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 cm^2), 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 ≥ 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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Disclosures: Authors have nothing to disclose with regard to commercial support.

Received for publication March 4, 2013; revisions received April 25, 2013; accepted for publication May 31, 2013; available ahead of print July 17, 2013.

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0022-5223/$36.00

http://dx.doi.org/10.1016/j.jtcvs.2013.05.047

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: $(\text{LVOT diameter}^2 \times 0.786 \times \text{LVOT}_{\text{VTI}})/\text{Aortic valve}_{\text{VTI}}$. 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: (prosthetic valve circumference/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 described[5]: 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