Multidetector Computed Tomography (MDCT) Angiography in the Pre-Procedural Assessment of Patients Undergoing Transcatheter Aortic Valve Replacement

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ABSTRACT

Transcatheter aortic valve replacement (TAVR) initially emerged as an alternative option to surgical aortic valve replacement (SAVR) for patients with severe aortic stenosis who were considered either inoperable or high-risk for surgery. However, since its advent the role of TAVR has been continuously evolving on the basis of clinical trials which showed that TAVR is non-inferior to SAVR in patients with moderate as well as low-risk for surgery. Because of recent technological advances, multidetector computer tomography (MDCT) is inherently suitable for the pre-procedural assessment of patients being considered for TAVR within a very short imaging time, MDCT can measure the diameter of the aortic annulus, provide detailed information regarding the status of the entire thoracoabdominal aorta, and assess the caliber of the peripheral vasculature used for transcatheter heart valve delivery. This information helps interventionists make optimal pre-procedural decisions and avoid complications. To familiarize non-imaging specialists with the role of MDCT in TAVR, we provide a concise overview of our approach to using this modality for the pre-procedural assessment of TAVR candidates.

Keywords: Aortic valve, TAVR, aortic stenosis, transcatheter aortic valve replacement, aortic root

Introduction

Aortic stenosis (AS) is the most common valvular heart disease that affects the elderly in developed countries [1]. Aortic stenosis affects up to 5% of the elderly population, and the American Heart Association's 2014 Heart and Stroke Statistics update indicates that the prevalence of moderate or severe AS is 2.8% in patients aged ≥75 years old [2]. In suitable candidates, even in the elderly population, surgical aortic valve replacement (SAVR) for symptomatic AS is associated with a favorable short-term and long-term prognosis [3]. However, transcatheter aortic valve replacement (TAVR) has emerged as a reasonable option for high-risk patients who are not surgical candidates [4, 5], and it is similar to surgery with respect to end-points of death and disabling stroke in patients who are at moderate risk [6]. There is increasing evidence that TAVR may not only be similar or non-inferior to surgery in patients who are low-risk surgery candidates [7], but it may be associated with a significantly lower rate of death, stroke, and re-hospitalization within 1 year of the procedure [8].

In patients who underwent TAVR, accurate sizing of the aortic annulus is of paramount importance for selecting the optimal transcatheter heart valve (THV) and for minimizing intra-procedural and post-procedural complications. Various imaging modalities, including transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), multidetector computed tomography (MDCT), and magnetic resonance imaging, have been used to measure the aortic annulus. Other important variables that must be assessed in patients who underwent TAVR include the status of the entire thoracoabdominal aorta and the caliber of the pelvic arterial-access site. Also, optimal co-planar projection angles for the valve deployment can be measured. We provide a concise review regarding the use of MDCT in the pre-procedural assessment of patients undergoing TAVR, as currently performed at our institution.

Clinical and Research Consequences

Over the past decade, advances in software and hardware have resulted in an improved MDCT gantry rotation speed and detector coverage. Current state-of-the-art MDCT scanners have 64

Cite this article as: *Duran C, Masood I, Duran A, et al. Multidetector Computed Tomography (MDCT) Angiography in the Pre-Procedural Assessment of Patients Undergoing Transcatheter Aortic Valve Replacement. Eurasian J Med 2020; 52(1): 86-93.*

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Received: February 28, 2019
Accepted: June 18, 2019

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DOI 10.5152/eurasianjmed.2019.18329

to 320 detectors that provide coverage of approximately 4-16 cm, allowing the entire heart to be imaged in a single-patient breath-hold. In addition, the introduction of dual-source scanners further improved the temporal resolution of data sampling up to 75 ms. With regard to size, current MDCT detectors range from 0.5 to 0.625 mm in the x, y, and z directions, thus providing high-spatial-resolution images with isotropic voxels. As a result, multiplanar reformation of the three-dimensional (3D) dataset provides accurate measurements of the aortic annulus diameter and pelvic arterial caliber, which are crucial for the success of THV placement.

Ideally, an MDCT scanner with a minimum of 64 detectors (single-source scanner) or a dual-source scanner should be used for data acquisition, so as to image the entire vascular tree in a single-patient breath-hold. Given the inherent motion of the aortic root, electrocardiographic (ECG) gating is mandatory, as it allows the measurement of the aortic annular size during mid systole and allows acquisition of best image quality with limited motion artifact (see below). A 20- to 18-gauge peripheral intravenous cannula is preferable, as an injection rate of at least 4 cc/s should be used to provide optimal enhancement of the entire vasculature. The timing of scan should be determined by using either a test-bolus technique or a bolus trigger technique, with the region of interest in the mid-descending aorta or proximal abdominal aorta. Depending on the patient's physical status, the contrast volume is adjusted accordingly (the average amount of contrast used at our institution is approximately 80-120 cc), after which a saline push is administered in a similar amount and at the same rate. A pre-contrast sequence targeted at the level of the aortic valve and covering the entire aortic root is obtained by using the coronary artery calcium scoring sequence. Thereafter, a high-spatial-resolution MDCT of the thoracoabdominal aorta is performed, starting from the lung apices and extending to the inferior margin of the femoral heads. We prefer to review the data and to perform the measurements in thin slices, which are reconstructed to a slice thickness of 1 mm in 50% increments.

With regard to typical scanning parameters, we use a voltage 100-140 kV, depending on the patient's body habitus and the presence or absence of surgical hardware; a milliamp setting that is adjusted according to the patient's body habitus; a pitch of 0.3; a rotation time of 0.37 s; and collimation of 128×0.625 mm. Data are sent to dedicated workstations for measurement and post-processing. Table 1 summarizes our basic scanning parameters.

The source images are stored in our picture archiving and communication system as per standard practice. In addition, the following volume-rendered images are reconstructed: images of the entire thoracoabdominal aorta, images of the pelvic arteries (including curved multiplanar reformations), and various captured still images such as those depicting the Agastston score for the aortic valve, the location of aortic valve calcification, and the angle of delivery of the aortic valve. In this manner, our hospital's heart valve team is provided with adequate information for pre-procedure planning.

Table 1. Basic scanning parameters

Preferably ≥64-detector CT scanner
ECG gating with data obtained at least in the tele-systolic phase
Large peripheral intravenous line
Pre-contrast series at the AV level using calcium-score sequence
Contrast injection rate ≥4 cc/s
Test bolus or bolus-tracking technique
High-iodine-concentration contrast, followed by saline push
CTA of the entire aorta (from lung apex to femoral heads)
Reconstruction <1 mm slice in 50% increments

CT: computed tomography; ECG: electrocardiography; CTA: computed tomography angiography

Aortic Root Anatomy

The aortic root (Figure 1) extends from the left ventricular outflow tract (LVOT) to the sinotubular junction (STJ). STJ marks the transition between the aortic sinuses of Valsalva and the ascending aorta. The aortic valve is located within the aortic sinus of the aortic root. The aortic valve usually has three leaflets (cusps). The right-sided cusp has the origin of the right coronary artery from its sinus and is called right coronary cusp; similarly, the left-sided cusp is called the left coronary cups. The third cusp is also called the noncoronary cusp since no coronary artery originates from its sinus. The aortic annulus is not an anatomic landmark, but it is a virtual ring formed by the nadir of the attachment sites of the aortic valve leaflets. The shape of aortic annulus varies at different levels; it is circular at the level of STJ, clover-shaped at the level of the sinus, and elliptical at the level of the annulus. Table 2 summarizes the measurements that may provide useful information to an interventionist performing TAVR.

Native Aortic Valve

MDCT allows accurate assessment of the native aortic valve, including degree of valvular calcification. As compared to TEE, MDCT can provide superior morphologic characterization of the aortic valve, as well as differentiation between bicuspid and tricuspid valves, which is an important factor since intervention in the bicuspid valve can be more challenging [9, 10].

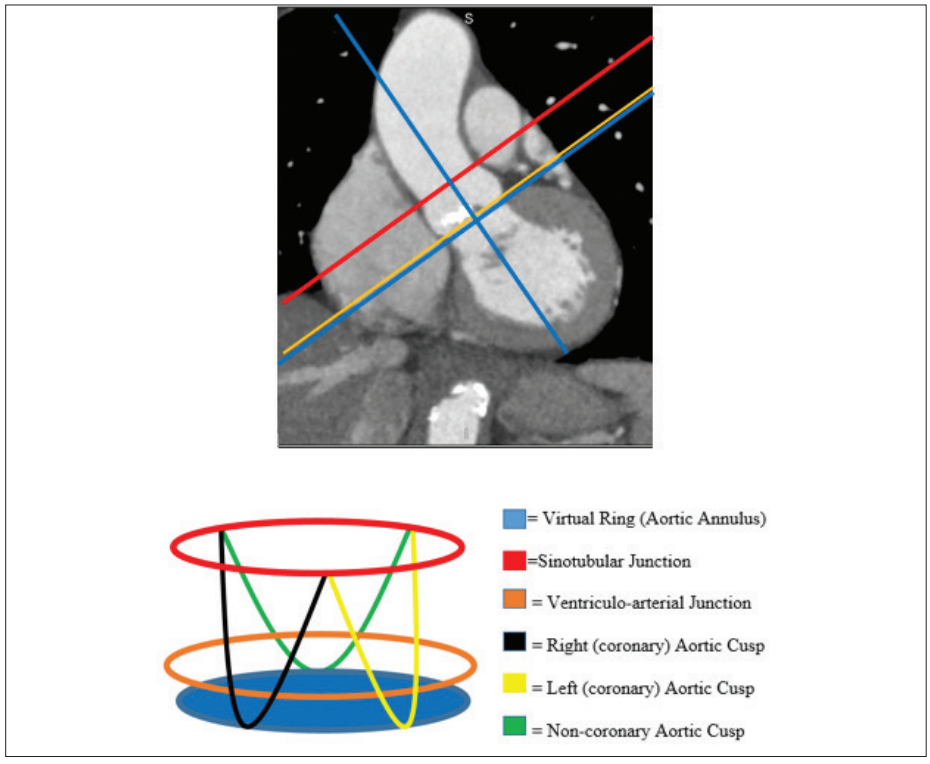

Figure 1. Aortic root anatomy.

The presence, distribution, and degree of aortic valve calcification may affect the peri- and postoperative success of TAVR [11, 12]. Extensive valvular calcification has also been associated with the development of paravalvular regurgitation (PVR) after TAVR [13]; and as per Azzalini and associates [14], it is an independent predictor of PVR after TAVR. The proposed mechanism of PVR is interposition of these calcifications between the deploying device and the native aortic valve [15].

The Agaston score quantifies Aortic Valve (AV) calcification using the same imaging sequence as for coronary artery calcium scoring. Haensig and colleagues [13] reported that the degree of AV calcification quantified by the Agaston score is associated with PVR after TAVR. In addition to determining the Agaston score, we capture a number of images-starting from the aortic annulus and advancing toward the sinotubular junction, parallel to the annular plane, to show the location of AV calcification at the level of the aortic root (Figure 2).

Aortic Annulus

Since the currently available implantable valves are designed for specific annular sizes, one of the main roles of MDCT is to accurately estimate the annular size for valve selection. Traditionally, the annular sizing for a THV was obtained with TEE [16, 17]. However, MDCT is increasingly being used to size the annulus for TAVR. Advantages of MDCT include its nature as an inherently 3D technique, with a high-spatial-resolution and isotropic voxels, and its short examination time. In contrast to TEE, which usually transects the annulus at the short axis, MDCT allows measurement of the annulus along the short and long axes. The clinical significance of this fact is that TEE underestimates the annular size as it yields measurements that approximate the short axis only [18], while MDCT slightly overestimates it.

In a retrospective analysis by Willson and colleagues [18], in which TEE was the imaging modality for annular sizing, and MDCT was used to measure the coronary ostial height and pelvic arterial diameter, MDCT showed a larger annular diameter (the average of the orthogonal diameters) than did TEE (23.9±2.4 mm vs. 22.5±1.9 mm; p<0.001). In addition, when compared to the known diameter of the implanted THV, the THV size was 2.2±1.2 mm larger than the diameter measured by TEE and 0.6±1.9 mm larger than the diameter measured by MDCT, suggesting that the annular diameter is underestimated by TEE compared to MDCT. Furthermore, in patients with a THV size smaller than the MDCT-obtained diameter, there were more instances of moderate-to-severe PVR with TEE (9/46; 19.6%) than with MDCT (4/56; 7.1%) (p=0.04), suggesting that cautious slight oversizing of the THV could be beneficial in preventing PVR.

The use of slightly over-sized THV is safe, and as per Dashkevich et al. [19], it may be beneficial in preventing PVR. Oversizing of THV may also prevent migration of THV by means of satisfactory anchoring and also prevent a patient–prosthetic mismatch [18, 20]. Vendors of both the Edwards Sapien XT valve (Edwards Lifesciences Corporation, Irvine, CA) and the CoreValve (Medtronic, Inc., Minneapolis, MN) recommend a degree of oversizing (Figures 3a, b). In a recent study by Binder and colleagues [20], 133 patients were assigned to TAVR guided by MDCT (involving cross-sectional-area measurement by MDCT and deployment of a THV with an area 5% to 10% larger than that suggested by MDCT), and 133 other patients were assigned to a control group, whose annular diameter was obtained by TEE. None of the MDCT group had severe PVR, but 6% of the control group had this complication (p<0.05). Similarly, 5% of

Table 2. Important measurements obtained with multidetector computed tomography angiography

Measurements	Comments
Native Aortic Valve	Quantitative Agaston score
	Location of calcification
Aortic annulus	Maximum and minimum diameter obtained by multiplanar reformation
	Cross-sectional area and perimeter
	Annular diameters obtained at sagittal and coronal orientation (similar to those obtained by transesophageal echocardiography)
Sinus of Valsalva diameter	At the level where the three coronary cusps are seen in the same plane (Mercedes-Benz sign)
Distance between aortic annulus and origins of left main and right coronary arteries	Measured by multiplanar reformation
Angle of transcatheter heart valve delivery	Obtained through 3D volume-rendered data
Heart	Coronary artery status, if possible
	Presence or absence of thrombus in left ventricle or left atrial appendage
	Presence of "sigmoid septum," especially in elderly patients, and angle between left ventricular outflow tract and aortic root, which may affect ease of valve delivery
Status of thoracoabdominal aorta	Degree and location of calcification and noncalcific plaques
	Any aortic pathology and/or previous intervention, such as endostent placement
	Tortuosity of thoracoabdominal aorta
	Minimal diameter of thoracoabdominal aorta
Pelvic arteries	Maximum and minimum cross-sectional diameter of common iliac, external iliac, and common femoral arteries, including degree of calcification and tortuosity, as well as any other important pathology, such as dissection or atherosclerotic ulceration
Subclavian arteries	Minimum and maximum cross-sectional diameter, including degree of calcification and tortuosity

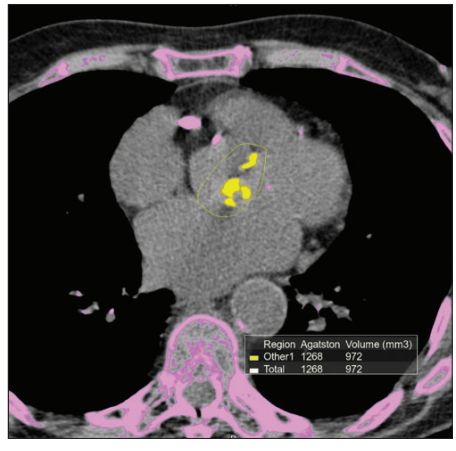

Figure 2. Multidetector computed tomography angiography scan of the aortic valve. The Agaston score is obtained by using the same imaging procedure and post-processing software as used for coronary artery calcium scoring. In this case, the AV Agaston score is represented by region Other1, which is also the total score. Care must be taken to avoid including the mitral annular calcification and aortic root calcification that is commonly associated with AV calcification.

Figure 3. a, b. a) Edwards valve sizing chart. Courtesy of Edwards Lifesciences Cooperation, Irvine, CA. b) CoreValve sizing chart. Courtesy of Edwards Lifesciences Cooperation, Irvine, CA.

the MDCT patients had more than mild PVR, whereas 13% of the control patients had this condition ($p<0.05$). Willson and associates [21] recently published their recommendations for choosing the Edwards valve based on the area of the annulus obtained by MDCT with a target of 10% to 15% oversizing, which has been shown to reduce the risk of PVR, in-hospital death, annular rupture, and valve embolization [20].

It is important to understand the anatomy of the aortic annulus and changes in its shape during the cardiac cycle to accurately assess its size with MDCT. Two separate research groups [22, 23] have shown that the aortic annulus is elliptical and that the annular diameter, surface area, and perimeter are all larger in systole than in diastole. In addition, Blanke and colleagues [23] demonstrated that the long-axis diameter changes relatively little throughout the cardiac cycle but that the short-axis diameter undergoes a larger change, predominantly during systole, causing the annulus to be more circular in systole and more oval in diastole. Annular measurements are typically made in the tele-systolic phase (between 25% and 35% of the electrocardiography interval), when the aortic annular

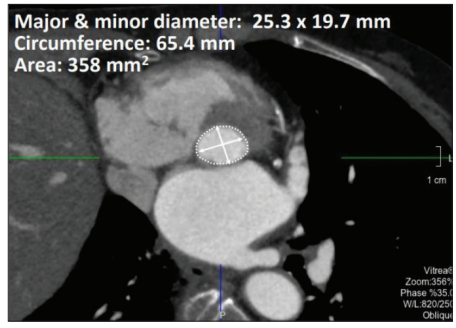

Figure 5. Multidetector computed tomography angiography measurement of the aortic annular diameter, showing the major and minor orthogonal diameters, as well as the perimeter and cross-sectional area, computed by the workstation after manual contour placement.

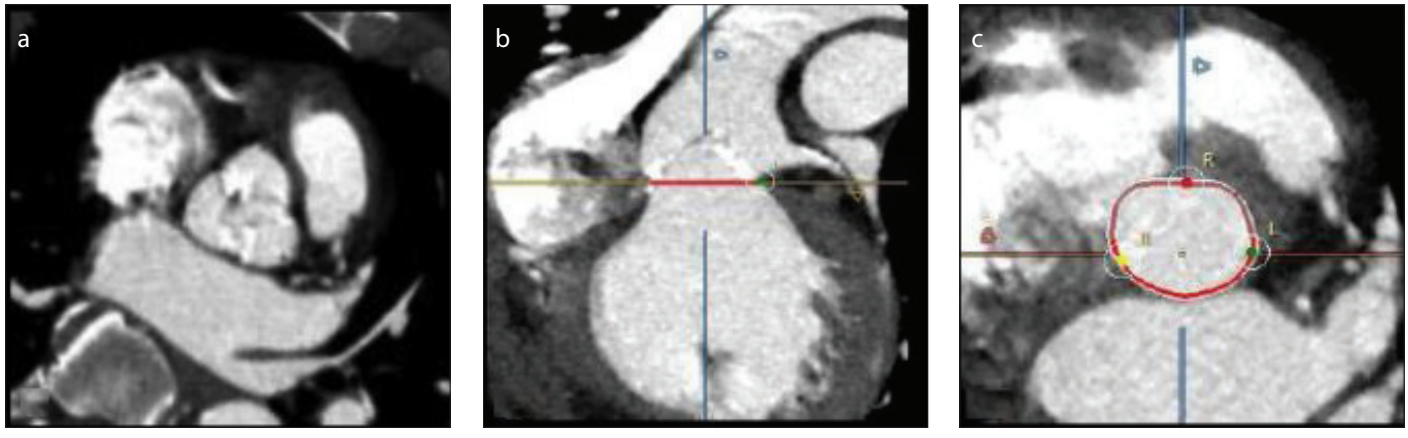

Figure 4. a-c. a, b, c) Evaluation of Aortic Valve (AV) using Circle software (Calgary, AB, Canada): Finding and locating the coronary cusps (red-right, green CoreValve sizing chart. Courtesy of Edwards Lifesciences Cooperation, Irvine, CA.

size is largest and cardiac contraction is limited (isovolumic contraction); in this phase, there are fewer motion artifacts, especially at higher heart rates, as commonly seen in patients with severe/critical aortic stenosis.

The first step of measurement of the annular size is to correctly identify the true annular plane, which is defined as the virtual ring that joins the basal attachments of the AV leaflets [17], located just distally to the LVOT. The aortic annular plane is double-oblique; therefore, the standard coronal, sagittal, and even single-oblique reformatted images are not suitable for defining the plane. The annular plane can be defined manually as well as automatically using specific software. Manual definition of the plane is comparatively more complex as it requires several adjustments in each of the three orthogonal planes. This can lead to a high inter-observer variance [24]. This situation has been improved by using standardized imaging tools for semi-automatic and automatic detection of the aortic root (Figures 4a-c). Nonetheless, the aortic annular plane can manually be obtained by double-oblique technique followed by free-hand rotation of the axial plane.

After defining the true aortic plane, the next step is obtaining the maximum and minimum orthogonal diameters. Using the analysis tool from the workstation, the cross-sectional area and perimeter can also be measured (Figure 5). The mean diameter is derived from the average of the maximum and minimum orthogonal diameters. Using the equation $area = (\pi.d^2)/4$ and $perimeter = \pi.d$, the respective diameters (d) could be derived from the cross-sectional area and perimeter measurements. The interventionist may decide which measurements are the most appropriate to use for THV sizing.

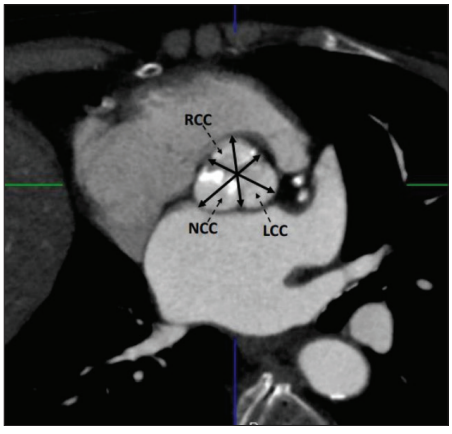

Figure 6. Multidetector computed tomography angiography measurement of the sinus of Valsalva diameter from the left, right, and noncoronary cusps (LCC, RCC, and NCC, respectively).

Sinus of Valsalva

Measurements of the width, maximal height, and diameter of the sinus of Valsalva (SOV) are important parameters for coronary perfusion with THV. SOV measurements will assess whether the THV will fit into the SOV without causing coronary occlusion from the displacement of native AV leaflets. Measurement of the SOV diameter is shown in Figure 6 at the level where the three aortic cusps resemble a Mercedes-Benz sign. This can be achieved by scrolling more cranially from the level of the aortic annulus and by using oblique tilting in order for the three sinuses of Valsalva and the coronary cusps to appear in the same plane. Smaller SOV diameters may predict coronary obstruction during TAVR. In a large multicenter registry, 44 of 6688 patients had coronary obstruction during TAVR; the SOV diameter was smaller in the affected subjects than in the control subjects (28.1±3.8 mm versus 31.9±4.1 mm, respectively; p<0.001) [25].

Distance between the Coronary Ostium and the Aortic Annulus

Coronary arteries arise within the SOV, below the STJ. Measurement of the distance between the coronary artery ostium (CAO) and the aortic annulus is important. AS can cause shortening of this distance; therefore, deployment of THV without knowing the CAO distance can result in coronary arterial obstruction. Delgado et al. [26] recommended a minimum distance of 10 mm between the COA and the aortic annu-

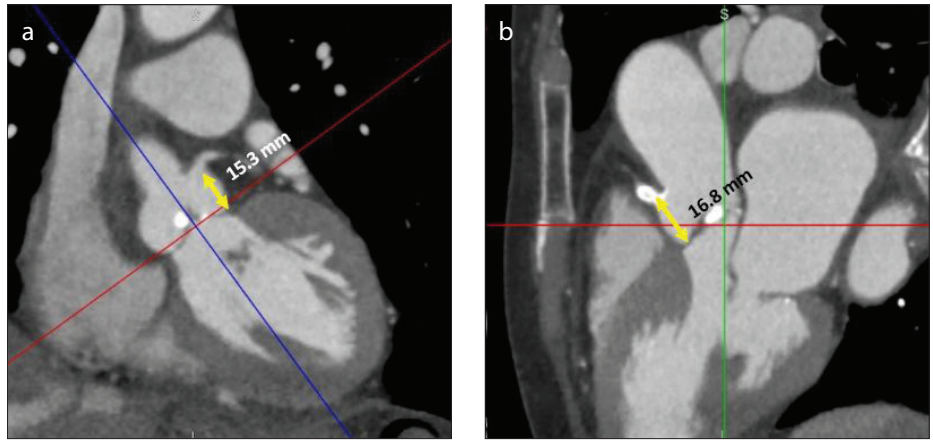

Figure 7. a, b. a) Distance between the aortic annulus and the origin of the left main coronary artery. b) Distance between the aortic annulus and the origin the right coronary artery.

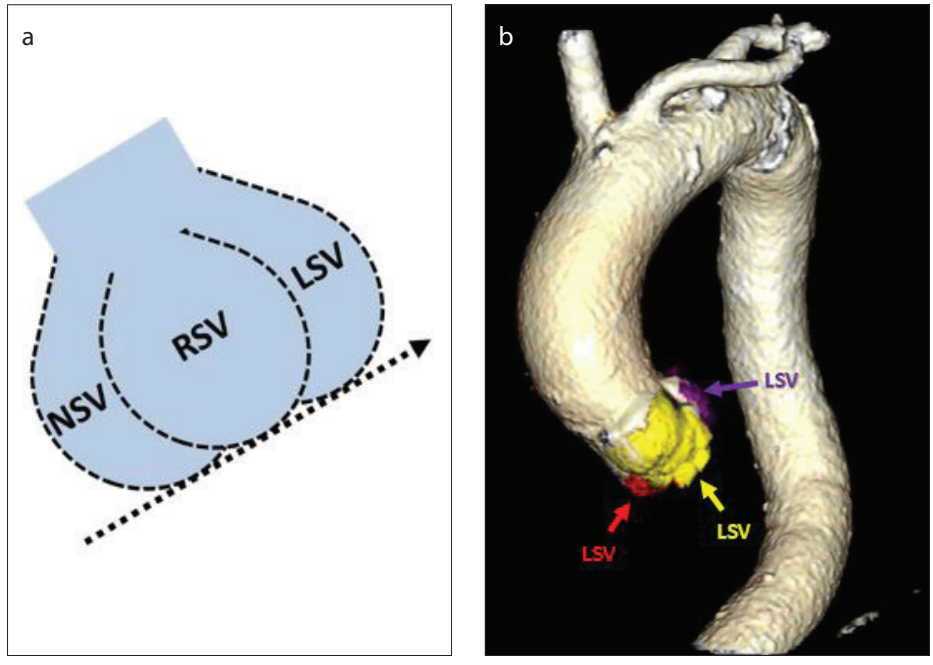

Figure 8. a, b. a) Diagram of the appearance of the aortic root when viewed by the interventionalist in the optimal plane, with the right sinus of Valsalva (RSV) in the center. b) Three-dimensional volume-rendered image of the thoracic aorta with a similar orientation as in view 8a. LSV (purple) = left sinus of Valsalva; NSV (red) = noncoronary sinus of Valsalva; RSV (yellow) = right sinus of Valsalva.

lus. This distance, however, has been shown to have significant inter-individual variation ranging from 7.1 to 21.7 mm [27].

By using multiplanar reformation, one may measure the distance of the coronary artery origins from the aortic annulus plane to the left main and right coronary artery ostia (Figures 7a, b). The distance of the right coronary artery is usually greater than that of the left coronary artery. For THVs that have been approved by the US Food and Drug Administration, the vendor's recommendation for the minimum distance between the coronary ostium and the aortic annulus is 10 to 11 mm for the Edwards Sapien or Sapien XT valve and 15 mm for the CoreValve. In the above-mentioned multicenter registry, Ribeiro and coauthors [25] found that 24 (87%) of the cases of coronary obstruction encountered after TAVR involved the left main coronary artery, and the mean left coronary ostial distance was 10.6±2.1 mm in the patients with coronary obstruction versus 13.4±2.1 mm in the control group (p<0.001). In this registry, 37 (84.1%) of the patients received the Edwards valve, and remainder received the CoreValve.

Angle of Transcatheter Heart Valve Delivery

The aortic annulus is not orthogonal to the body planes. To do a successful implantation, the prosthetic valve needs to be deployed coaxially to the centerline of the aorta. The angle of THV delivery is one of the most important pieces of information to be obtained from the MDCT data. An incorrect angle of delivery could result in inappropriate THV deployment, potential device embolization, and/or PVR [28]. This is the angle at which the X-ray tube C-arm is aligned perpendicularly to the aortic annulus plane, with the right coronary SOV facing directly toward the interventionalist in the center, the left coronary cusp to the patient's left, the noncoronary cusp to the patient's right (Figures 8a, b and 9a, b), and the patient facing forward.

During actual TAVR procedure, angiography provides only a 2D projection image as compared to 3D visualization offered by MDCT. Therefore, without MDCT, the operator must perform several intravenous contrast injections to define the correct angle of delivery, exposing the patient to high contrast load. MDCT with its excellent 3D capabilities can preoperatively predicate a suitable angulation of the angiographic tube. All commercially available CT workstations automatically provide the orientation of the heart/aorta (e.g., left anterior oblique [LAO] 15° and caudal [CAU] 30°) in a volume-rendering mode similar to that viewed in the cardiac catheterization laboratory. In addition, certain vendors can provide additional software that calculates the angle of THV delivery automatically. Use of this angle can potentially reduce the procedure time, as well as the amount of contrast used, which is particularly important in these patients, whose renal function is often compromised.

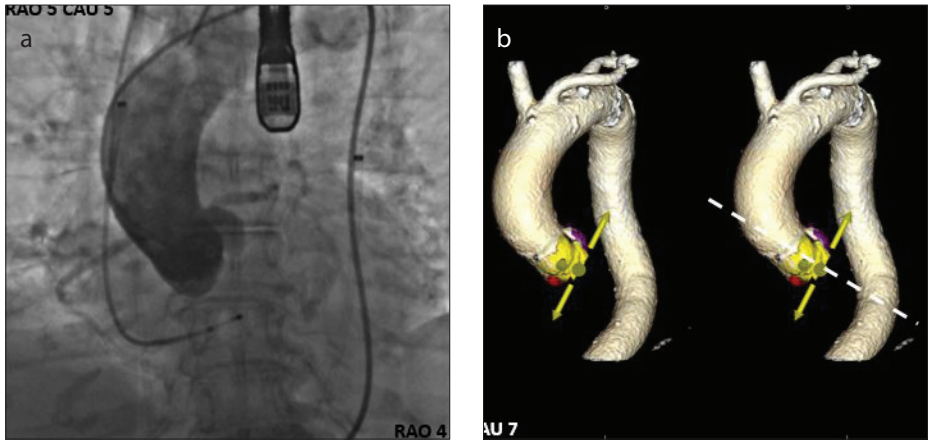

Figure 9. a, b. a) Aortic root angiogram showing the angle of delivery obtained during transcatheter aortic valve replacement (RAO 5°, CAU 5°). b) Three-dimensional volume-rendered image of the thoracic aorta, with the aortic annulus plane aligned and the right sinus of Valsalva (yellow) in the center. The angle is estimated to be RAO 4°, CAU 7°, which is very close to the implantation angle. When the tips of the arrows are connected, they are seen to be in the same plane, perpendicular to the arrows placed for identifying the center of the right sinus of Valsalva (C). RAO = right anterior oblique orientation; CAU = caudal orientation.

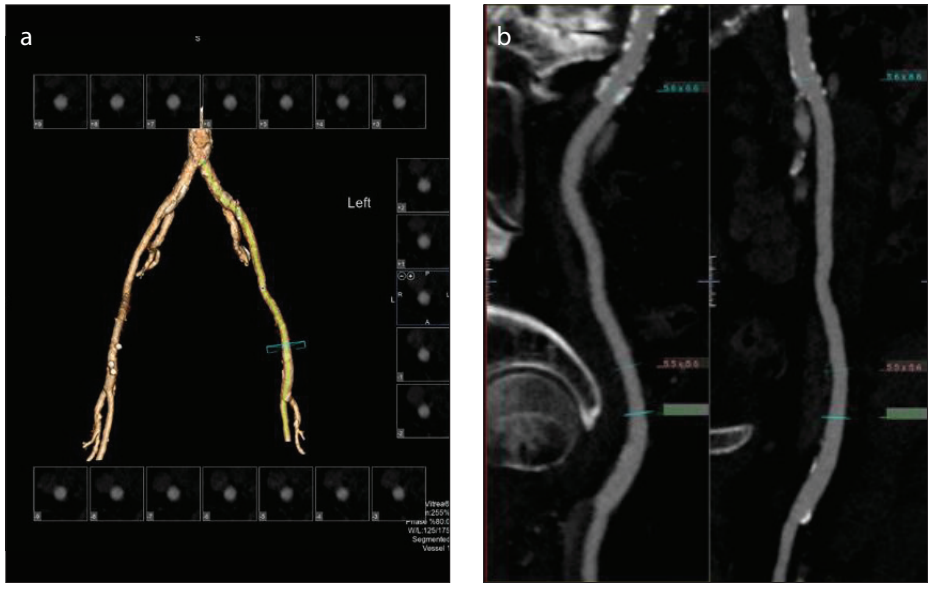

Figure 10. a, b. a) Three-dimensional volume-rendered image of the pelvic vasculature. b) Using the vessel probe function, we were able to show the curved multiplanar reformation of the left pelvic arteries in orthogonal views and to measure the maximum and minimum orthogonal diameters of the left common iliac, external iliac, and common femoral arteries.

Peripheral Arterial Assessment

THV transport to its target requires a device-specific delivery system. MDCT plays an important role in the evaluation of access route and predicting possible complications in a chosen route. Computed tomography angiography has a high

Table 3. Minimal arterial-access diameter

Valve Type	Valve Size (mm)	Sheath Size (F)	Minimal Luminal Diameter (mm)
CoreValve	23	18	6
	26	18	6
	29	18	6
	31	18	6
Edwards Sapien	23	22	7
	26	24	8
Edwards Sapien XT	23	18	6
	26	19	6.5

sensitivity and specificity in the diagnosis of aortoiliac and femoropopliteal disease (96% and 98% versus 97% and 94%, respectively) [29]. With this method, one can use high-spatial-resolution data, including both the source data and volume-rendered images, to define the presence and absence of stenosis, the location of noncalcific and calcific atherosclerosis, and the tortuosity of vessels. In a recent study by Genereux and colleagues [30], major vascular complications, including vascular dissection, vascular perforation, and access-site hematoma, occurred in 15% of the patients in the PARTNER A and B cohorts, who were treated with the 1st generation Edwards THV and delivery system via a trans-femoral approach. Other investigators have noted a complication rate of 6%-31% [31-33].

The target pelvic vessel can be displayed in a 3D format by using vessel segmentation, e.g., by seeding or by using the vessel-probe function available from all major MDCT vendors (Figured 10a, b). The vessel-analysis software can define and provide maximum and minimum orthogonal diameters, or these variables can be measured manually. The common iliac, external iliac, common femoral, and subclavian arteries should be measured bilaterally, and comments should be recorded about the degree of calcification and vessel tortuosity, as well as any other abnormalities observed.

Table 3 shows the minimal arterial-access diameters recommended for the Edwards Sapien, the Sapien XT, and the CoreValve [34].

Conclusion

Because of recent advances in technology, newer-generation THVs and smaller delivery devices, improved procedural skills (a reduced learning curve), and availability of outcome studies, TAVR will likely assume a major role in the treatment of AS with increasing evidence that in appropriately selected patients, TAVR has been non-inferior to SAVR in patients at high risk, moderate risk, and even low risk for surgery [4, 6, 7, 35].

A number of researchers have suggested that MDCT is the modality of choice for the pre-procedural evaluation of patients undergoing TAVR [3, 18, 22, 33, 36] because MDCT provides a comprehensive assessment of the aortic annulus, thoracoabdominal aorta, and potential vascular-access sites, thereby helping the interventionalist to make optimal pre-procedural decisions and avoid potential complications [37].

Informed Consent: Written informed consent was received from the patient who participated in this study.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – I.M., A.D., A. S.; Design – C.D., L.F., R.M.; Supervision - C.D., L.F., B.C.; Resources – B.C., C.D., A.D.; Materials – I.M., C.D., B.C.; Data Collection and/or Processing – A.D., A.S., I.M.; Analysis and/or Interpretation – I.M., C.D., L.F.; Literature Search – A.D., C.D., I.M., M.A.A.; Writing Manuscript – C.D., I.M., A.D.; Critical Review – C.D., A.S., B.C.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that this study has received no financial support.

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