimetry and VEPC imaging make CMR a robust diagnostic tool for the assessment of AVA, particularly in patients with uncertain or discrepant findings by other modalities.

ABBREVIATIONS

AVA	aortic valve area
AS	aortic stenosis
CMR	Cardiovascular magnetic resonance
EF	ejection fraction
LVOT	left ventricular outflow tract
TTE	transthoracic echocardiography
VEPC	velocity-encoded phase contrast

REFERENCES

1. Selzer A. Changing aspects of the natural history of valvular aortic stenosis. N Engl J Med 1987;317:91–8.
2. Skjaerpe T, Hegrenaes L, Hatle L. Noninvasive estimation of valve area in patients with aortic stenosis by Doppler ultrasound and two-dimensional echocardiography. Circulation 1985;72:810–8.
3. Zoghbi WA, Farmer KL, Soto JG, et al. Accurate noninvasive quantification of stenotic aortic valve area by Doppler echocardiography. Circulation 1986;73:452–9.
4. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986;1:307–310.
5. Kilner PJ, Firmin DN, Rees RSO, et al. Valve and great vessel stenosis: assessment with MR jet velocity mapping. Radiology 1991;178:229–235.
6. Sondergaard L, Hildebrandt P, Lindvig K, et al. Valve area and cardiac output in aortic stenosis: quantification by magnetic resonance velocity mapping. Am Heart J 1993;127:1156–1164.
7. Caruthers SD, Lin SJ, Brown P, Watkins et al. Practical value of cardiac magnetic resonance imaging for clinical quantification of aortic valve stenosis: comparison with echocardiography. Circulation 2003;108(18):2236–43.
8. Kilner PJ, Manzara CC, Mohiaddin RH, et al. Magnetic resonance jet velocity mapping in mitral and aortic valve stenosis. Circulation 1993;87:1239–1248.
9. Eichenberger AC, Jenni R, von Schulthess GK. Aortic valve pressure gradients in patients with aortic valve stenosis: quantification with velocity-encoded cine MR imaging. AJR 1993;160:971–977.
10. Kupfahl C, Honold M, Meinhardt G, et al. Evaluation of aortic stenosis by cardiovascular magnetic resonance imaging: comparison with established routine clinical techniques. Heart 2004;90(8):893–901.
11. John AS, Dill T, Brandt RR, et al. Magnetic resonance to assess the aortic valve area in aortic stenosis: how does it compare to current diagnostic standards? J Am Coll Cardiol 2003;42(3):519–26.
12. Haghi D, Papavassiliu T, Kalmar G, et al. A hybrid approach for quantification of aortic valve stenosis using cardiac magnetic resonance imaging and echocardiography. J Cardiovasc Magn Reson 2005;7(3):581–6.
13. Debl K, Djavidani B, Seitz J, et al. Planimetry of aortic valve area in aortic stenosis by magnetic resonance imaging. Invest Radiol 2005;40(10):631–6.
14. Thomas B, Freitas A, Ferreira, et al. The complementary role of cardiac magnetic resonance imaging in the evaluation of patients with aortic stenosis. Rev Port Cardiol 2005;24(9):1117–21.
15. Ahmed S, Shellock FG. Magnetic resonance imaging safety: implications for cardiovascular patients. J Cardiovasc Magn Reson 2001;3:171–82.