Dynamic characterization of aortic annulus geometry and morphology with multimodality imaging: Predictive value for aortic regurgitation after transcatheter aortic valve replacement

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Background: Patients undergoing transcatheter aortic valve replacement (TAVR), as compared with those undergoing surgical aortic valve replacement (AVR), have higher postprocedural aortic regurgitation (AR), associated with higher mortality. We hypothesized that reduced annular deformation is associated with higher postprocedural AR and sought to assess incremental value of assessment of aortic annular deformation in prediction of post-TAVR AR.

Methods: We included 87 patients with high-risk severe aortic stenosis (AS) (81 ± 10 years, 54% men) who underwent preprocedural echocardiography and contrast-enhanced (4-dimensional) multidetector computed tomography (MDCT) of the aortic root, followed by TAVR ($n = 55$) or surgical AVR ($n = 32$). On MDCT, minimal/maximal annular circumference, circumferential deformation (maximum-minimum over cardiac cycle), and eccentricity (largest/smallest diameter during systole) were calculated. Degree of commissural/annular calcification was graded semiquantitatively (scale 1-3). Oversizing/undersizing of the prosthesis during TAVR was assessed.

Results: Pre-AVR aortic valve area (0.6 ± 0.1 vs 0.6 ± 0.1 cm²), mean aortic valve gradient (46 ± 14 vs 45 ± 11 mm Hg), AR (1 ± 0.8 vs 0.9 ± 0.7), maximal annular circumference (8 ± 1 vs 7.9 ± 0.8 cm), annular deformation (0.3 ± 0.1 vs 0.3 ± 0.1 cm), eccentricity (1.2 ± 0.1 vs 1.2 ± 0.1), commissural (2.1 ± 0.6 vs 2 ± 0.7), and annular calcification scores (1.7 ± 0.8 vs 1.7 ± 0.8) were similar in TAVR and surgical AVR groups ($P =$ not significant). A higher proportion of patients had $\geq$ mild AR in the TAVR than in the surgical AVR group (58% vs 34%; $P < .03$). In TAVR patients, reduced annular deformation ($P = .01$) predicted postprocedural AR, in addition to prosthesis undersizing ($P = .03$) and higher annular calcification ($P = .03$).

Conclusions: Residual post-TAVR AR is predicted by reduced aortic annular deformity, higher annular calcification, and prosthesis undersizing. Pre-TAVR 4-dimensional annular assessment aids in prediction of post-TAVR AR. (J Thorac Cardiovasc Surg 2014;147:1847-54)

Video clip is available online.

Recent trials have established transcatheter aortic valve replacement (TAVR) as a viable alternative for patients with severe, symptomatic aortic stenosis (AS) and high operative risk.¹⁻⁴ In addition, it has been recently demonstrated that post-TAVR aortic regurgitation (AR) is associated with

worse outcomes.⁴ Because transcatheter implantation is performed without direct visualization of the device landing zone, preprocedural and intraprocedural imaging is critical,⁵ for which multimodality imaging (angiography, transthoracic/transesophageal echocardiography [TEE], and multidetector computed tomography [MDCT]) is routinely used.⁵ The procedural goal is secure, coaxial fit of the stent valve at the aortic annulus and root. Recent studies have examined imaging-derived predictors of procedural complications and specifically post-TAVR AR.⁶⁻⁸

We sought to assess whether patients undergoing TAVR had higher degree of postprocedural AR, compared to those undergoing surgical aortic valve replacement (AVR). Although it is known that aortic annulus geometry changes during the cardiac cycle,^{6,9,10} most of the data are derived from static images at a single cardiac phase. Recent advances in software technology allow advanced time-resolved 3-dimensional computed tomographic (CT) reconstructions (ie, 4-dimensional reconstructions), by integration and interpolation of multiple image sets along the cardiac cycle. We

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Abbreviations and Acronyms

AR	= aortic regurgitation
AS	= aortic stenosis
AVR	= aortic valve replacement
CT	= computed tomography
LVOT	= left ventricular outflow tract
MDCT	= multidetector computed tomography
TAVR	= transcatheter aortic valve replacement
TEE	= transesophageal echocardiography
VTI	= velocity time interval

hypothesized that a detailed geometric analysis of such data could provide insight into the impact of differences in aortic annular deformability in patients with AS. In turn, such an insight could improve our understanding of post-TAVR paravalvular AR.

METHODS

Eighty-seven consecutive patients with severe symptomatic AS, referred for evaluation for surgical versus percutaneous valve replacement, were included in this observational study. Severe AS was confirmed and severity was graded according to established echocardiographic guidelines.¹¹ Patients deemed to be at high surgical risk were included if they had undergone clinically indicated comprehensive echocardiography and contrast-enhanced MDCT of the aortic root at our institution within 1 week of each other. According to current protocols, we excluded patients with bicuspid aortic valve morphology.¹⁻⁴ Patients with advanced renal insufficiency or other contraindications to intravenous contrast dye were also excluded. The final population consisted of high-risk patients with severe AS who underwent either TAVR (n = 55) or conventional surgery (n = 32). Clinical, demographic, and imaging data were collected. Surgical risk was assessed and an additive EuroSCORE was calculated.¹² This observational study was approved by the institutional review board, with waiver of individual informed consent.

Preprocedural Transthoracic Echocardiography

Surface echocardiograms were obtained using commercially available systems (Siemens, Erlangen, Germany; General Electric, Milwaukee, Wis; and Philips, Best, The Netherlands). Left ventricular ejection fraction was calculated according to American Society of Echocardiography guidelines.¹³ Peak and mean transaortic valvular gradients were measured using continuous wave Doppler in standard views. Velocity time integrals (VTI) across the aortic valve (using continuous wave Doppler) and left ventricular outflow tract (LVOT; using pulsed wave Doppler) were recorded. LVOT diameter was measured from the parasternal long-axis during midsystole and LVOT area was derived. Aortic valve area was calculated using the continuity equation: $(LVOT\ diameter^2 \times 0.786 \times LVOT_{VTI}) / Aortic\ valve_{VTI}$. Degree of AR was recorded on a scale of I to IV, using multiple Doppler and 2-dimensional criteria. All measurements were performed according to guidelines.^{11,14}

MDCT Acquisition and Analysis

Image acquisition. All subjects were scanned on standard MDCT scanner (Definition Dual Source/Definition Flash, Siemens Medical Solutions, Erlangen, Germany; or Brilliance 256-slice, Philips Medical Systems, Best, The Netherlands) after administration of iodinated contrast (80-100 mL of Ultravist 370) at 4 to 5 mL/s followed by 30 to 50 mL of normal saline. Bolus tracking technique using a region of interest in the

ascending aorta was used, and scanning (from the carina to the mid left ventricle) was initiated in the craniocaudal direction during a single inspiratory breathhold. Spiral data were acquired with retrospective electrocardiogram gating using the following parameters: gantry rotation time = 270 to 330 ms; beam collimation ranging from 128×0.6 mm to 32×0.6 mm; tube voltage = 100 to 120 kVp; tube current adjusted per patient weight; and beam pitch of 0.2 to 0.5. Electrocardiogram-based tube current modulation was used for all patients, with maximum current turned on between 30% to 70% phases of the cardiac cycle (hence maintaining image quality during the systolic phases). For the remaining phases, the current was reduced. Images were reconstructed during 10 phases of the cardiac cycle with a section thickness of 0.75 mm. Radiation in the study sample was < 12 mSEV.

Image analysis. Advanced MDCT image processing was performed using Ziostation PhyZiodynamics software (Qi Imaging, Redwood City, Calif). Each volume of the 10-phase data set was deformably registered to both neighboring phases, using a cyclic method whereby the first and last series were considered neighbors. Subsequently, a noise reduction algorithm was applied followed by improvement in motion coherence using interpolation of 4 additional phases between the original phases based on the registered voxels. These first 2 steps resulted in a newly generated data set consisting of 50 phases. To generate the dynamic measurement data, the user activated a tool to define the aortic annulus to calculate the circumference and area, or the tool could be used to place 2 points to calculate a length. Aortic annular plane was defined on a double oblique reconstruction at the level of the virtual basal ring, as previously described.^{15,16} In cases of annular calcification, the annular tracing excluded areas of calcification from the measurements. All data was exported as .csv files and uploaded into Excel for statistical processing.

For the current study, the following parameters were measured (Figure 1 and Videos 1 and 2): maximal and minimal aortic annular circumference, delta annular circumference (maximum-minimum over the cardiac cycle, representing the deformation of the annulus through the cardiac cycle), maximal and minimal aortic annular area, delta annular area (maximum-minimum over the cardiac cycle), largest and smallest diameters of the aortic annulus (maximum and minimum measurements for both), delta annular diameters (maximum-minimum diameter over the cardiac cycle), and eccentricity index (ratio of largest to smallest diameter at 40% systolic phase). Using established valve circumference (72 mm for 23-mm and 82 mm for 26-mm prosthetic valve), percentage of prosthetic valve versus aortic annulus oversizing (positive percentage) and undersizing (negative percentage) was calculated using the following formula: $(\text{prosthetic valve circumference} / \text{annular circumference} - 1) / 100$.⁷ Additionally, degree of leaflet calcification was semiquantitatively assessed, using the following grades: 1: single lesion < 5 mm, 2: lesion > 5 mm, or affecting 2 leaflets, 3: severe calcification affecting 3 leaflets. Similarly, the degree of aortic annular calcification was assessed as follows: grade 1, 1 or several lesions < 5 mm; grade 2, 2 to 3 lesions > 5 mm; and grade 3, >3 lesions > 5 mm.

Surgical AVR, TAVR, and Intraprocedural TEE

For the purpose of this study, all echocardiographic measurements were remeasured by an experienced echocardiographer in a blinded manner. Surgical AVR was performed in a standard fashion under transesophageal guidance and general anesthesia. TAVR implantation (using the Edwards Sapien valve; Edwards Lifesciences, Irvine, Calif) was performed using general anesthesia and intraprocedural TEE as described.⁵ Annular size was reconfirmed using intraprocedural TEE on a zoomed long-axis midsystolic frame (hinge point to hinge point). Prosthetic valve size selection was performed as previously described⁵: 23-mm prosthesis for annuli measuring 18 to 21 mm and 26-mm prosthesis for annuli measuring 22 to 25 mm. By means of fluoroscopic and TEE guidance, the deployment of the prosthetic valve was ascertained, according to guidelines.¹⁷ Subsequently, positioning of the valve was retrospectively assessed on long-axis TEE

FIGURE 1. Four-dimensional multidetector computed tomographic image of the aortic annulus in a patient with severe aortic stenosis demonstrating various annular measurements including largest/smallest diameter, circumference, and area.

view and right anterior oblique projection of the intraprocedural cineangiogram. A ratio of valve depth below the annulus to total prosthetic valve length was measured in each patient. If the ratio was $\geq 60\%$, the device was considered malpositioned, according to published data.⁶

In both groups, degree and location (paravalvular vs central) of postprocedural AR was again ascertained on a scale of I to IV using multiple Doppler and 2-dimensional criteria, as described above. In addition, offline measurement of vena contracta (for paravalvular AR) was made in all patients.

Postprocedural Echocardiography

A postprocedural, predischarge echocardiogram was also performed in all patients, (typically postprocedural day 2-3) in a manner similar to

preprocedural echocardiography. Degree of AR (including paravalvular AR) was ascertained on a scale of I to IV, according to guidelines using multiple 2-dimensional, color and Doppler criteria.^{11,13,14} In addition, offline measurement of vena contracta (for paravalvular AR) was made in all patients.

Statistical Analysis

All values presented are the mean $\pm$ standard deviation for continuous variables and percentage for categorical variables. Two independent samples test was used to compare continuous variables. The χ^2 test was used for comparison of categoric variables. In addition, interobserver and intraobserver (A.M. and M.D.) reproducibility of various MDCT parameters (annular area and circumference) were measured using the Bland-Altman method. Receiver operator characteristic curve analysis was performed to test the association between dependent variable (post-TAVR AR) and continuous variable (potential predictors). Univariable logistic regression analysis was initially used to determine the association between dependent variable (residual post-TAVR AR) and potential predictors. Subsequently, predictors with a *P* value $< .05$ on univariable analysis were entered into the multivariable model. All *P* values were 2 sided. Data assembly statistical comparisons were performed with SPSS version 11.5 (SPSS Inc, Chicago, Ill).

RESULTS

Baseline Characteristics

The baseline clinical and echocardiographic characteristics of the total group, as well as the 2 subgroups, TAVR and high-risk surgical AVR, are shown in [Tables 1](#) and [2](#). All patients were symptomatic on maximally tolerated medical therapy. No patient had post-CT scan nephrotoxicity requiring dialysis. In all patients, the aortic valve disease was predominantly AS. There were no patients with severe mitral regurgitation. The baseline MDCT characteristics are shown in [Table 3](#). Intraobserver (A.M.) and interobserver (M.D.) reproducibility of minimal and maximal annular area was assessed using the Bland-Altman method ([Figure 2, A and B](#)).

TABLE 1. Baseline clinical characteristics of the study population

Variable	Total group (n = 87)	Surgical AVR (n = 32)	TAVR (n = 55)	<i>P</i> value
Age (y)	81 $\pm$ 10	84 $\pm$ 6	80 $\pm$ 11	.06
Male gender	47 (54%)	19 (59%)	28 (51%)	.3
Hypertension	70 (80%)	27 (84%)	43 (78%)	.3
Diabetes mellitus	29 (33%)	10 (31%)	19 (35%)	.5
Myocardial infarction	18 (21%)	7 (22%)	11 (20%)	.5
Stroke	22 (25%)	13 (41%)	9 (16%)	.01
COPD	26 (30%)	11 (36%)	15 (27%)	.3
Prior cardiac surgery	42 (48%)	17 (53%)	25 (45%)	.5
Beta-blockers	58 (57%)	25 (86%)	33 (60%)	.02
ACE inhibitors	40 (46%)	11 (40%)	29 (53%)	.2
NYHA class (I-IV)	3 $\pm$ 0.5	3 $\pm$ 0.6	3 $\pm$ 0.5	.9
BUN (mg/dL)	23 $\pm$ 8	22 $\pm$ 7	24 $\pm$ 9	.5
Creatinine (mg/dL)	1 $\pm$ 0.3	1.02 $\pm$ 0.6	1.01 $\pm$ 0.31	.5
Additive EuroSCORE	13.0 $\pm$ 1.8	13.3 $\pm$ 1.7	12.8 $\pm$ 1.8	.2

AVR, Aortic valve replacement; TAVR, transcatheter aortic valve replacement; COPD, chronic obstructive pulmonary disease; ACE, angiotensin-converting enzyme; NYHA, New York Heart Association; BUN, blood urea nitrogen.

ACD

TABLE 2. Baseline echocardiographic characteristics of the study population

Variable	Total group (n = 87)	Surgical AVR group (n = 32)	TAVR group (n = 55)	P value
LV ejection fraction (%)	51 ± 13	48 ± 14	53 ± 13	.1
LV end-diastolic dimension (cm)	4.7 ± 0.9	4.8 ± 1.1	4.6 ± 0.8	.4
LV end-systolic dimension (cm)	3.3 ± 1	3.6 ± 1.3	3.2 ± 1	.08
AV peak gradient (mm Hg)	78 ± 22	74 ± 18	79 ± 24	.3
AV mean gradient (mm Hg)	46 ± 13	45 ± 11	46 ± 14	.6
AV area (cm ²)	0.6 ± 0.1	0.62 ± 0.1	0.63 ± 0.1	.5
LV outflow tract diameter (cm)	1.96 ± 0.2	2.03 ± 0.1	1.92 ± 0.2	.02
AR (I-IV+)	1.0 ± 0.7	0.86 ± 0.7	1.1 ± 0.8	.2
MR (I-IV+)	1.3 ± 0.8	1.4 ± 0.7	1.2 ± 0.8	.2
TR (I-IV+)	1.2 ± 0.9	1.2 ± 0.9	1.2 ± 0.9	.9
RV systolic pressure (mm Hg)	43 ± 17	42 ± 15	44 ± 17	.5

AVR, Aortic valve replacement; TAVR, transcatheter aortic valve replacement; AV, aortic valve; LV, left ventricular; AR, aortic regurgitation; MR, mitral regurgitation; TR, tricuspid regurgitation; RV, right ventricular.

Postprocedural Findings in Surgical AVR and TAVR Groups

There were no intraprocedural deaths in either group. The predischarge echocardiographic findings are shown in Table 4. A significantly higher proportion of patients had postprocedural paravalvular AR (mild or more) in the TAVR than in the surgical AVR group (58% vs 34%; $P < .03$). Within the surgical AVR group, 2 patients had 2+ residual AR; the rest had mild (1+) AR. On the other hand, moderate or higher degree of postprocedural paravalvular AR was seen in 5 (9%) patients in the TAVR group. The paravalvular aortic regurgitant vena contracta was significantly higher in the TAVR group than in the surgical AVR group (2 ± 0.16 vs 1 ± 1.3 ; $P = .03$). Otherwise, there were no significant differences in the 2 subgroups.

Analysis of the TAVR Group

We further explored the imaging characteristics of the TAVR group (n = 55), separated into 2 subgroups on the basis of degree of paravalvular AR: (1) trivial AR, n = 23) and (2) at least mild AR (n = 32). The findings are shown in Table 5. There was a significantly higher degree of annular (but not leaflet) calcification in the nontrivial AR group as compared with the trivial AR group. The deformation of the annular circumference and area were significantly lower (suggesting a “stiffer” annulus) in the mild or more AR group as compared with the trivial AR group. A significantly higher proportion of patients in the nontrivial AR group had an undersized prosthetic valve, defined as a negative prosthetic valve to annular circumference ratio (74% vs 33%; $P = .004$). The eccentricity index was similar in

TABLE 3. Baseline MDCT characteristics of the study population

Variable	Total group (n = 87)	Surgical AVR group (n = 32)	TAVR group (n = 55)	P value
Minimal annular circumference (mm)	77 ± 9	76 ± 8	77 ± 10	.5
Maximal annular circumference (mm)	80 ± 9	79 ± 8	80 ± 10	.5
Deformation in annular circumference during cardiac cycle (mm)	3 ± 1	3 ± 1	3 ± 1	.7
Minimal annular area (mm ²)	445 ± 102	435 ± 89	450 ± 109	.5
Maximal annular area (mm ²)	482 ± 111	472 ± 98	488 ± 118	.5
Deformation in annular area during cardiac cycle (mm ²)	38 ± 17	37 ± 17	38 ± 17	.9
Minimal largest diameter (mm)	25 ± 3	25 ± 3	25 ± 3	.9
Maximal largest diameter (mm)	26 ± 3	26 ± 3	26 ± 3	.8
Deformation in largest diameter during cardiac cycle (mm)	1.2 ± 0.5	1.1 ± 0.6	1.3 ± 0.5	.2
Minimal smallest diameter (mm)	20 ± 3	20 ± 3	20 ± 4	.8
Maximal smallest diameter (mm)	21 ± 3	22 ± 3	21 ± 3	.8
Deformation in smallest diameter during cardiac cycle (mm)	1.2 ± 0.5	1.2 ± 0.7	1.2 ± 0.4	.8
Eccentricity index	1.2 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	.9
Commissural calcification	2.1 ± 0.7	2.0 ± 0.7	2.1 ± 0.6	.6
Annular calcification	1.7 ± 0.7	1.7 ± 0.8	1.7 ± 0.8	.9

MDCT, Multidetector computed tomography; AVR, aortic valve replacement; TAVR, transcatheter aortic valve replacement.

FIGURE 2. A, Bland-Altman graphs showing intraobserver variability for maximal and minimal aortic annular area (mm²). B, Bland-Altman graphs showing interobserver variability for maximal and minimal aortic annular area (mm²). SD, Standard deviation.

both subgroups. The deployment height was also similar in 2 subgroups. No patient had a malpositioned prosthesis, and none required a valve-in-valve procedure. On receiver operator characteristic curve analysis, the area under the curve for degree of annular circumferential deformation predicting mild or greater post-TAVR AR was significant (0.72; $P < .001$; Figure 3). A cutoff value of less than 3 mm for annular circumferential deformation had a sensitivity of 74% and specificity of 72% for prediction of nontrivial post-TAVR AR. Similarly, the area under the curve for degree of annular area deformation was also significant (0.69; $P < .001$).

Subsequently, we performed logistic regression analysis to test for predictors of nontrivial AR in the TAVR group. The results are shown in Table 6. On multivariable analysis, in addition to higher annular calcification and prosthesis undersizing, reduced annular deformation remained independent predictors of nontrivial AR. The results were similar when deformation of annular area was substituted for annular circumference. In the study population, only 5 patients in the TAVR group had moderate or more residual AR. Although the deformation of annular area during the cardiac cycle did not reach statistical significance, it was indeed lower (suggesting a trend toward a stiffer annulus) in

TABLE 4. Postprocedural echocardiographic characteristics of the study population

Variable	Total group (n = 87)	Surgical AVR group (n = 32)	TAVR group (n = 55)	P value
LV ejection fraction (%)	52 ± 11	49 ± 12	53 ± 11	.2
AV mean gradient (mm Hg)	22 ± 11	11 ± 6	11 ± 5	.9
AV peak gradient (mm Hg)	11 ± 6	23 ± 11	22 ± 11	.9
Aortic regurgitant vena contracta	0.19 ± 0.2	0.1 ± 0.1	0.2 ± 0.2	.03
Patients with more than trivial AR	34 (39%)	11 (34%)	32 (58%)	.03
MR (I-IV)	0.9 ± 0.6	1 ± 0.8	0.9 ± 0.5	.4
TR (I-IV)	1.2 ± 0.8	1.2 ± 0.9	1.2 ± 0.1	.9
RV systolic pressure (mm Hg)	40 ± 12	40 ± 11	40 ± 12	.9

AVR, Aortic valve replacement; TAVR, transcatheter aortic valve replacement; LV, left ventricular; AV, aortic valve; AR, aortic regurgitation; MR, mitral regurgitation; TR, tricuspid regurgitation; RV, right ventricular.

TABLE 5. Clinical and imaging characteristics of the TAVR group

Variable	Trivial AR (n = 23)	More than trivial AR (n = 32)	P value
Age (y)	79 ± 11	80 ± 11	.9
Gender (%)	12 (52%)	16 (50%)	.5
LV ejection fraction (%)	53 ± 13	52 ± 14	.9
Mean AV gradient (mm Hg)	48 ± 17	45 ± 12	.5
AV area (cm ²)	0.63 ± 0.1	0.64 ± 0.13	.7
LV outflow tract (cm)	1.9 ± 0.2	1.9 ± 0.2	.8
RV systolic pressure (mm Hg)	42 ± 15	46 ± 19	.4
Commissural calcification	2 ± 0.5	2.2 ± 0.7	.2
Annular calcification	1.4 ± 0.6	1.8 ± 0.02	.02
Deformation in annular circumference during cardiac cycle (mm)	3.6 ± 1.3	2.6 ± 0.8	.001
Deformation in annular area during cardiac cycle (mm ²)	46 ± 21	32 ± 10	.003
Deformation in largest diameter during cardiac cycle (mm)	1.4 ± 0.5	1.1 ± 0.4	.05
Deformation in smallest diameter during cardiac cycle (mm)	1.2 ± 0.5	1.2 ± 0.4	.6
Prosthetic valve to annular circumference sizing ratio (%)	−0.03 ± 7	−7 ± 10	.007
Eccentricity index	1.3 ± 0.2	1.2 ± 0.1	.3
Prosthetic valve position ratio	0.33 ± 0.1	0.34 ± 0.1	.7

TAVR, Transcatheter aortic valve replacement; AR, aortic regurgitation; LV, left ventricular; AV, aortic valve; RV, right ventricular.

the moderate-severe AR group as compared with the mild or lesser AR group ($32 \pm 9 \text{ mm}^2$ vs $38 \pm 9 \text{ mm}^2$; $P = .3$).

DISCUSSION

In the current study, we demonstrate that patients undergoing TAVR had a higher degree of paravalvular AR than did those undergoing surgical AVR. We demonstrate that reduced deformation (suggesting reduced compliance) of annular circumference was a predictor of nontrivial AR after TAVR. This association was independent of established predictors of post-TAVR AR (prosthetic valve undersizing and annular calcification, which have been previously described).^{7,8,18} The results were similar when deformation of annular area during the cardiac cycle was substituted for deformation of annular circumference. These results,

obtained with an advanced time-resolved (4-dimensional) analysis, provide important insights into the interaction between stent/valve and annulus and demonstrate the impact of device landing zone deformability on procedural outcomes. In the current study, neither aortic annular eccentricity nor position of valvular prosthesis vis-à-vis the annulus was associated with post-procedural AR.

The study population was typical of those undergoing evaluation followed by high-risk AVR (either TAVR or surgical). The study population was old with a relatively high proportion of conventional risk factors and a high EuroSCORE. Other than difference in the degree of postprocedural AR, there were no significant differences in the clinical and imaging characteristics of patients who underwent surgical AVR versus TAVR. The proportion of postprocedural AR in the surgical AVR group was higher than what has been reported previously; this is likely because of older population in the current study with higher degree of annular calcification.¹⁹ However, only 2 patients had moderate (2+) paravalvular aortic valve leak; the rest had mild (1+) residual AR.

During surgical AVR, sewing of the annulus on the valve ring forces the annulus into the shape required for a tight fit. In contrast, during TAVR, device deployment is associated with incompletely understood interaction between the expanding stent valve and the compliance of the landing zone. Not surprisingly, our data and prior studies demonstrate a higher proportion of AR in high-risk patients undergoing TAVR versus surgical AVR, despite similar baseline and imaging characteristics.⁴ Although, traditionally, moderate or severe AR has been thought to be associated worse outcomes, the presence of mild or more post-TAVR AR has assumed increased clinical significance since it was recently associated with worse outcomes.⁴

Post-TAVR AR is very likely related to an undersized stent valve or focal incomplete coaptation secondary to

FIGURE 3. Receiver operator characteristic curve analysis showing the area under the curve for ability of aortic annular circumferential deformability to predict mild or more aortic regurgitation in patients undergoing transcatheter aortic valve replacement.

TABLE 6. Univariable and multivariable logistic regression analysis evaluating the predictors of postprocedural aortic insufficiency in the TAVR group

Variable	Univariable		Multivariable	
	Wald statistic	P value	Wald statistic	P value
Age	0.006	.9		
Gender	0.03	.9		
Hypertension	0.42	.5		
Diabetes mellitus	0.4	.5		
Myocardial infarction	0.9	.3		
Beta-blockers	0.2	.7		
Preprocedural ejection fraction	0.005	.9		
LV end-diastolic dimension	1.17	.3		
LV end-systolic dimension	0.05	.8		
Diastolic dysfunction	0.69	.4		
Mean AV gradient	0.56	.5		
AV area	1.11	.6		
Preprocedure AR	2.9	.09		
Commissural calcification	1.12	.3		
Annular calcification	4.9	.03	4.4	.03
Eccentricity index	1.12	.3		
Deformation of annular circumference during cardiac cycle	8.99	.003	6.6	.01
Valve prosthesis: size 23 or 26	1.7	.2		
Prosthesis position ratio	0.14	.7		
Prosthesis to annular circumference sizing ratio	6.5	.01	4.3	.03
Postprocedural ejection fraction	0.02	.9		

When deformation of annular area was entered into the model instead of circumference, the results were similar. TAVR, Transcatheter aortic valve replacement; LV, left ventricular; AV, aortic valve; AR, aortic regurgitation.

deviation from a perfect circular postprocedural anatomy (owing to reduced deformation and/or annular calcification). An expanding literature demonstrates that undersizing can be avoided with careful preprocedural measurements.^{7,8} In contrast, prediction of focal coaptation is more difficult, in particular because of the complex and dynamic shape of the annulus and concomitant annular calcification. Multiple prior studies have demonstrated the oval shape of the annulus,^{16,20,21} and recent studies have shown that the aortic annulus geometry changes during the cardiac cycle.^{6,9,10}

Multiple studies have examined imaging-derived predictors of procedural complications and specifically postprocedural AR.⁶⁻⁸ They have demonstrated that annular calcification and valve undersizing are important contributors of residual post-TAVR AR. However, none of these studies has systematically evaluated dynamic deformation of the aortic annulus. Recent advances in software technology allow advanced high temporal resolution time-resolved 3-dimensional CT reconstruction (ie, 4-dimensional reconstruction) by integration and interpolation of multiple image sets along the cardiac

cycle. With this approach, our results, for the first time, demonstrate that annular deformability has an impact on postprocedural AR. The differences in annular deformity in patients with significant versus nonsignificant post-TAVR AR were subtle, likely because of the homogeneity of the study population (all were older high-risk AS patients). To demonstrate differences in deformability, we need to study patients with a wider spectrum of age and disease severity to establish thresholds of normal values of deformation of the aortic annulus. Once the thresholds are established, they could be used to identify patients who have a stiffer annulus (less deformability), which could help predict post-TAVR AR. Another potential utility is probably to help design future stents that are more malleable and confirm to the dynamic nature of the annulus.

Limitations

This is a small observational study of patients who were able to have a contrast-enhanced CT scan followed by AVR. Hence, there is insufficient power to evaluate hard outcomes. As an initial step, we wanted to ascertain that there indeed was a higher prevalence of AR in the TAVR as compared with the surgical group. As a result, we report data on both surgical and TAVR groups, followed by a detailed analysis of the TAVR group. The concept of 3-dimensional assessment of the aortic annulus is a rapidly evolving one. When the current study population was imaged, the standard of care was to use 2-dimensional echocardiography (obtained on surface echocardiography and subsequently confirmed by TEE in the catheterization laboratory) to obtain annular measurements and decide on appropriate valve size. It is only recently that 3-dimensional measurements have become more prevalent. As a result, those were not uniformly available and, hence, not reported. Annular calcification was performed semiquantitatively, rather a calcium score (which is not validated in contrast-enhanced studies). In older TAVR patients, iodinated contrast is associated with increased risk of nephrotoxicity. However, in the current study, no patient had significant post-CT scan nephrotoxicity. Although MDCT is also associated with significant radiation exposure, the risks of long-term deleterious effects of radiation are of lesser concern in older TAVR patients. As a result, a reasonable compromise would be to avoid radiation dose modulation to maintain optimal image quality. Still, for the MDCT community, it is important to continue to work on minimizing radiation exposure. With availability of newer imaging techniques, the concept of aggressive radiation reduction is rapidly evolving. We divided postprocedural AR into trivial and nontrivial, with nontrivial defined as AR equal to or greater than mild. This definition appears controversial, inasmuch as current clinical practice typically differentiates between mild and significant (ie, $\geq$ III+) AR. However, this may not apply to TAVR, inasmuch as recent studies demonstrate that presence of nontrivial, post-TAVR AR was associated with increased mortality.⁴

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CONCLUSIONS

In high-risk symptomatic patients with severe AS, there is a higher incidence of postprocedural nontrivial AR in the TAVR group as compared with the surgical AVR group. Using 4-dimensional MDCT imaging, we demonstrate that reduced deformation of annular circumference during the cardiac cycle, in addition to prosthesis undersizing and annular calcification, is an independent predictor of postprocedural AR. These results provide important insights into the interaction between the stent/valve and the aortic annulus and demonstrate the impact of device landing zone deformability on TAVR outcomes.

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