

Pre-procedural assessment of aortic annulus dimensions for transcatheter aortic valve replacement: comparison of a non-contrast 3D MRA protocol with contrast-enhanced cardiac dual-source CT angiography

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Aims

To evaluate the feasibility of a non-contrast three-dimensional (3D)-FLASH magnetic resonance angiography (MRA) protocol for pre-procedural aortic annulus assessment for transcatheter aortic valve replacement (TAVR) in comparison with cardiac dual-source computed tomography angiography (CTA).

Methods and results

In this prospective study, 69 of 104 consecutive patients (mean age 81.8 ± 5.4 years, 37.7% arrhythmic) with severe aortic stenosis who had undergone pre-TAVR cardiac CTA received a respiratory and ECG-triggered, non-contrast 3D-FLASH MRA at 3 T. Annular area measurements were obtained at mid-diastole for both modalities whereas maximum systolic area was assessed by CTA only. Systolic MRA dimensions were modelled, by adding the relative difference of systolic and diastolic CTA area dimensions as a corrective factor. Hypothetical prosthesis sizing was performed based on systolic CTA, diastolic, and modelled systolic MRA area measurements. MR image quality and degree of annular calcifications were evaluated using 4-point-grading scales. The mean acquisition time was 14 ± 4.2 min. The mean image quality was 3.1 ± 0.9 with only two examinations rated non-diagnostic. The mean degree of calcifications was equal. As assessed by Bland–Altman analysis, there was no relevant systematic difference between area measurements for modelled systolic MRA and systolic CTA [the mean difference -3.1 mm^2 (limits of agreement -44.4 mm^2 ; 38.2 mm^2)]. Agreement for hypothetical prosthesis sizing was found in 63 of 67 (94%) patients for systolic CTA and modelled systolic MRA.

Conclusion

The employed non-contrast 3D-FLASH MRA protocol allows for reliable assessment of aortic annulus dimensions and calcifications even in the presence of arrhythmias in an all-comers pre-TAVR population. Implementation of this technique appears legitimate in patients at an increased risk for contrast-induced nephropathy.

Keywords

magnetic resonance angiography • computed tomography • transcatheter aortic valve replacement • TAVI • TAVR

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Introduction

Transcatheter aortic valve replacement (TAVR) is an established treatment alternative for inoperable or high-risk patients with severe aortic stenosis.^{1,2} The most common adverse event related to TAVR is the occurrence of paravalvular regurgitation, which is associated with an increased in-hospital and midterm mortality.^{3–5} Computed tomography angiography (CTA) is an essential component of pre-procedural TAVR work-up as it allows for three-dimensional (3D) assessment of the aortic annulus.⁶ As compared with echo-based sizing alone, CTA-based prosthesis selection can reduce the occurrence of paravalvular regurgitation.⁷ However, CTA-based annulus assessment requires the use of intravenous contrast media, which may place the patient at an increased risk for contrast-induced nephropathy, in particular given the high prevalence of impaired renal function at baseline in these commonly elderly, multi-morbid patients.⁸ Moreover, procedural outcome can be negatively influenced by contrast-induced nephropathy.⁹ This prospers the desire for cross-sectional imaging techniques which do not rely on iodinated contrast material, such as magnetic resonance imaging (MRI). While several studies have shown the capability and diagnostic accuracy of respiratory and ECG-triggered 3D non-contrast MR angiography (MRA) techniques for assessment of thoracic aortic disease,^{10,11} this technique is commonly limited to diastole as opposed to dynamic CT data acquisition which can obtain image data in both systole and diastole. However, annular dimensions are subject to pulsatile changes throughout the cardiac cycle with the largest dimensions commonly observed during systole.¹² Despite this potential drawback and conceivable limitations in patients with non-sinus rhythm, who constitute a significant portion of the general TAVR population¹³ further investigation of this technique for its potential application in the context of pre-TAVR assessment appears desirable.

Thus we sought to evaluate the feasibility and accuracy of a respiratory and ECG-triggered 3D non-contrast MRA for aortic annulus assessment in comparison to ECG-gated cardiac dual-source CT acquisition in an unselected, consecutive cohort of patients evaluated for TAVR. In particular, we hypothesize that a corrective factor may compensate for the systematic difference in annular dimensions between the diastolic dimensions on MRA compared with systolic dimensions on CT.

Methods

Study population

This prospective study was approved by the institutional review board and complies with the Declaration of Helsinki. All patients with severe symptomatic aortic stenosis referred for ECG-gated cardiac CTA for TAVR evaluation were candidates for inclusion into this study and were consecutively and prospectively enrolled if none of the following exclusion criteria were present: permanent pacemaker, the presence of a metallic foreign bodies with relevance for MRA, severe claustrophobia, denial of the MRA examination or incapability to remain in a supine position due to severe orthopnoea or reduced general state of health. Patients were recruited from March to June 2014.

CTA data acquisition

All CT examinations were performed using a second generation dual-source CT scanner (Somatom Definition Flash, Siemens Healthcare, Forchheim, Germany) with a temporal resolution of 75 ms. The contrast-enhanced examination consisted of a retrospective ECG-gated data acquisition of the aortic root followed by a non-gated aortofemoral high-pitch spiral dual-source acquisition. The ECG-gated data acquisition extended from the inferior margin of the heart to the carina to cover the aortic root in a caudo-cranial fashion. The examination was conducted with a dual phasic injection protocol with a total of 50 mL iodinated contrast agent (Imeron 400®, Bracco, Konstanz, Germany) divided into an initial bolus of 40 mL at 4 mL/s followed by 20 mL of a 50:50% mixture with NaCl at 4 mL/s. Injection via an 18-gauge needle in an antecubital vein was followed by a saline bolus chaser of 40 mL at 4 mL/s. Data acquisition was initiated 7 s after the attenuation of a region of interest placed in the left atrium reached 70 Hounsfield units (bolus tracking technique). For cardiac CTA, ECG-gated dose modulation was omitted to deliberately cover the entire cardiac cycle. Tube voltage and tube current time product were adapted to each patient using FASTCARE® (Siemens Healthcare). ECG tracings were recorded to determine heart rate and rhythm.

Cardiac CTA data were reconstructed at 5% steps throughout the cardiac cycle with a section thickness of 1 mm and an increment of 0.8 mm using a medium soft tissue convolution kernel (B26f). ECG editing was performed if necessary. All datasets were transferred to a dedicated post-processing workstation (Syngo Multimodality Workplace, Siemens Healthcare). Multiplanar reformations were used for aortic root measurements.

MRA data acquisition

All examinations were performed on a 3T system (Siemens Somatom Skyra, Siemens Healthcare, Erlangen, Germany). For the assessment of the aortic annulus, a T1-weighted RF-spoiled 3D gradient echo FLASH sequence with navigator respiration control and frequency selective fat saturation technique (SPAIR) was used. Data were acquired with TE = 1.54 ms, TR = 3.5 ms, bandwidth = 610 Hz/pixel, flip angle = 20°, parallel acquisition using GRAPPA with a reduction factor of 2, centric *k*-space reordering, matrix = 256 × 184 × 80, and a spatial resolution of 1.25 × 1.25 × 1.3 mm. Thirty-four *k*-space lines per cardiac cycle were acquired resulting in an acquisition window of 120 ms. The trigger delay controlling the start of data acquisition was set according to the temporal window where the ascending aorta and the aortic root were motionless during diastole. This window was determined from an axial time-resolved bSSFP scan at the level of the pulmonary trunk. The width of the navigator acceptance window was set to 6 mm. Depending on the ECG, patients were classified as being in sinus rhythm or arrhythmic at the time of examination.

Assessment of aortic root dimensions on CTA and MRA

MRA analyses were performed by two independent readers (T.K. and P.R. with 8 years and 1 year experience in cardiac MR imaging, respectively), blinded for the CTA data. Systolic and diastolic CTA measurements were conducted by a third reader (G.P. with 11 years experience in cardiac imaging).

As previously described, the aortic annulus was defined employing the concept of a virtual ring transecting through the most basal hinge points of all three aortic valve cusps.¹⁴ Using the coronal and sagittal oblique views, the corresponding double-oblique transverse view was adjusted to transect through the most caudal attachments of all three native cusps, defining the orientation and position of the virtual ring.

The cross-sectional annular area was assessed by means of planimetry, manually tracking the luminal contours on the double-oblique transverse plane (Figure 1). The distance to the right/left coronary ostium was assessed perpendicular to the annulus plane. The width of the sinus of Valsalva was assessed by averaging the three distances from each commissure to the opposing sinus.

For CTA, aortic annulus dimensions were assessed during systole (in specific, using the systolic reconstruction phase with the largest annulus dimension) and at mid-diastole (75% of the R-R interval). The difference between the maximal systolic area and the mid-diastolic area was calculated. The distances to the coronary ostia were assessed using diastolic image reconstructions. Owing to restraints of the employed technique, MRA data acquisition was limited to diastole, allowing for only one static diastolic measurement.

For MRA, annular area assessment and assessment of coronary ostia locations were additionally performed by a second observer independently blinded to CTA results.

Image quality assessment for 3D MRA

The subjective image quality of 3D MRA reconstruction at the level of the aortic annulus was graded by both observers in consensus using the following semi-quantitative 4-point scale: 4, excellent visibility and differentiation of the annulus contour; 3, good visibility of the annulus contour, minor blurring; 2, moderate delineation of the annulus contour, still diagnostic; however, further imaging techniques (e.g.

transoesophageal echocardiography) recommended; 1, poor delineation of the annulus contour not possible, non-diagnostic (Figure 2).

Assessment of annular calcifications

The degree of calcification of the aortic annulus was also assessed in a semi-quantitative fashion for MRA and CTA using a 4-point scale as described previously¹⁵: 1, mild calcification; 2, moderate calcification; 3, heavy calcifications; 4, massive calcifications protruding into the subannular lumen.

Hypothetical prosthesis selection

Hypothetical prosthesis sizing for the balloon-expandable Edwards SAPIEN 3 heart valve (Edwards Lifesciences, Irvine, CA, USA) was based on the cross-sectional area measurement employing an incremental but overlapping sizing regimen. The manufacturer's sizing recommendations were deliberately adapted to avoid annular area oversizing of $\sim >20\%$ and an area undersizing of $\sim >5\%$. Therefore, the sizing regimen was subdivided into seven groups (1–7) as illustrated in Table 1. Annular area dimensions ranging between 425–431 mm² (3) and 538–549 mm² (5) were regarded as borderline zones allowing for the choice of either adjacent prosthesis size (Table 1).

Hypothetical prosthesis sizing was performed for systolic CTA and diastolic MRA area measurements. As opposed to CTA, the 3D MRA sequence employed is not temporally resolved and provides only a static, diastolic 3D dataset. To account for the conformational and pulsatile changes between systole and diastole, the systolic annular MRA

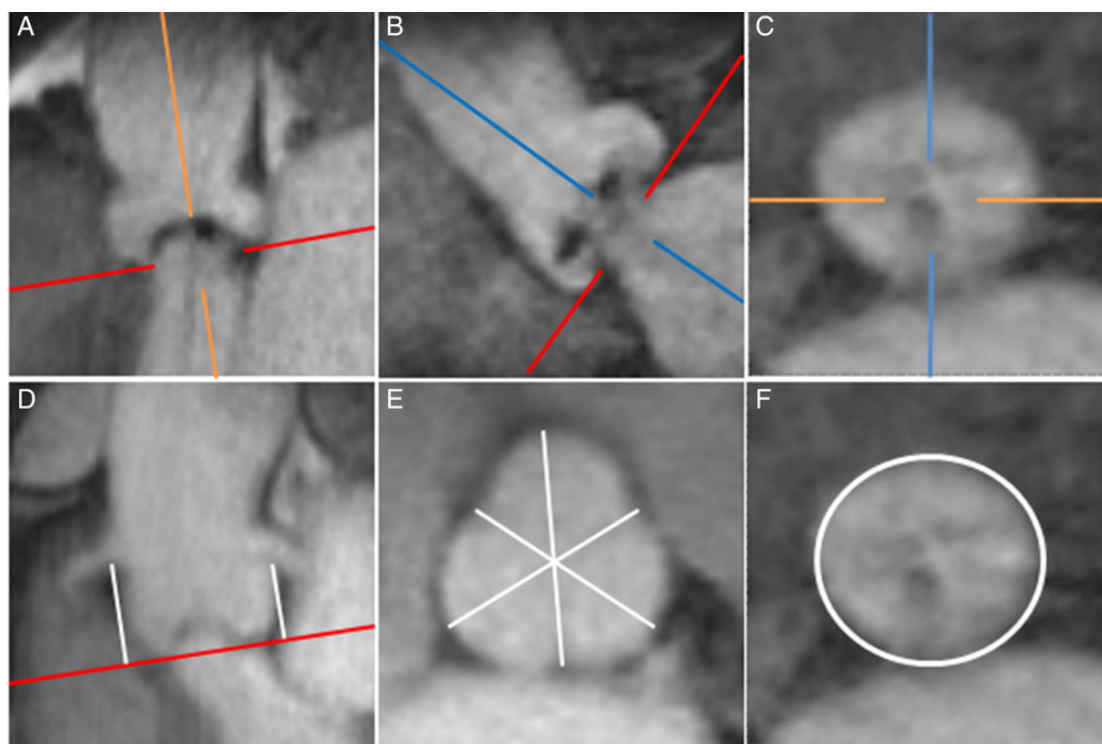


Figure 1 Non-contrast 3D-FLASH MRA: sagittal (A) and coronal oblique (B) views with the corresponding double-oblique transverse view (C) transecting through the most caudal attachments of all three native cusps. The distance to the right/left coronary ostium was measured perpendicular to the annulus plane (D). The width of the sinus of Valsalva was assessed by measuring the distance from each commissure to the opposite coronary cusp (E). The cross-sectional area is assessed by means of planimetry (F).

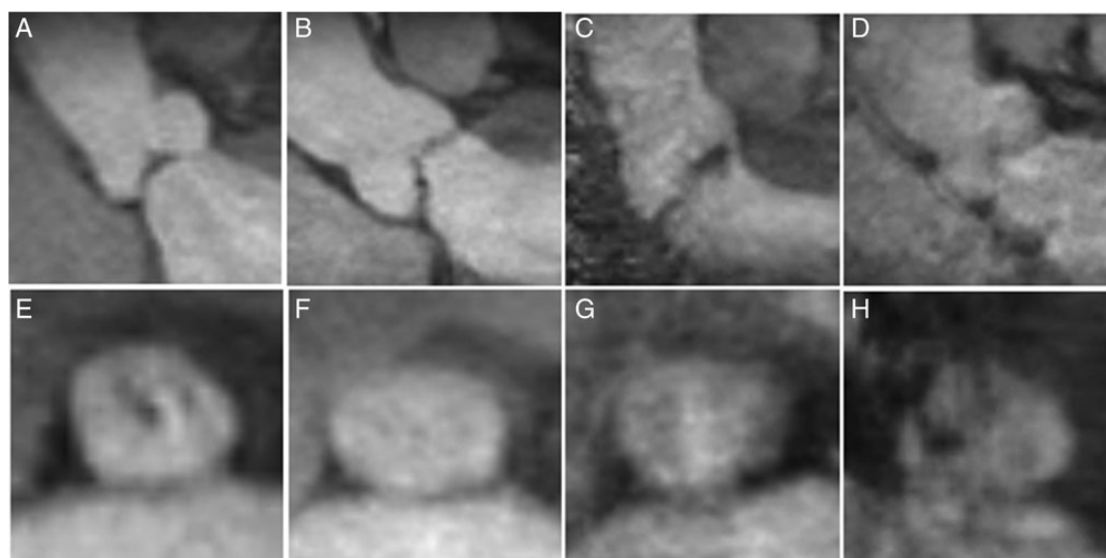


Figure 2 Non-contrast 3D-FLASH MRA: coronal (A–D) and double-oblique transverse views (E–H) exemplarily illustrating image quality grading by a semi-quantitative 4-point scale: 4 = excellent delineation (A and E); 3 = good image quality (B and F); 2 = moderate delineation of the annulus contour, still diagnostic; however, further imaging techniques required (C and G); and 1 = non-delineable annulus contour, non-diagnostic (D and H).

Table 1 Adapted sizing regimen for hypothetical prosthesis sizing for the balloon-expandable Edwards SAPIEN 3 heart valve based on annular area assessment

Group	1	2	3	4	5	6	7
3D annular area (mm ²)	<335	335–424	425–431	432–537	538–549	550–680	>680
23 mm prosthesis							
26 mm prosthesis							
29 mm prosthesis							

dimensions were modelled by adding the mean relative difference between systolic and mid-diastolic annular CTA dimensions of the entire cohort to the diastolic annular MRA dimensions measurements.

Prosthesis selection by systolic CTA was considered gold standard. Selection of the identical sizing category by MRA was considered as 'exact agreement'. Discrepancy of 1 sizing category was considered as 'extended agreement'. Discrepancies of ≥ 2 categories were considered as 'disagreement'.

Statistical analysis

All statistical analyses were performed using SPSS software (SPSS version 17.0, SPSS, Chicago, IL, USA). Continuous variables are distributed normally and are reported as mean and standard deviation. The differences between groups for categorical variables were tested with the χ^2 test. Categorical data are reported as frequencies and percentages. Pearson analysis, paired Student's *t*-test, and Bland–Altman analysis were performed for comparison of annular dimensions derived from MRA and CTA data. Observer agreement was calculated as an intraclass correlation coefficient (ICC). A *P*-value of <0.05 was considered statistically significant.

Results

Study population

During the 4-month period, a total of 104 patients with severe aortic stenosis (49 women, mean age 82.3 ± 5.6 years, mean aortic valve area 0.77 ± 0.16 cm²) had undergone an ECG-gated cardiac CTA for TAVR evaluation and were subsequently assessed for enrolment. MRA was not performed in 35 patients (34%) due to the following reasons: permanent pacemaker ($n = 12$), metallic foreign body ($n = 2$), severe orthopnoea ($n = 5$), claustrophobia ($n = 4$), reduced general state of health ($n = 8$), or refusal of the MRA examination ($n = 4$). Thus, MRA imaging was performed in 69 of 104 patients (66%, 34 women, mean age 81.8 ± 5.4 years). The mean time interval between CTA and MRA was 0.9 ± 1.4 days (range 0–4 days).

There were no statistical significant differences in baseline characteristics between patients who had undergone MRA and patients who had been excluded from MRA (Table 2). In the initially screened patient-cohort, 59 patients (56.7%) had moderately

impaired renal function (creatinine clearance >30 and <60 mL/min). Fifteen patients (14.4%) had severely impaired renal function (creatinine clearance <30 mL/min), of whom 10 patients (66%) underwent MRA.

MRA image quality

The mean total imaging time was 29 ± 6.1 min, including a mean imaging time of 14 ± 4.2 min for the 3D-FLASH acquisition. The mean subjective image quality was 3.1 ± 0.9 . Separate analysis of arrhythmic patients ($n = 26$, 37.7%) showed a mean image quality of 2.9 ± 0.8 . Two patients were rated as non-diagnostic, of whom one was in atrial fibrillation.

Aortic root dimensions

As anticipated there was a significant difference between mean diastolic and systolic CTA annular area measurements (430.0 ± 81.6 vs. 461.4 ± 83.9 mm², $P < 0.001$, Table 3). The mean diastolic annular area was not significantly different between MRA and CTA ($P = 0.27$). According to Pearson and Bland–Altman analyses, there was a positive correlation ($r = 0.966$, $P < 0.001$) and no

systematic difference [mean of differences 2.5 mm² (limits of agreement -42.8 mm²; 37.7 mm²)] between area measurements for diastolic MRA and CTA (Table 3). The mean difference between systolic and diastolic CTA annular area was 31.4 ± 16.2 mm². Hence, the corrective factor for modelled systolic MRA sizing was $+7.3\%$ (Figure 3). Employing this corrective factor there was no significant difference in mean annular area measurements between modelled systolic MRA and systolic CTA ($P < 0.001$). Again there was a positive correlation between modelled systolic MRA and systolic CTA mean annular area ($r = 0.956$, $P < 0.001$) with no systematic difference [mean of differences 3.1 mm² (limits of agreement -44.4 mm²; 38.2 mm²)] (Table 3).

There was no significant difference in the mean width of the sinus of Valsalva between diastolic CTA and diastolic MRA (32.1 ± 3.9 vs. 31.9 ± 3.6 mm, $P = 0.983$).

Excellent correlation ($r = 0.733/0.786$, $P < 0.001$) was found for the distance to the right or left coronary ostium between diastolic CTA and diastolic MRA (Table 3). Interobserver agreement for diastolic MRA annular area measurements as well as for the distances to the right and left coronary artery ostium was excellent (Table 4).

Assessment of annular calcifications

The mean degree of annular calcifications for CTA and MRA was 2.94 ± 0.6 and 2.85 ± 0.7 , respectively. Nine patients were classified as having massive calcifications (Grade 4) both by CTA and MRA (Figure 4). One patient exhibited mild calcifications on MRA, whereas all patients were at least classified as Grade 2 calcifications by CTA.

Hypothetical prosthesis sizing

Area-based prosthesis sizing showed exact agreement for diastolic MRA with systolic CTA in 43 of 67 patients (64.2%) and for modelled systolic MRA with systolic CTA in 55 of 67 patients (82.1%) (Figure 5). This was accompanied by a decrease in patients with extended agreement from 12 (17.9%) with diastolic- to 8 (11.9%) with modelled systolic MRA prosthesis sizing (Figures 4 and 5). Disagreement was found in 12 patients (17.9%) for diastolic MRA and in 4 patients (6%) for modelled systolic MRA-based sizing (Figure 5).

Thus, overall agreement (combined exact and extended agreement) for hypothetical prosthesis sizing improved from 55 of 67

Table 2 Baseline characteristics of in- and excluded patients

	Included patients (n = 69)	Excluded patients (n = 34)	P-Value
Age (years)	81.8 ± 5.4	83.6 ± 5.7	0.119
Male sex	35 (50.7%)	20 (57.1%)	0.536
Body mass index (kg/m ²)	27.5 ± 4.2	25.9 ± 4.9	0.101
Atrial fibrillation	26 (37.7%)	18 (51.4%)	0.179
Creatinin clearance (mL/min) ^a	51.7 ± 19.2	49.3 ± 16.3	0.520
Aortic valve area (cm ²) ^b	0.77 ± 0.16	0.78 ± 0.14	0.853
Logistic EuroSCORE (%)	12.99 ± 9.96	17.3 ± 15.0	0.114
STS score (%) ^c	5.07 ± 3.46	6.5 ± 4.0	0.090

^aCreatinin clearance calculated according to the Cockcroft–Gault equation.

^bAortic valve area by means of planimetry by transoesophageal echocardiography.

^cSociety of Thoracic Surgeons score.

Table 3 MRA and CTA measurements of the aortic annulus and the distances to the right and left coronary ostium

	MRA diastolic	CTA diastolic	Pearson correlation coefficient	Bland–Altman analysis	MRA systolic (modelled)	CTA systolic	Pearson correlation coefficient	Bland–Altman analysis
Annular area (mm ²)	433.5 ± 78.1	430.0 ± 81.6	0.966*	-2.55 ± 20.51	465.2 ± 83.9	461.4 ± 83.9	0.956*	-3.09 ± 21.06
Distance to the right coronary artery (mm)	15.4 ± 3.1	16.1 ± 3.0	0.733*	n.a.	n.a.	n.a.	n.a.	n.a.
Distance to the left coronary artery (mm)	13.6 ± 2.6	14.3 ± 2.7	0.786*	n.a.	n.a.	n.a.	n.a.	n.a.

Values are presented as mean \pm SD.

n.a., not applicable.

* $P < 0.001$.

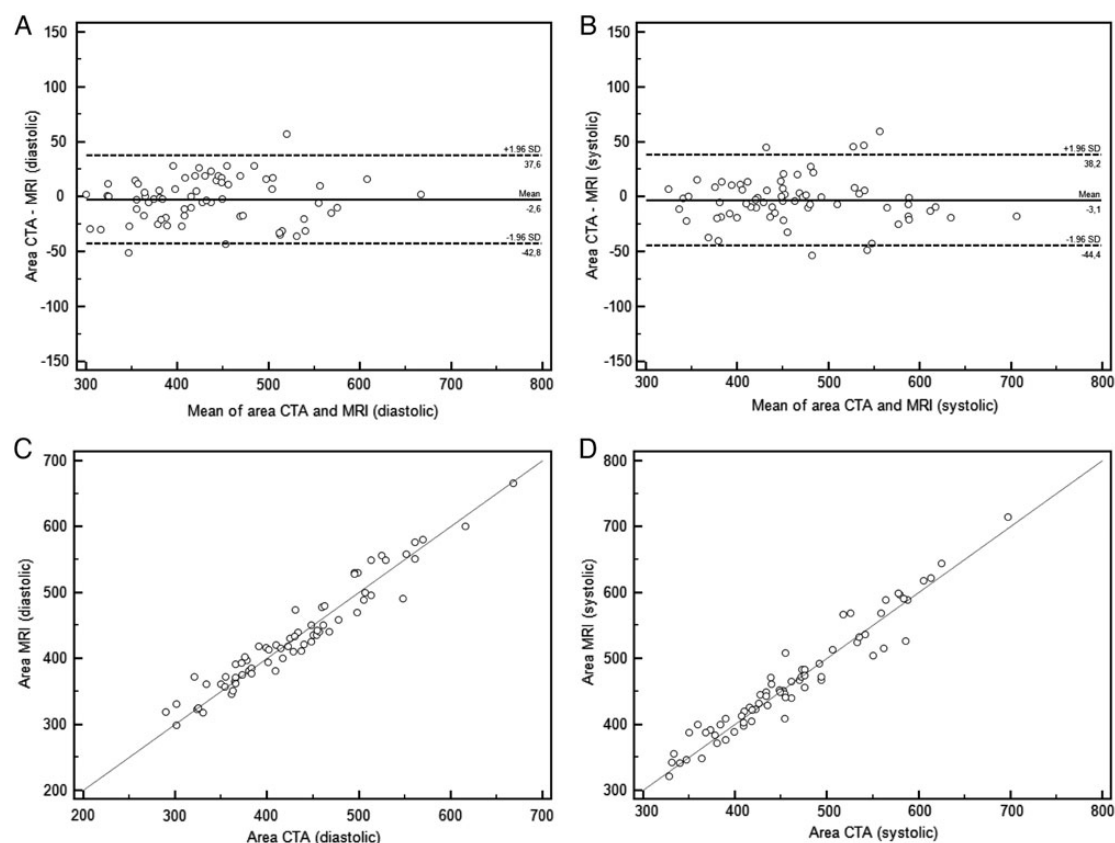


Figure 3 Bland–Altman plots (A and B) and Pearson correlations (C and D) confirm no significant differences of cross-sectional area measurements for diastolic MRA vs. CTA (A and C) and corrected systolic MRA vs. systolic CTA (B and D) measurements.

Table 4 Intraclass correlation coefficient and lower and upper limit of the 95% CI for interobserver variability

	ICC (95% CI)
Aortic annulus area (diastolic)	0.961 (0.937–0.976)
Distance right coronary artery	0.797 (0.667–0.876)
Distance left coronary artery	0.894 (0.828–0.935)

(82.1%) with diastolic- to 63 of 67 (94%) of the patients with modelled systolic MRA (Figure 5).

Discussion

The main findings of this study are:

- (1) As compared with the gold standard CTA assessment of aortic annulus dimensions can be reliably obtained with a non-contrast 3D MRA protocol in the majority of an all-comers pre-TAVR patient population.
- (2) Employment of a corrective factor allows to compensate for the pulsatile differences found between diastolic MRA and systolic

CTA measurements with regard to hypothetical prosthesis sizing.

Owing to its 3D-capacity CTA has evolved as the gold standard for assessing aortic root dimensions prior to TAVR.^{6,7} Accurate sizing of the aortic annulus is particularly important for choosing the correct prosthesis size, as over- or undersizing can lead to annulus rupture, device migration, or paravalvular regurgitation.^{6,7,16} This requires that patients with impaired renal function, who constitute a significant portion of these generally elderly patients, will be exposed to iodinated contrast material for pre-TAVR work-up. Likewise the majority of the patients eligible in this study showed moderate or severely impaired renal function.

To reduce the risk for contrast-induced nephropathy, efforts have been made to lower the amount of contrast media required for CTA.⁶ However, considering the cumulative amount of contrast media required for the complete TAVR process, any avoidance of contrast media exposure may be desirable. Although measurement of ascending aorta dimensions can be performed by non-contrast CT,¹⁷ clear delineation and measurement of the annulus CSA will be regularly prevented by the non-differentiable adjacent cardiac structures.

Here MRA offers a promising approach, as the aortic root can be visualized without the use of contrast media. However, as opposed

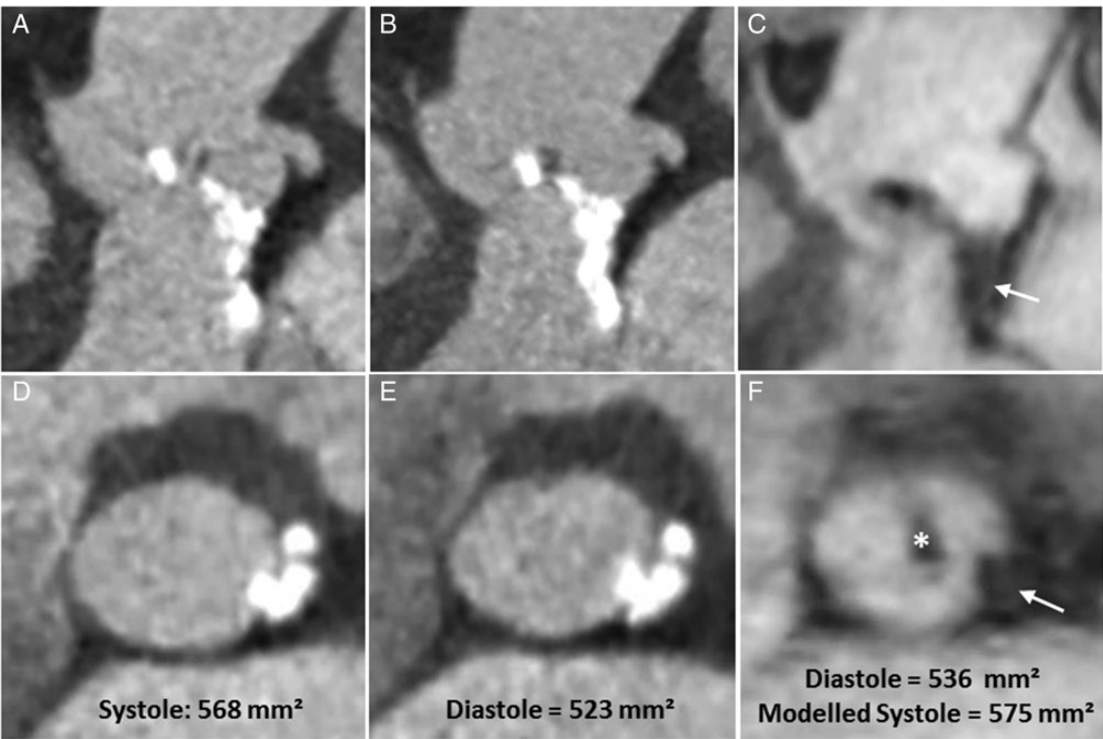


Figure 4 Contrast-enhanced retrospectively ECG-gated midsystolic CTA (A and D), diastolic CTA (B and E), and non-contrast 3D-FLASH MRA (C and F) in a 79-year-old woman with severe aortic stenosis (aortic valve area 0.4 cm²) evaluated for TAVR. Upper row, sagittal double-oblique reconstructions; lower row, transverse double-oblique reconstructions. Owing to pulsatile changes of the aortic annulus, the annular is larger during systole (D) when compared with diastole (CT, E; MRA, F). While hypothetical sizing by systolic CTA and diastolic MRA would result in different prosthesis size groups, a modelled systolic MRA area of 575 mm² would dissolve this difference. The large calcium deposits protruding into the annular (Grade 4) can equally be depicted by CTA and MRA (arrows, C and F). The central flow void (*) in the transverse MRA plane is caused by an accompanying moderate to severe aortic insufficiency (F).

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		Systolic CTA									
Modelled Systolic MRA	1	1									
	2	2	20		1						
	3		1	1	1						
	4			1	23	1	1				
	5					1	1				
	6				2	1	8				
	7										1

Figure 5 Comparison of hypothetical prosthesis sizing based on systolic CTA with sizing based on diastolic or modelled systolic MRA. Agreement is indicated by the green boxes whereas the group differences of ± 1 (extended agreement) or ± 2 (disagreement) are indicated by the yellow and red boxes, respectively.

to former studies employing 3D non-contrast MRA techniques for the thoracic aorta,^{10,11} the assessment of aortic annulus dimensions has only been evaluated using 2D techniques to date: Paelinck et al.¹⁸ demonstrated similar assessment of the aortic annulus dimensions when compared with transoesophageal echocardiography in 24 patients with severe aortic stenosis employing

repetitive 2D-bSSFP sequences. However, annulus assessment was performed by measuring the distance between the hinge points of the aortic valve cusps, thereby exhibiting the same drawbacks as 2D-echocardiography with regard to the non-circular shape of the aortic annulus which can be assessed more precisely by means of planimetry.¹⁴

Pontone et al.¹⁹ measured area derived diameters employing time-resolved bSSFP sequences at a 1.5 T system. However, when compared with our study, only 2D single-slice breath-held measurements with a lower spatial resolution (1.4 × 2.2 × 3 mm) were acquired. Thus, manifold 2D measurements are required to position the slices perpendicular to the aortic root long axis and to cover the entire aortic root. An improper positioning of the slices may result in deviations in the geometric assessment of the aortic root. Vice versa pulsatile movement of the aortic root structures may temporarily displace the annulus outside the 2D slice acquisition.¹²

Despite these limitations, the authors achieved a good agreement for 2D MR-based and CTA bases annular assessment. Although meanwhile other studies using cine- or gated-SSFP acquisitions reported more competitive resolutions of up to 1.2–1.4 mm,^{20,21} the disadvantages of a 2D-acquisition and the need for breath-holding remain. In the study by Pontone et al.,¹⁹ patients not able

to sustain a 10-s breathhold or with cardiac arrhythmias were excluded.

As bSSFP-based sequences are more prone to image artefacts at higher field strength, we deliberately used a gradient echo FLASH sequence. With this 3D-FLASH MRA acquisition, we achieved excellent agreement between diastolic CTA and diastolic MRA CSA and coronary distance measurements with good reproducibility as shown by a good interobserver agreement, most importantly within an unselected patient population.

To account for the drawback of a diastolic MRA data acquisition, we introduced a modelled systolic MRA sizing by adding a correction factor onto the diastolic MRA annular area measurement. In doing so, we were able to increase overall agreement for hypothetical prosthesis sizing in regard to systolic CTA from 82.1 to 94% of the patients. Most importantly, relevant disagreement as defined by a discrepancy of ≥ 2 sizing categories was only observed in 4 as opposed to 12 patients. Approximately 12% of patients exhibited a shift by only one sizing category using the modelled approach. We considered this an extended agreement, because given the deliberate integration of the borderline category into the sizing regime, a shift in one category does not necessarily result in a different prosthesis size, especially with the small range of the borderline zones. This reflects the true clinical scenario, as the interventionalist's prosthesis choice will not be solely based on a single measurement, but rather be influenced by various additional factors.

Overall image quality was excellent with 83.3% of the examinations rated as good or excellent even in the presence of cardiac arrhythmias, observed in 37.7% of the patients which is in line with previously reported trials.²² There are two main reasons for the robustness of our 3D-FLASH sequence: first the use of a respirator control system seems advantageous for patients with severe aortic stenosis that inherently present with shortness of breath. Secondly, the 3D-FLASH MRA sequence is less prone to a reduction of image quality in case of arrhythmias compared with continuously acquired data. Importantly, the mean image quality was rated only slightly lower in patients with atrial fibrillation compared with patients with sinus rhythm.

Yet, these technical benefits are at the expense of a longer mean acquisition time. Although the 3D-MRA data acquisition accounted for on average 14 min of the entire examination time. Although this, it was well tolerated by all patients further reduction of acquisition time would be desirable. In this context, radial acquisition techniques as recently employed for coronary-MRA might provide an option. Basically, the presented 3D MRA protocol allows systolic data acquisition in case an adequate length of a quiescent systolic window is provided. However, as this is only found in a minority of patients the aforementioned reduction of acquisition time could help to achieve this. In fact, it might then even be possible to acquire a short systolic and diastolic window parallel within one R-R interval, which would provide information about annular dynamism.

Additionally, we believe that the majority of our patients that were excluded due to severe orthopnoea or reduced general state of health would also have been unsuitable for less time consuming MRA protocols, such as those employing 2D-bSSFP sequences. Here, CTA with its fast acquisition time seems more appropriate. Overall we only had to exclude 18 patients (17% of all patients) due to strong contraindications such as a permanent pacemaker.

Thus, MRA is principally feasible in a large majority of this all-comers TAVR screening population. Although CTA radiation concerns are largely negligible in these elderly patients, the expected expansion of TAVR to younger patients might augment the interest in a radiation-free imaging modality.

Study limitations

Still, the overall inclusion rate of 66% in our study is relatively low. However, considering the elderly and frail patient population this might represent the true clinical scenario. Further technical improvements like faster acquisition times might though improve the number of patients eligible for this imaging technique.

Determination of the corrective factor was solely based on the CTA measurements in an elderly though TAVR typical patient population including various annulus shapes and sizes. However, it can be assumed that this corrective factor might not be deliberately applied to a different, e.g. younger patient population. For this purpose, future validation studies including different patient populations are warranted.

Evaluation of the calcium load of the aortic root is an important issue as calcifications of the aortic annulus and left ventricular outflow tract (LVOT) are associated with a higher degree of paravalvular regurgitation and an increased risk for aortic root rupture, respectively.^{19,23} Although MRA is associated with an inferior depiction of aortic valve calcifications¹⁹ when compared with CTA, we were able, unlike Pontone *et al.*, to achieve a comparable grading of the amount of annular calcifications for both techniques. However, despite our 3D technique, we were still limited to a rather simple semi-quantitative approach. Nevertheless, as the exact quantification of the calcium load is not required for TAVR planning, the equal detection of the extension of calcifications beyond the annulus margin and towards the LVOT with the 3D-FLASH MRA technique seems promising to filter patients at risk for annular rupture.

Even though annulus measurements can be obtained by non-contrast MRA, pre-TAVR assessment usually comprises visualization of the aortofemoral access route.²⁴ Although this could be accomplished by available non-contrast MRA angiography techniques,²⁵ the feasibility especially referring to the length of a combined non-contrast examination has yet to be investigated. Although we did not specifically evaluate the time for data analysis, we found this process to be comparable with a manually performed CTA aortic root assessment. Hence, this novel technique has easily been integrated into our clinical workflow.

In conclusion, when compared with CTA our non-contrast 3D-FLASH MRA protocol allows reliable assessment of aortic annulus dimensions and the grade of calcification even in the presence of cardiac arrhythmias. The implementation of this technique, which is applicable to the majority of an all-comers pre-TAVR population, could possibly reduce the risk for contrast-induced nephropathy.

Conflict of interest: J.L. and P.B. are consultants for Edwards Lifesciences Inc.

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