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Deformation Dynamics and Mechanical Properties of the Aortic Annulus by 4-Dimensional Computed Tomography

Insights Into the Functional Anatomy of the Aortic Valve Complex and Implications for Transcatheter Aortic Valve Therapy

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Objectives The purpose of this study was to assess deformation dynamics and in vivo mechanical properties of the aortic annulus throughout the cardiac cycle.

Background Understanding dynamic aspects of functional aortic valve anatomy is important for beating-heart transcatheter aortic valve implantation.

Methods Thirty-five patients with aortic stenosis and 11 normal subjects underwent 256-slice computed tomography. The aortic annulus plane was reconstructed in 10% increments over the cardiac cycle. For each phase, minimum diameter, ellipticity index, cross-sectional area (CSA), and perimeter (Perim) were measured. In a subset of 10 patients, Young's elastic module was calculated from the stress-strain relationship of the annulus.

Results In both subjects with normal and with calcified aortic valves, minimum diameter increased in systole ($12.3 \pm 7.3\%$ and $9.8 \pm 3.4\%$, respectively; $p < 0.001$), and ellipticity index decreased ($12.7 \pm 8.8\%$ and $10.3 \pm 2.7\%$, respectively; $p < 0.001$). The CSA increased by $11.2 \pm 5.4\%$ and $6.2 \pm 4.8\%$, respectively ($p < 0.001$). Perim increase was negligible in patients with calcified valves ($0.56 \pm 0.85\%$; $p < 0.001$) and small even in normal subjects ($2.2 \pm 2.2\%$; $p = 0.01$). Accordingly, relative percentage differences between maximum and minimum values were significantly smallest for Perim compared with all other parameters. Young's modulus was calculated as 22.6 ± 9.2 MPa in patients and 13.8 ± 6.4 MPa in normal subjects.

Conclusions The aortic annulus, generally elliptic, assumes a more round shape in systole, thus increasing CSA without substantial change in perimeter. Perimeter changes are negligible in patients with calcified valves, because tissue properties allow very little expansion. Aortic annulus perimeter appears therefore ideally suited for accurate sizing in transcatheter aortic valve implantation. (J Am Coll Cardiol 2012;59:119–27) © 2012 by the American College of Cardiology Foundation

The challenges of transcatheter valve therapy have forced structural heart specialists to rediscover the complex anatomy of the aortic valve in all its intricate details (1,2). Although much was known for centuries (3), insight into the in vivo anatomy of the aortic valve complex—unavailable from surgical or pathological inspection of a non-beating heart—became possible only with modern 3-dimensional imaging techniques (4–10). Importantly,

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sizing for transcatheter aortic valve implantation (TAVI), unlike with surgical valve replacement, relies exclusively on cardiac imaging. Accurate assessment of the target anatomy, specifically the aortic annulus—its size, shape, and mechanical properties—is paramount to avoid complications such

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Abbreviations and Acronyms

CT = computed tomography

CSA = cross-sectional area

ECG = electrocardiogram

EI = ellipticity index

LV = left ventricular

Max = maximum diameter

Min = minimum diameter

Perim = perimeter

TAVI = transcatheter aortic valve implantation

as device dislodgment, perivalvular leakage, or annular rupture (10,11). In case of beating heart procedures like TAVI, assessing the dynamic aspects of functional anatomy, such as potential time-varying changes of the aortic annulus throughout the cardiac cycle, may be particularly important.

The purpose of the present study was therefore to investigate deformation dynamics and in vivo mechanical properties of the aortic annulus in patients with and without calcified aortic valves and to analyze the implications for the clinical practice of TAVI. Specifically, the major hypotheses of the study were as follows: 1) cyclic conformational changes of the anatomic structures that form the annulus will generate periodic variations in the degree of its ellipticity and thus its cross-sectional area and diameters; 2) mechanical properties of the annulus allow only minimal stretch under physiological pressures (if any), particularly in patients with calcified valves; and 3) aortic annulus perimeter will therefore, by continuity, remain stable throughout the cardiac cycle, despite changes in shape and area, and thus represents the most robust parameter for accurate sizing in TAVI.

These hypotheses were tested in a cohort of candidates for TAVI who underwent 4-dimensional computed tomography and compared with findings in subjects without evidence of cardiac disease.

Methods

Study population. The study group included 35 consecutive patients with symptomatic severe aortic stenosis evaluated with computed tomography (CT) before TAVI and 11 subjects without evidence of cardiovascular disease, initially referred to CT angiography to rule out coronary artery disease, who served as a control group (Table 1). The study was approved by the local institutional review board.

Acquisition protocol. All patients underwent CT angiography for evaluation of aortic annulus, aorta, and the iliofemoral arteries before TAVI using a 256-slice system (Brilliance iCT, Philips Healthcare, Cleveland, Ohio). Data were acquired with a collimation of 96 × 0.625 mm and a gantry rotation time of 330 ms. The tube current was 485 mA at 100 kV, the pitch value was 0.2, and the scan direction was cranio-caudal.

Intravenous injection of 60 to 90 ml of nonionic contrast agent (Iomeron 350, Bracco, Milan, Italy) at a flow rate of 5 ml/s was followed by a 30-ml saline chase bolus (5 ml/s). Automated peak enhancement detection in the descending aorta was used for timing of the scan. Data acquisition was automatically initiated at a threshold level of 100 Hounsfield units. Acquisition was performed during an inspiratory breath-hold while the electrocardiogram (ECG) was recorded simultaneously to allow retrospective gating of the data. For assessment of the aortic annulus, the 3-dimensional dataset of the contrast-enhanced scan was reconstructed at 10% increments over the cardiac cycle, generating a 4-dimensional CT dataset. All images were reconstructed with a slice thickness of 0.67 mm and a slice increment of 0.34 mm.

Subjects in the control group were scanned (according to the clinical indication) from the carina to below the diaphragmatic face of the heart. Because of the increased susceptibility of younger subjects to ionizing radiation, ECG-gated tube current modulation was used to minimize radiation exposure.

Assessment of the aortic annulus. The complete dataset was transmitted to a dedicated CT workstation (Philips, Extended Brilliance Workspace, version 4.5) to allow for multiplanar reformations. The aortic annulus was defined as the virtual circumferential connection of the aortic leaflets' basal attachments (virtual basal ring) (1,2). Accordingly, the standard coronal and sagittal views were used for initial orientation and definition of the lowest point of attachment of the aortic leaflets (11) to generate double-oblique axial images of the aortic annulus, as shown in Figure 1. The following measurements were performed at each 10% phase of the cardiac cycle (Fig. 1): Minimum diameter of the aortic annulus (Min), maximum diameter (Max), cross-sectional area (CSA), and perimeter (Perim). Ellipticity index (EI) was calculated as the ratio of Max to Min. In order to minimize measurement error, the aortic annulus plane was reconstructed in 1 phase, and the same multiplane reformations were used for measurements throughout all other phases (with slight adjustments to account for motion of the left ventricle during long-axis contraction, as necessary).

Calculation of Young's elastic modulus. In a subgroup of 10 patients, left ventricular (LV) pressure tracings before TAVI were analyzed by dividing them into 10 equal intervals between 2 consecutive R waves on the ECG. LV pressures and perimeters at corresponding phases of the cardiac cycle were related to derive the Young elastic modulus. Because invasive pressure measurements and CT could not be performed simultaneously, only patients whose heart rate differed <10 beats/min between CT examination and invasive pressure measurements, and whose systolic

Table 1 Baseline Characteristics of Study Population

	Patients With Aortic Stenosis	Normal Subjects
Age, yrs	80.1 ± 7.4	56.2 ± 11.8
Male	16 (46)	5 (11)
BMI, kg/m^2	28.1 ± 4.7	29.1 ± 8.0
BSA, m^2	1.86 ± 0.25	1.87 ± 0.22
CAD	12 (34)	0 (0)
Previous MI	7 (20)	0 (0)
Previous CAGB	6 (17)	0 (0)

Values are mean ± SD or n (%).
BMI = body mass index; BSA = body surface area; CABG = coronary artery bypass grafting; CAD = coronary artery disease; MI = myocardial infarction.