Aortic stenosis is a common disorder. Aortic valve replacement is indicated in symptomatic patients with severe aortic stenosis, as the prognosis of untreated patients is poor. Nevertheless, many patients pose a prohibitively high surgical risk and are not candidates for surgical valve replacement. Transcatheter aortic valve implantation (TAVI) is a novel method to treat selected high-risk patients with aortic stenosis. Patient screening and anatomic measurements of the aortic root are of great importance to ensure procedural success and appropriate patient selection. Multidetector computed tomography (CT) is playing an increasingly important role in patient screening protocols before TAVI, provides detailed anatomic assessment of the aortic root and valve annulus, assesses the suitability of iliofemoral access, and determines appropriate coaxial angles to optimize the valve implantation procedure. Additionally, CT is providing a greater understanding of medium-term valve durability and integrity. This review outlines an evolving role for CT angiography in support of a TAVI program and describe step by step how CT can be used to enhance the procedure and provide a practical guide for the utilization of CT angiography in support of a transcatheter aortic valve program. (J Am Coll Cardiol Img 2011;4:416–29) © 2011 by the American College of Cardiology Foundation

Aortic stenosis is a common disorder that affects nearly 5% of persons >75 years of age (1). Aortic valve replacement is indicated for symptomatic patients with severe aortic stenosis, as the prognosis of untreated patients is poor (2). Nevertheless, many patients with symptomatic severe aortic stenosis do not undergo surgical valve replacement, which has been attributed to comorbidities (3). Transcatheter aortic valve implantation (TAVI) is a novel method to treat selected high-risk patients with aortic stenosis (4–7). As of early 2010, >15,000 procedures have been performed worldwide, mostly confined to patients at high surgical risk. Thus far, short- and medium-term outcomes have been encouraging (4,6,8).

Recently, the landmark PARTNER B (Placement of AoRTic TraNscaTheter Valve) trial was published (9) in which 358 patients with aortic stenosis were considered too high risk for...
standard surgery were randomly assigned to medical management (including balloon aortic valvuloplasty) versus TAVI. This multicenter study showed a 20% absolute reduction in 1-year all-cause mortality in the TAVI cohort as compared with the standard of care (30.7% vs. 50.7%, respectively; p < 0.001), establishing that transfemoral TAVI is superior to conservative therapy in this patient population of high-risk patients, and defining a new treatment option.

Procedural Overview and Background

Two TAVI systems have seen wide clinical application: the balloon-expandable Edwards Sapien valve (Edwards Lifesciences, Irvine, California), and the self-expandable CoreValve ReValving system (Medtronic, Minneapolis, Minnesota) (Figs. 1A and 1B). Both systems have been extensively described elsewhere (10–12). The native valve can be approached using a retrograde transarterial technique (generally using the femoral or subclavian arteries), or using an anterograde transapical technique. Balloon aortic valvuloplasty is initially performed to facilitate passage of the valve prosthesis through the stenotic native valve. Subsequently, the unexpanded valve is appropriately positioned within the native aortic valve. The Edwards Sapien valve (Edwards Lifesciences) is expanded by a balloon during burst ventricular pacing to minimize cardiac output and prevent migration of the valve during deployment. The CoreValve (Medtronic) is self-expanding and is generally deployed without pacing.

Optimal positioning of the transcatheter aortic prosthesis is paramount to procedural success, as the goal is to displace the native valve leaflets and deploy within the native valve annulus. If valve deployment is too high, there is increased risk of aortic injury, paravalvular regurgitation, or embolization into the aorta (13). Conversely, if deployment is too low, there is increased risk of mitral valve dysfunction, heart block, paravalvular regurgitation, or embolization into the left ventricular cavity (14).

The relatively large delivery catheters currently required for valve implantation using the transfemoral route have been associated with attendant vascular complications, and limit the number of patients who are candidates for this technique. Recent technological efforts have culminated in significantly lower profile delivery systems requiring 18-F sheaths (outer diameter of approximately 7 mm), and include the Edwards NovaFlex and CoreValve third-generation devices. These smaller catheters may reduce vascular complications and expand patient eligibility for the procedure. Routine screening with multidetector computed tomography (MDCT) to determine the feasibility of the transfemoral approach permits identification of patients who may be candidates for these lower profile systems.

Whether a femoral, subclavian, or apical approach is used, accurate measurements of the aortic annulus are important in patient selection and proper implantation, as existing valves are designed for specific annular sizes. Unlike with surgical aortic valve replacement, where sizing occurs under direct visualization and using a sizing probe, aortic annulus measurements

---

**Figure 1. Edwards Sapien XT Valve and Medtronic CoreValve**

(A) Edwards Sapien XT valve. The balloon expandable valve stent frame is composed of cobalt-chromium, with bovine pericardial leaflets. (B) Medtronic CoreValve. The self-expanding valve stent frame is composed of nitinol, with porcine pericardial leaflets.

---

---

**ABBREVIATIONS AND ACRONYMS**

- **CT** = computed tomography
- **ECG** = electrocardiography
- **LAO** = left anterior oblique
- **MDCT** = multidetector computed tomography
- **RAO** = right anterior oblique
- **TAVI** = transcatheter aortic valve implantation
- **TEE** = transesophageal echocardiography
- **TTE** = transthoracic echocardiography
- **3D** = 3-dimensional
- **2D** = 2-dimensional
for TAVI rely exclusively on imaging. Annulus measurements are typically performed using 2-dimensional (2D) transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), or calibrated aortic angiography—with comparison between methods limited and controversial (12,15).

One limitation of both 2D TTE and TEE is that they provide a diameter measurement based on a single annular plane, and assume a circular annular orifice. In fact, the annulus is a complex structure that is often oval in shape (16,17). There has been significant interest in better defining the shape and size of the annulus by alternate imaging methods. Three-dimensional (3D) TEE has reported larger annular sizes than observed using traditional 2D TEE (16,17). Electrocardiography (ECG)-gated MDCT is typically performed in patients before TAVI implantation, and can also be used to measure the annular size in addition to evaluating access sites (16,17). Interestingly, the annular size by MDCT is typically larger than when measured with either 2D or 3D TEE (16,17).

In current clinical practice, however, patient eligibility for transcatheter valve therapy and sizing of the prosthesis is largely based upon the aortic annulus measurements on TTE and TEE, as this has traditionally been used for TAVI and existing results suggest good outcomes. Nevertheless, many investigators also consider the annular size by MDCT in the evaluation of patients (16,17). At present, there are specific annular size limitations for TAVI. For the Edwards Sapien valve (Edwards Lifesciences), the annulus must measure between 18 mm and 25 mm; for the current generation of CoreValve (Medtronic), the annulus must range between 20 mm and 27 mm.

### Integrating MDCT Into a TAVI Program

Successful integration of CT requires a multidisciplinary team approach similar to every component of a TAVI program. Simple reporting of findings and measurements may result in confusion and error. At our center, we routinely review all pertinent data in a collaborative rounds format for all patients being considered for TAVI. The measurements and data are reviewed, but additionally, the images are reviewed as well. We find that by having the interventionalist, echocardiographer, and CT reader all present for review of images reduces the likelihood for error in evaluation and communication. Static measurements of iliofemoral diameter or of the basal ring of the aortic root rarely tell the whole story, and we have observed that this combined image review has altered patient management in approximately 10% of patients.

**MDCT acquisition protocol.** There are a number of scan protocols for TAVI assessment. At minimum, an MDCT scanner with 64-detectors is recommended for image acquisition. While a proportion of patients with severe aortic stenosis may already be established on beta-blockers, we do not routinely provide additional beta-blockade at the time of scanning, even with higher heart rates. We recommend retrospective gating to allow more latitude in image reconstruction, which is particularly important given the high incidence of arrhythmia in patients eligible for TAVI. This technique does result in rather high estimated radiation dose, which is accepted given the advanced age and multiple comorbidities of the patients being considered for TAVI. Also, systolic phases are highly informative, allowing valve area measurements and annular assessment in a phase of the cardiac cycle similar to echocardiographic studies. Alternatively, an axial acquisition triggered during a systolic phase of the cardiac cycle may also be considered. At our institution, we have experience using 2 scanner platforms: a single source high-definition 64 detector scanner (HD750 Discovery, General Electric, Milwaukee, Wisconsin) (Table 1) and a first-generation dual-source CT scanner (Somatom, Siemens Medical, Erlangen, Germany) (Table 2).

### How to Analyze CT Data for TAVI

Whether measuring the annulus, evaluating root geometry, or interrogating post-implanted aortic

---

**Table 1. Single Source, High-Definition Scanner**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ECG-Gated CTA Thorax and Abdomen</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG gating</td>
<td>Retrospective with ECG dose modulation</td>
</tr>
<tr>
<td>Collimation, mm</td>
<td>64 × 0.625</td>
</tr>
<tr>
<td>Section acquisition, mm</td>
<td>0.625 mm</td>
</tr>
<tr>
<td>Tube voltage, kV</td>
<td>100 unless BMI &gt;30 kg/m²</td>
</tr>
<tr>
<td>Tube current</td>
<td>BMI based</td>
</tr>
<tr>
<td>Rotation time, ms</td>
<td>330</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.25–0.35 (depending on heart rate)</td>
</tr>
<tr>
<td>Scan direction</td>
<td>Craniocaudal</td>
</tr>
<tr>
<td>Iterative reconstruction</td>
<td>40% ASIR</td>
</tr>
</tbody>
</table>

ASIR = adaptive statistical iterative reconstruction; BMI = body mass index; CTA = computed tomography angiography; ECG = electrocardiography; HDCT = high-definition computed tomography.
valves, the CT data are typically evaluated in a similar fashion. All data are transferred to an offline post-processing workstation (such as Advantage Workstation 4.4, General Electric), and analyses are performed using dedicated software (such as CardIQ X-Press, General Electric). The data are loaded into a standard multiplanar cardiac reformat package with images reconstructed in the coronal, sagittal, and transverse (axial) orientation, and then analyzed using a multiplanar oblique tool. By convention, we begin the post-processing and analysis in the coronal plane with an axial cutplane rotated in an anticlockwise direction so that the line runs from a right caudal to a left cranial position. After ensuring that the various imaging planes are locked, attention is turned to the sagittal reconstruction, which is vertically oriented so as to be orthogonal to the long axis of the aortic annulus. At this point, the horizontal line representing the axial cutplane is moved up or down on either the sagittal or coronal projection so as to create a double oblique transverse or axial image of the aortic root. This horizontal line is pulled down through the root of the aorta until the

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ECG-Gated CTA Thorax</th>
<th>Aortoiliac CTA Below Diaphragm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECG gating</td>
<td>Retrospective ECG gating</td>
<td>Helical non gated</td>
</tr>
<tr>
<td>Collimation, mm</td>
<td>2.0 x 32.0 x 0.6</td>
<td>32.0 x 0.6</td>
</tr>
<tr>
<td>Section acquisition, mm</td>
<td>2.0 x 64.0 x 0.6</td>
<td>64.0 x 0.6</td>
</tr>
<tr>
<td>Tube voltage, kV</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Tube current–time product, mAs per rotation</td>
<td>320 160</td>
<td>240</td>
</tr>
<tr>
<td>Rotation time, ms</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>Pitch</td>
<td>0.2–0.43</td>
<td>0.7</td>
</tr>
<tr>
<td>Scan direction</td>
<td>Craniocaudal</td>
<td>Craniocaudal</td>
</tr>
</tbody>
</table>

Abbreviations as in Table 1.

Figure 2. Reconstructing a Double Oblique Transverse Image of Basal Ring

(A) On a coronal projection of the aortic root, a vertically orient oblique tool is placed to produce a sagittal oblique reconstruction of the ascending aorta. (B) A transverse or axial cut-plane is placed on the sagittal reconstruction at the level of the aortic valve hinge point. (C) This transverse cut-plane yields a double oblique transverse image of the aortic root. (D) The dataset is then scrolled up or down until the most caudal attachments of the aortic valve are identified. Importantly, the nadir of all 3 cusps must be identified on 1 transverse image to ensure the appropriate plane for assessment of the aortic annulus. At this point, both short (minimum) and long (maximum) dimensions can be obtained.
most caudal attachments of the 3 aortic leaflets are identified. Importantly, to define the basal ring and provide accurate measurements, the plane must be balanced so that all 3 leaflets come in to view when scrolling cephalad at the same time. If this is not the case, the CT physician must alter the angle of the oblique tools in either the sagittal plane or coronal plane. When the inferior aspect of all 3 aortic cusps are identified in the same plane, a true double oblique transverse image of the root has been achieved, and the correct plane for the majority of measurements germane to TAVI has been obtained (Fig. 2).

Although CT is a robust 3D measuring tool, it is not without limitations. The temporal resolution of cardiac CT, particularly on single-source platforms, can result in suboptimal image quality at higher heart rates. Moreover, severe valve calcification may obscure annulus assessment, particularly the determination of the appropriate angle of deployment. It is imperative that the CT interpreting physician describe these limitations when encountered, and describe the overall image quality as with any CT examination. At our center, a comment about overall image quality and the quality of the assessment of the annulus is the first statement in any TAVI CT report.

The Aortic Annulus: What We Have Learned and How We Measure It

The aortic annulus is a complex 3D structure. Previous anatomic studies have well established that the aortic annulus is a 3-pronged coronet rather than a circular structure, with 3 anchor points at the nadir of each aortic cusp (18). The attachment of the aortic cusps is semilunar, extending throughout the aortic root from the left ventricle distally to the sinotubular junction. Further, the annulus is often oval shaped, which has been observed using both 3D TEE (13) and MDCT (17,19). Tops et al. (17) reported that the annulus had an oval configuration in approximately 50% of patients evaluated for TAVI, with a mean difference between coronal and sagittal measurements of 3.0 ± 1.9 mm. An oval configuration of the annulus was also noted by Delgado et al. (20), who reported a significant difference between mean coronal (25.1 ± 2.4 mm) and sagittal (22.9 ± 2.0 mm) measurements in 53 patients with severe aortic stenosis. This oval geometry of the annulus has been previously underappreciated on imaging but has been well described in the surgical literature.

There have been a number of published methods for measurement of the aortic annulus on MDCT. Initial published reports had evaluated the annulus in a coronal and sagittal fashion (Fig. 3). Recently, the annulus has been evaluated by using a 3-chamber reconstruction that replicates the parasternal long axis acquired from TTE and TEE (19) (Fig. 4). In addition, double oblique transverse imaging orthogonal to the aortic root incorporating the maximal and minimal diameter measurements of the basal ring below the hinge point of the aortic valve cusps are taken, with some groups reporting a mean of these 2 measurements (Fig. 5) (19,21). It is often useful to include bidimensional measurements of the basal ring as well as a 3-chamber measurement that most closely approximates the orientation used for TTE and TEE measurement. For all of these measurement techniques, the annulus is as-
assessed at the lowest hinge point of the aortic valve leaflets at the virtual basal plane. Measurements are taken from systolic phase reconstructions ranging from 20% to 45% of the R-R interval, using the phase with maximum valve opening, as is performed using echocardiography.

Regardless of the methods used, the absolute differences between MDCT and TTE or TEE are greater than the differences between TEE and TTE (19). These differences may have significant clinical implications. Messika-Zeitoun et al. (19) have shown that MDCT would have influenced or modified the TAVI strategy in 38% of patients using long-axis and short-axis diameters, and in 42% of patients using the 3-chamber projection. These differences in absolute measurements between the modalities often results in confusion among operators as to the nature of the differences and the appropriate gold standard to use, although the impact on procedural success and post-implant stent circularity is unclear (Fig. 6). The measurement of the annulus has significant implications for TAVI, and although MDCT may afford exceptional spatial resolution and multiplanar reformatting capabilities, good results and clinical outcomes have been achieved using TEE. Given the importance of accurate assessment of the annular size, it may be useful to report and consider measurements from both TEE and MDCT, and carefully examine both in cases of significant inter-test disagreement. This combined assessment may reduce the chance for error and provide a more comprehensive definition of the annular size and shape in patients considered for TAVI.
Figure 6. Double Oblique Transverse Reconstruction of Aortic Root

(A) Double oblique transverse reconstruction of the aortic root below the commissural insertion in an 87-year-old female patient with aortic stenosis being evaluated for transcatheter aortic valve replacement. The annulus is rather elliptical, with a long-axis measurement of 27.6 mm and short-axis measurement of 22.9 mm. (B) Despite the elliptical configuration, the post-implantation examination shows a circular valve deployment.

Figure 7. How to Generate a 3-Chamber Reconstruction

Multiplanar image reconstruction of a gated computed tomography angiogram in an 85-year-old male with severe symptomatic aortic stenosis for the evaluation of the aortic root and annulus. (A) The transverse image is bisected with an oblique tool through the mitral valve to the ventricular apex, resulting in the formation of a vertical long-axis reconstruction. (B) The left ventricle is then cut in a plane from the left atrium through the center of the mitral valve through the left ventricular apex, resulting in a relative 4-chamber projection. (D) An oblique tool is then used rotated in a perpendicular fashion to the interventricular septum so as to create a short-axis projection. (E) Finally, a cut-plane is placed in an oblique fashion at the base of the short-axis projection out the left ventricular outflow tract and aorta to create a 3-chamber projection.
Annulus Sizing: How We Do It

Multidetector CT angiography produces imaging data that is isotropic in that it can be reconstructed in any 2D imaging plane, including those typically used in TTE such as the 3-chamber view (Fig. 7). These measurements, not surprisingly, seem to correlate best with the corresponding ECG measurements, which is enticing as valve sizing and patient screening has largely been done using TTE and TEE. In using these 2D measurements, however, much of the valuable and unique data available from CT is ignored. In our experience, these 2D measurements are also not particularly reproducible across readers of varying experience, and that has the potential to be a significant issue as TAVI expands to new centers. We have, therefore, moved away from using CT to predict annular measurements on echocardiography and now focus on providing unique 3D data in a noninvasive fashion to gain a better understanding of the aortic root and left ventricular outflow tract geometry. To do so, we recreate the anatomic definition of the annulus on MDCT by constructing an image that is orthogonal to the root of the aorta immediately below the nadir of the aortic cusps, which provides the plane of the annulus (Fig. 8). In recreating the plane of the aortic root, a true transaxial image orthogonal to the aortic annulus is achievable, allowing for short-axis and long-axis measurements of the basal ring.

It is important that users recognize that these 2 measurements will yield values that will often differ from the measurements acquired using echocardiography, but in our experience, the mean of these 2 measurements appears to be the most reproducible measure across multiple readers. Furthermore, these orthogonal projections provide an understanding of the circularity or elliptical nature of the root. These measurements are not only provided to the interventional team but also representative images are reviewed in a collaborative fashion to allow for a more individualized approach for each patient.

Important Aortic Root Measurements

Aortic measurements vary with individual valve specifications. The Medtronic CoreValve has requirements regarding the height and width of the aortic sinus and dimensions of the aorta at the sinotubular junction, unlike the Sapien and Sapien XT, which do not. For both of the commonly used valves, the distance between the insertion of the left coronary

Figure 8. Aortic Root and Anatomic Location of Aortic Annulus
The 3 red rings represent the aortic valve cusps, with the green circle placed at the nadir of the aortic cusps denoting the annular plane. LC = left coronary cusp; NC = noncoronary cusp; RC = right coronary cusp.

Figure 9. Coronal Oblique Image From Coronary CT Angiogram
Coronal oblique image from a coronary computed tomography (CT) angiogram in (A) an 84-year-old male patient and (B) an 87-year-old female patient undergoing CT assessment before transcatheter aortic valve replacement (TAVR). The distance between the left coronary cusp and left coronary ostium is 15 mm (A) and 10.8 mm (B), respectively. A distance of 14 mm is considered adequate in most centers for TAVR.
cusp and the left coronary artery ostium is an additional important measurement and can be measured from an oblique sagittal or coronal projection (Fig. 9). This measurement may predict patients at risk for coronary occlusion during the TAVI procedure with displacement of the native leaflets and heavy leaflet calcification. At present, no definite criteria exist to exclude patients on the basis of the risk of coronary obstruction, but an 11- to 14-mm distance cutoff range has been proposed (22) between the coronary ostia and the leaflet insertion. At our institution, we pay careful attention to the distribution and burden of calcification of the aortic valve cusps. We have greater concern in the setting of heavily and diffusely calcified cusps than when the calcification is isolated calcification near the commissural insertion. We also assess the length of the left coronary cusp and its relationship to the height of the left main coronary ostium.

For the CoreValve (Medtronic), we provide other measurements required for device selection, namely, a measurement of the aortic sinus diameter of the aorta measured on a double oblique projection as well as the sinus height and diameter of the ascending aorta. A minimum trans-sinus dimension of 27 mm is required, and the ascending aorta must be <43 mm in diameter.

**Iliofemoral Access**

In early TAVI cases, vascular complications were reported that were largely attributable to the large device size and significant atherosclerosis that was often present (10,22,23). Initial iliofemoral assessments were performed with single plane angiography at the time of coronary artery assessment. In comparison, the multiplanar capabilities of MDCT allow a thorough and complete 3D assessment of the iliofemoral system. Kurra et al. (23) reported that 33% of patients with critical aortic stenosis had unfavorable iliofemoral arteries, with 77% of those patients having minimal luminal diameters of <8 mm. In addition to providing more elaborate 3D reconstructions and accurate assessments of the minimal luminal diameter, MDCT can assess vessel tortuosity, burden and pattern of calcification, extent of atherosclerosis, and identify other high-risk features including dissections and complex atheroma (Fig. 10). Successful implants have been completed in patients with arterial size and moderate calcification. Circumferential and/or horseshoe calcification in association with small caliber vessels or stenotic segments is considered a contraindication to a transfemoral artery approach.
as these may not allow the artery to expand to accommodate the large-profile delivery catheter, and may increase the risk of arterial dissection or perforation. Early transarterial device delivery failures have been attributed in part to circumferential iliofemoral calcification that was not appreciated on screening calibrated angiography studies (24). Currently, alternative transapical or transaxillary approaches may be considered in these patients.

In our experience, a standardized approach to iliofemoral assessment yields the best results and greatly reduces morbidity and mortality rate from vascular injury. We incorporate a number of reconstructions into our standard iliofemoral evaluation by MDCT, including 3D volume rendered imaging, curved multiplanar reformats, and maximum intensity projection images. Multiple measurements are taken along the entire course of the iliofemoral system bilaterally with the minimum luminal measurement recorded for each side and included in the report. Identifying the specific location of areas with reduced luminal size is important; in some cases, access can be achieved proximal to the site by a cutdown approach. A moderate descriptor of the overall plaque burden and presence of iliofemoral calcification is noted. Particular attention is given to any regions of circumferential or horse shoe calcification. Importantly, the minimal luminal diameter is provided along the entire course of both the right and left iliofemoral system down to the femoral head. We provide annotated volume rendered images with the

Figure 11. 3D Volume Rendered Image of Iliofemoral Vasculature and Boney Pelvis

Three-dimensional (3D) volume rendered image of the iliofemoral vasculature and boney pelvis in an 86-year-old female patient with severe symptomatic aortic stenosis. Modeling the boney pelvis with the arterial system provides landmarks to display the site of minimal luminal diameter and to help guide the arterial puncture. In this case, the minimal diameter on the right was 5.2 mm (arrow) at the mid-femoral head, thereby guiding a higher puncture.

Figure 12. Stepwise Approach to Construction of 3D Volume Rendered Image of Aortic Root

A 3-dimensional (3D) volume rendered projection of the aorta in an 84-year-old male patient with aortic stenosis is reconstructed with points denoting the inferior margin of the aortic cusps in a double oblique transverse reconstruction. The aorta is first bisected from a standard coronal projection (A), resulting in a sagittal oblique projection (B), from which a double oblique transverse image of the aortic root (C) is created by again using the workstation oblique tool. The images are reviewed, and the most inferior margins of the aortic cusps on the orthogonal projection of the root are identified. Points are then deposited on these most inferior margins and linked, thereby creating a triangle that is meant to overlay the inferior margin of the root (D). A 3D volume rendered image of the ascending aorta is then created with the triangle in place. In this 84-year-old male patient, anterior posterior (AP) caudal 14 was considered an appropriate coaxial angle (E) of deployment, as the triangle is no longer evident because all 3 points are in the same plane; but at AP caudal 40, the triangle is well defined (F), suggesting that the inferior margins of the cusps are not in the same plane, and therefore, are an inappropriate angle for deployment.
femoral heads in place denoting the location of the measured minimal luminal diameter (Fig. 11).

**How to Predict an Appropriate Angle of Deployment Using CT**

There is also significant potential of MDCT to assess the aortic root in relation to the body axis (21). Traditionally, standard practice has been to determine root orientation using multiple repeat catheter aortograms in 1 or 2 orthogonal planes before starting the procedure. This process is considered critical to ensure precise coaxial positioning of the stent along the centerline of the aorta (21), as the valve stent needs to be deployed in a projection that is perpendicular to the native valve annulus. Thus, physicians performing TAVI need to choose an implant projection in which the valve is perpendicular or orthogonal to the native valve plane. The need for multiple aortograms to define this optimal orientation increases procedural time, contrast use, and radiation exposure. Further, if appropriate orientation is not achieved, there is a potential for inappropriate positioning of the device, and increased risk of procedural complications such as stent embolization (21,25).

It is understood that there are many potential angles representing the appropriate native aortic valve plane in any individual patient. From aortography and anatomic studies, it is known that the aortic valve is typically directed in a cranial and anterior fashion with angulation to the right. On the basis of this assumption, the team typically uses caudal angulation when in a right anterior oblique (RAO) projection and cranial angulation when in the left anterior oblique (LAO) projection. However, there are significant variations in patient anatomy, and pre-procedural assessment of a patient’s aortic root geometry has been shown to be beneficial in predicting the appropriate angle of implantation (21,25).

As many patients routinely have MDCT performed before TAVI, the dataset can be used to provide orientation of the aortic root, which may predict the appropriate angle of implantation. Similar to the evaluation of the aortic annulus, double oblique transverse multiplanar reconstructions are performed to assess the internal diameter of the aortic annulus and root. From this projection, points are deposited on the most inferior aspect of the aortic sinuses, and the points are then linked to form a triangle. A 3D volume rendered reconstruction of the aorta is then created with the triangle superimposed upon it. The reconstruction can then be rotated through a series of any angles (Fig. 12). At our center, we aim to find angiographic projections representing perpendicularity to the native valve plane in 3 axes: 1) cranial-caudal with no RAO or LAO angulation; 2) straight RAO to LAO as needed with no cranial or caudal angulation; and 3) LAO 30° with cranial or caudal angulation as needed. These axes were chosen on the basis of past experiences and the preferred
working angles, given the physical constraints of the catheterization laboratory.

Pre-procedural angle prediction with MDCT may decrease the number of aortograms required during the procedure, shortening both procedure time and contrast usage, and potentially increases the likelihood of coaxial implantation by optimizing the orientation during device placement. MDCT may be particularly helpful in patients with unusual anatomy requiring steep projections that would be difficult to predict, as may be observed in patients with musculoskeletal abnormalities, kyphoscoliosis, and markedly unfolded aortas. Although one may select 3 predicted angles of implantation, there are many other appropriate angles for deployment. We have found that a “line of perpendicularity” can be generated in each patient, where any point in the RAO to LAO spectrum can be utilized as long as the correct amount of caudal or cranial angulations is added (Fig. 13).

**How and Why CT Should Be Used for Long-Term Follow Up**

Similar to annular sizing, deriving a double oblique transverse projection that is orthogonal to the aortic root is integral to evaluate transcatheter aortic valve stents. This allows for the assessment of expansion, circularity, and apposition. From a long-axis or coronal oblique projection, assessment of implantation depth in relation to the native annulus and the coronary arteries can be performed. The stents are also interrogated using multiplanar reformats, maximum intensity projections, and volume rendering for stent fracture.

Circularity can be defined in a number of ways both qualitatively and quantitatively. We typically use an eccentricity index (26), using a simple formula derived from measurements on the double oblique projections: \(1 - \frac{D_{\text{min}}}{D_{\text{max}}}\), where \(D_{\text{min}}\) and \(D_{\text{max}}\) are 2 perpendicular diameters representing the smallest and largest external diameters at each level. We will typically do this analysis at 3 levels, spanning from the most ventricular (inferior) margin of the stent through to the aortic (upper) end. We consider a circular deployment an eccentricity index of \(<0.1\) (26).

Implantation depth is evaluated on a coronal oblique reconstruction meant to display the inferior margin of the stent, the position of the left main coronary artery, and the floor of the sinuses of Valsalva. Measurements are taken from the floor of the sinus on the coronal plane to the inferior margin of the stent, as well as the distance from the outer border of the frame to the coronary ostium (Fig. 14), with the distance considered positive if there was coronary overlap and negative if the superior margin of the stent was below the left main. The meaning of a change in this final measurement is not certain, but is being evaluated as a potential means to assess for stent migration.

**Figure 15. Coronal Oblique Reformat and 3D Image of Ascending Aorta**

(A) Coronal oblique reformat and (B) 3-dimensional (3D) volume rendered image of the ascending aorta in an 86-year-old male patient >4 years after transcatheter aortic valve replacement (TAVR) with an Edwards Sapien valve in situ. Note the position of the stent, the absence of in-stent stenosis, and the integrity of the valve stent struts.
Clinical and hemodynamic follow-up is now available >5 years after TAVI. MDCT can further evaluate these cases for valve durability (both leaflet and stent), lack of coaptation of the stent to the annulus suggestive of paravalvular regurgitation, and stent migration. Although the value of post-procedural evaluation of these patients remains uncertain (27), MDCT may certainly be useful in assessing these valves and add valuable incremental information. We have evaluated 21 patients at least 3 years after TAVI with MDCT. In this cohort, there were no stent fractures or visible leaflet thickening (Fig. 15). The valve stent leaflets were free of calcification or fusion, and there was no evidence of thrombus in the aortic sinus (28). Eight patients had MDCT scans immediately post-procedure and again after at least 3 years, allowing for serial comparisons. There was no evidence of stent migration detected as measured by the distance from the top of the stent to the origin of the left main coronary artery ostium. There was no significant stent recoil or decrease in diameter at the level of the annulus, but there was a trend toward reduction in stent diameter in the aortic side of the stent. This is not entirely unexpected as the aortic end tends to preferentially dilate as the annular end is confined by the fabric skirt of the Edwards Sapien valve. The lack of stent recoil at the level of the annulus is reassuring, because it would be at the annular level that the stent leaflets would be compressed and potentially compromised by stent recoil. These patients had echocardiographic findings also suggesting appropriate valve function, with stable aortic valve area and gradients. Future studies may be warranted in larger cohorts. Importantly, while there are growing follow-up data for TAVI with CT, there is no defined role at present for the routine clinical use of CT for TAVI follow-up in patients without evidence of perivalvular regurgitation on echocardiography.

Conclusions

Therapy with TAVI has seen rapid advancements over the last 5 years and is now being performed at many centers with good clinical outcomes. Echocardiography has been the most commonly used tool for pre-procedural assessment and provides physiologic data; however, MDCT can evaluate 3D annular and aortic root morphology and dimensions, which may supplement data provided by echocardiography, in addition to additional assessment of iliofemoral access by MDCT. Continuing development of devices and the utilization of advanced imaging tools such as MDCT continue to improve the safety and potential application of TAVI in the management of symptomatic aortic stenosis.

Reprint requests and correspondence: Dr. Jonathon Leipsic, Department of Medical Imaging, St. Paul’s Hospital, 1081 Burrard Street, Vancouver, British Columbia V6S 1Y6, Canada. E-mail: jleipsic@providencehealth.bc.ca.


Key Words: aortic stenosis • cardiac CT • transcatheter aortic valve implantation.