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REVIEW Cardiac Imaging

The contribution of Computed Tomography for the planning of Transcatheter Aortic Valve Implantation. An overview of required measurements and their use

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Abstract

Transcatheter aortic valve implantation (TAVI) is an alternative treatment for inoperable patients with symptomatic severe aortic valve stenosis. This procedure is a validated and effective treatment option with increasingly clinical implementation in the last decade. The careful selection of TAVI candidates is of great importance for a successful procedure and can be achieved with the contribution of Computed Tomography (CT), as CT is the main imaging method that provides information required for the selection of bio-prosthesis and the access routes. CT pre-TAVI includes specified measurements of the aortic valvular complex on reconstructed CT images in the true plane of the aortic annulus and also the investigation of possible endovascular or extravascular access routes. The CT scanning protocol and the contrast agent dose must be modified in such a way to provide high-quality CT images with a minimum of contrast amount, regarding the advanced age patients. There are advantages and limitations of CT-examination that will be discussed. Finally, the derived results of CT pre-TAVI have to be reported in a template to facilitate communication between radiologists and cardiologists.

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KEY WORDS
Transcatheter aortic valve implantation; Computed Tomography; Aortic valve stenosis.

Introduction

Aortic valve stenosis (AS) is the most common valvular heart disease in the Western world. As the valve stenosis worsens, symptoms progress from mild to severe, leading to heart failure or even death [1]. Although surgical aortic valve replacement (SAVR) has been considered the standard treatment, approximately 30% of AS patients are non-eligible for surgery due to very high surgical mortality risk, because of other existing co-morbidities [2]. Transcatheter aortic valve implantation (TAVI) or otherwise known as transcatheter aortic valve replacement (TAVR) is a minimally invasive technique, which has significantly evolved in the last decade as an alternative treatment for patients with symptomatic severe AS, who are considered inoperable and high-risk for SAVR. This technique is based on transcatheter therapies, in which a bio-prosthetic aortic valve can be transported to the aortic root replacing functionally the native valve. Information about the anatomy of aortic valve and possible access routes is of great importance in order to ensure accurate prosthesis deployment and minimize peri- and postprocedural complications [3, 4]. Preprocedural multidetector computed tomography (CT pre TAVI) provides essential information which are required for patient selection, device size selection, and the preprocedural mapping of access routes. In this review, we discuss the current role of CT pre-TAVI emphasizing on the technical consideration, the anatomy and measurements of the aortic valve and its pathological findings.

Discussion

Definition of TAVI

TAVI is a catheter-based procedure that consists of deploying a bio-prosthetic aortic valve in the aortic root after transporting the device from a chosen entry point. The most common approach is retrograde via femoral or subclavian artery. Other alternative options can be a percutaneous transapical approach through the apex of the left ventricle, a suprasternal approach through the brachiocephalic trunk, an anterior approach through a minimal right anterior thoracotomy, or a partial ministernotomy for transaortic placement through the ascending aorta [5,6,7]. The currently available devices for TAVI are the balloon-expandable Sapien valve from Edwards Lifesciences and the self-expandable CoreValve from Medronic. In order to cover a range of diameter values of the native aortic valve, there are several sizes available of these bio-prosthetic valves from 16 to 30mm and their delivery systems have a sheath size of 14-16F.

Indications for TAVI

TAVI procedure has been consolidated as the solution for inoperative patients with severe symptomatic AS and a life expectancy of more than 1 year. However, recent trials show that patients with an intermediate surgical risk can also be highly benefited [8,9,10] as the efficacy of TAVI is comparable with that of SAVR in these patients. The decision should be taken by the Heart Valve Team based on the benefits and risks of both procedures. In the case of a degenerated surgical bio-prosthesis of the aortic valve, the deployment of a second bio-prosthesis using TAVI procedure is an option treatment and a further indication for TAVI. This procedure is also known as valve-in-valve. The American College of Cardiology/American Heart Association and the European Society of Cardiology/European Association of Cardio-Thoracic Surgery has issued guidelines for the current clinical indications to TAVI [8, 9, 10].

The role of CT in the diagnosis of severe aortic valve stenosis

Transthoracic echocardiography using Doppler techniques is the imaging method of choice to diagnose AS and assess its quantitative and qualitative severity. In patients with a discordant result on Doppler Echocardiography, a non-contrast CT is performed for the assessment and grading of the AS [11]. The AS severity is

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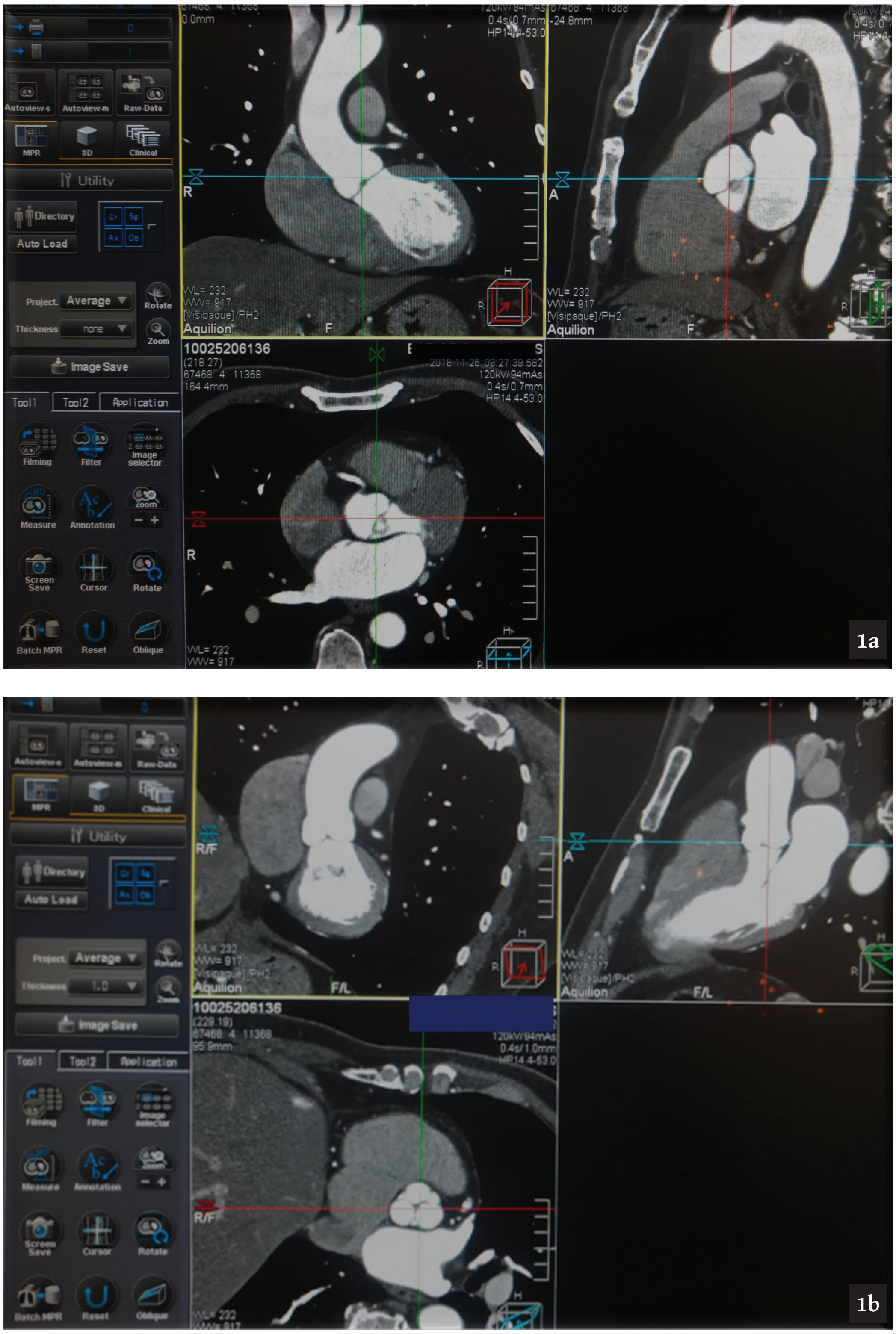


Fig. 1: ***a)*** *The CTA dataset (in systolic phase) as it is loaded on the workstation. The original three imaging planes are orthogonal to each other at a 90° angle and the reference lines are located on the center of the aortic valve.* ***b)*** *the three imaging planes after reformation to the annular plane: the derived axial image shows the three valvular leaflets, which are symmetric.*

associated with the load of valve calcification that can be evaluated either qualitatively or quantitatively. The qualitative classification as none, mild, moderate or severe is based on visual grading and is proposed by consensus of the ESCR [11]. A large amount of calcification affecting all cusps of the aortic valve is graded as severe. For the exact quantification of calcifications, the Agatston score technique is used, which is similar to the protocol for Calcium scoring of the coronary arteries. The CT protocol technical parameters are 120 KV and axial reconstructed images of 3mm thickness. Agatston score values ≥ 2000 for men and ≥ 1200 for women are considered to make severe AS likely and values ≥ 3000 for men and ≥ 1600 for women indicate that severe AS is highly likely [12,13].

Protocols for CT pre-TAVI

To obtain high-quality CT- images of the aortic valve complex and the assess route, a Dual-Source scanner or at least a 64-detector scanner is required [11]. Reconstructed CT images at 1.0 mm or less without motion artifacts are needed to enable multiplanar reformation for better evaluation and accurate measurements. The large anatomic CT scan range from the subclavian to the femoral arteries in combination with the need of the least possible contrast material dose, demands fast acquisition with low radiation. Because of the fragile nature of the patients that undergo this procedure, the reduction of the contrast material dose is essentially more important than that of the radiation dose to prevent contrast-induced nephropathy [14]. This is feasible with the latest generation multidetector CT scanners with a large anatomic coverage per rotation, which rendered fast scanning possible of both the heart and aortoiliac vessels with a reduced dose of contrast material [15].

For the CT-imaging of the aortic valve, a retrospectively ECG-gated or prospectively ECG-triggered CT Angiography (CTA) is obligatory to avoid motion artifacts and to enable reconstruction of several cardiac phases. The CT scan range should include the following anatomical parts of the aortic valve complex: left ventricular outflow tract (LVOT), annulus, sinus of Valsalva, sinotubular junction, ascending aorta, and coronary ostia. A small field of view focused on the aortic root should be used to increase spatial resolution. As the aortic annulus shows a difference in the dimensions between systole and diastole during the cardiac cycle, measurements should be performed in the systolic phase, where the aortic complex is often largest [16, 17].

Additionally, a CTA of aortoiliac vessels follows the CT of the aortic valve. The scan range extends from above the subclavian arteries to the proximal common femoral arteries. It can be performed in an ECG-gated or non-gated acquisition, depending on the scanner hardware. On the ECG-gated CTA acquisition, the radiation dose is higher compared with the non-gated acquisition, and a higher dose of contrast material is needed. As non-gated CTA offers images of sufficient quality with reduced contrast material dose, it is preferably for the evaluation of the aortofemoral vessels, since advanced age is often associated with depressed renal function.

For this reason and according to the consensus by the European Society of Cardiovascular Radiology (ESCR) [11] fast anatomic coverage and low KV (70–80 kV) imaging is recommended to allow for a reduction in the amount of contrast agent [18]. Low kilovolt settings have been shown to reduce radiation dose for multidetector CT angiography without compromising image quality [19]. Contrast material (minimum of 350 mg/mL) should be administrated in a single injection of around 50ml in total for both acquisitions with a flow rate of 3– 4 ml/s, depending on body weight and CT system [18].

Anatomy and assessment of the aortic root

The aortic valve root consists of the aortic valve annulus, commissures, sinuses of Valsalva [SOV], ostia of coronary arteries [OCA], and sinotubular junction [STJ]. It extends from the left ventricular outflow tract (LVOT) to the sinotubular junction, which is the transition from the aortic sinuses of Valsalva to the tubular ascending aorta. It has a relatively central and double-oblique orientation in the heart and a crown-shaped three-dimensional morphology. The aortic valve root contains the aortic valve within the aortic sinus (15). The aortic valve is composed of three leaflets which are often significantly calcified in most severe AS patients. A variant of a bicuspid valve may be present in TAVI candidates, as valve degeneration occurs faster and more often than in tricuspid valves [20].

The evaluation of the aortic root, regarding the TAVI procedure, includes information about the morphology of the valve, the leaflets number, the grade, and mor-

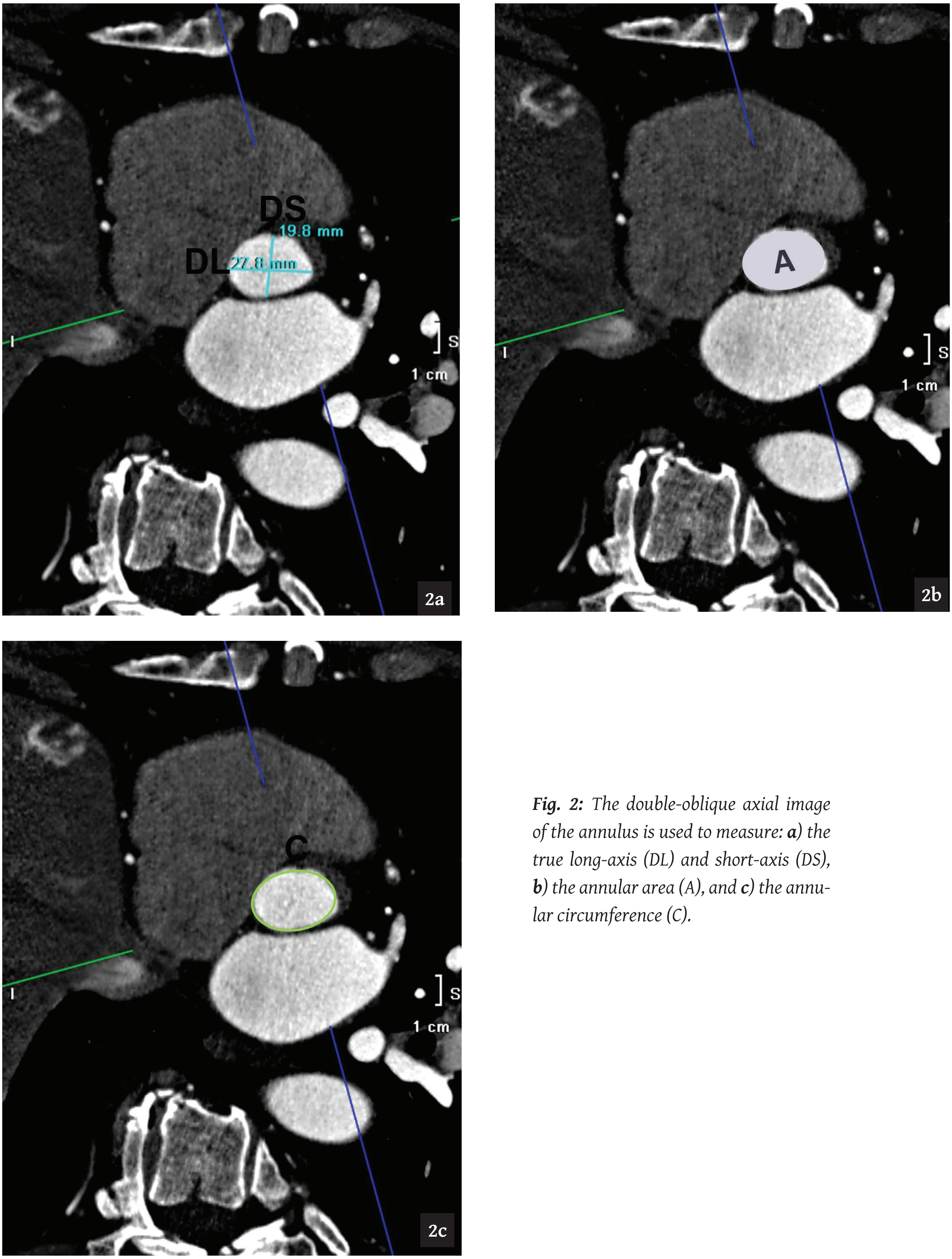


Fig. 2: The double-oblique axial image of the annulus is used to measure: ***a****) the true long-axis (DL) and short-axis (DS),* ***b****) the annular area (A), and* ***c****) the annular circumference (C).*

phology of the calcifications.

CT can evaluate the calcifications either qualitatively (mild, moderate, severe) or quantitatively using the Agatston Score technique [12,13]. The distribution pattern is also important, if calcifications are focal or diffuse, symmetric, or asymmetric, on the aortic valve leaflets and the attachment sites. Depending on the degree and distribution, aortic valve calcifications affect the alignment and deployment of the bio-prosthesis during the TAVI- procedure. This may lead to a paravalvular leak [21] due to the interposition of calcifications between the device and the native aortic valve. Furthermore, severe aortic valve calcification is a known risk factor for annular rupture, prosthesis dislodgement, or coronary ostium occlusion [21,22].

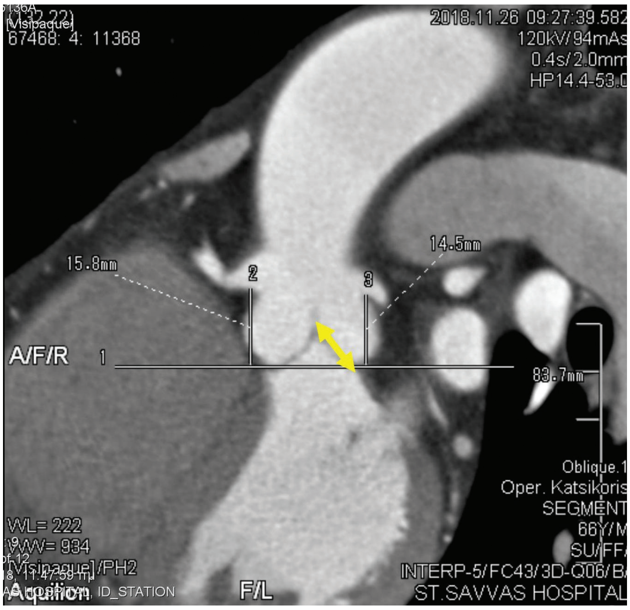


Fig. 3: *On the derived sagittal CT image, the distance of the inferior edge of each coronary ostium from the annulus plane is measured, and also the length of the leaflets. If this distance is less than 10 mm or is greater than the length of the aortic valve leaflets, the risk of occlusion is high.*

CT assessment of the aortic annulus

The aortic annulus is not a real anatomic structure of the aortic root but a term to describe a virtual ring formed by the nadir of the attachment sites of the aortic valve leaflets. The shape of the annulus is more oval than circular. Exact measurements of the annulus are of great importance for choosing the size of the bio-prosthesis. Therefore, images of high quality are required to provide reliable measurements. Even minor differences in these measurements can produce different results, which affect the choice of the bio-prosthetic valve size. According to the consensus by ESCR [11], the main elements of CT in annular sizing are: (a) obtaining a correct image orientation in the true plane of the aortic annulus, (b) correctly measuring the annulus using different methods, and (c) implementing these measurements in the selection of transcatheter valve size.

Because of the double-oblique orientation of the aortic root and annulus in the heart, the standard axial CT plane is not corresponding to the real axial view of the annulus. A double-oblique axial image is reformatted orthogonally to the long axis of the aortic root, to correspond to the real axial view (Fig. 1). This is achieved by interactively manipulating the reconstruction planes on a workstation so that the nadirs of all three leaflets are identified on one transverse plane. This double-oblique axial image can be used to measure the true long-axis (DL) and short-axis (DS) diameters of the annulus, the annular area (A), and the annular circumference (C). The annular area (A) and annular circumference (C) can be measured manually using a planimetry tool on a workstation (Fig. 2). The following three methods are proposed for the calculation of the mean annular diameter [11,15,23]:

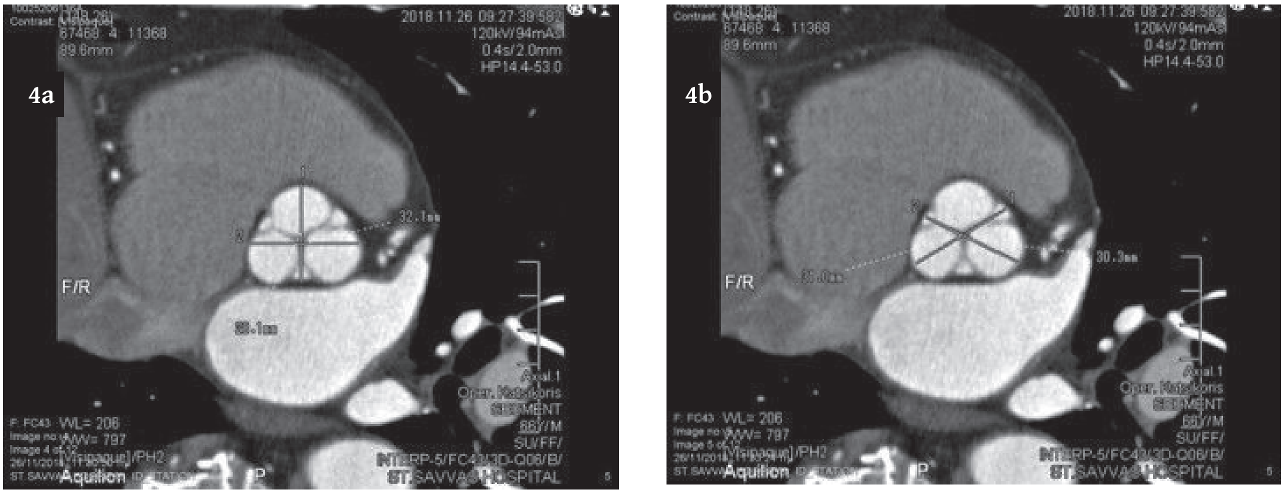
1.The cross-sectional derived mean diameter (DCS) is estimated by simple averaging (DCS = (DL + DS):2).

2. The area-based diameter (DA) is calculated as follows, DA = 2 × √(A/ π), π =3.14

3. The circumference-based diameter DS is calculated as follows DC = C/ π, π =3.14

Circumference - and area-based diameters are used most as reliable parameters for choosing the appropriate size of the bio-prosthesis. As the circumference-based diameter is not significantly affected by the dynamics of the cardiac cycle and shows low interobserver variability, it should be preferred for the device size selection [23-25].

The aortic bio-prothesis extending into the ascending aorta by design leaves the coronary ostia open. A rare complication during the TAVI procedure is the coronary ostia obstruction from the displacement of the



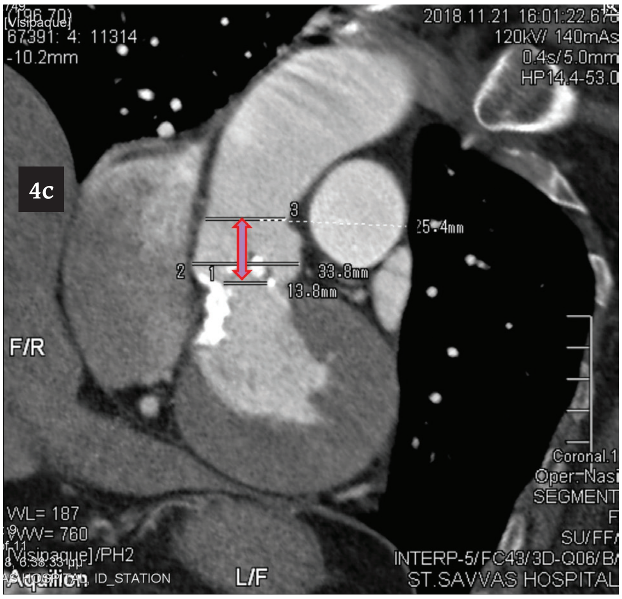


Fig. 4: a- b) *Measurements of the Sinus Valsalva on the derived axial CT images.* ***c)*** *Double-headed arrow shows the maximal height of the sinus Valsalva.*

native aortic valve leaflets. The reported incidence of this complication is about 0.8%, increasing to 3.5% in valve-in-valve procedures [26]. Patients with large native aortic valve leaflets in combination with low-lying ostia of the coronary arteries have a high risk of coronary obstruction. For this reason, the distance of the inferior edge of the coronary ostium from the annulus plane should be measured (Fig. 3). If this distance is less than 10 mm or is greater than the length of the aortic valve leaflets, the risk of occlusion is high [15, 27]. In addition, the size of the sinus could also play a role in this complication, since the sinus of Valsalva acts as a reservoir for the displaced native aortic valve calcifications after device deployment. The width and maximal height of the sinus of Valsalva should be measured on a double-oblique projection (Fig. 4) and are also important parameters to select a suitable device system without causing coronary occlusion [11].

Another point, which is crucial during the TAVI procedure, is to choose the correct tube projection to define the optimal fluoroscopic orientation of the aortic root. This fluoroscopic orientation of the aortic root is consistent with an orthogonal view of the aortic valve plane and enables the correct positioning of the bio-prosthesis along the centerline of the aortic root and perpendicular to the aortic annular plane. It is a time-consuming procedure for the operator to find the correct fluoroscopic orientation, increasing not only the radiation dose but mainly the need for contrast material volume, leading to potential contrast-induced ne-

Fig. 5: The atrioventricular angle is determined from the original CT coronal view, namely by determining the angle of the horizontal plane at the level of the ventricle and annulus angulation.

phrotoxicity [28,29]. The aortoventricular angle, which is best determined from the CT coronal view, namely by determining the angle of the horizontal plane at the level of the ventricle and annulus angulation (Fig. 5), corresponds to the optimal fluoroscopic projection [23]. These angulation data can be obtained manually through manipulation of the multidetector CT dataset or derived using specialized software tools [29,30]. The CT-based prediction of annulus projection assumes, that a patient's position between the CT acquisition and the TAVI procedure would be comparable.

Severe calcifications in the aortic valve complex and higher heart rates produce artifacts on CT images, that often prevent the optimal annulus measurements and the estimation of the annular plane. Therefore, images free of artifacts and of high quality are needed for sufficient evaluation of the CT pre-TAVI examination.

CT assessment of the access route

As already mentioned, the bioprosthetic aortic valve can be transported to the aortic root using a specific device delivery system. The most preferred access route to the aortic valve is retrograde via the femoral artery and if this is not possible, a trans-subclavian, trans-apical, or trans-aortic approach can be chosen alternatively (Fig. 6). However, these optional approaches require a surgical incision. The decision for the selection of one of the possible access routes is based on the type of the bio-prosthesis device, the size and properties of the delivery system, and the adequacy of the investigated route [15]. Therefore, the role of CT is important in the evaluation of the potential access routes. For the endovascular approach, the minimal diameter of the arteries is estimated in CTA using curved multiplanar reformation

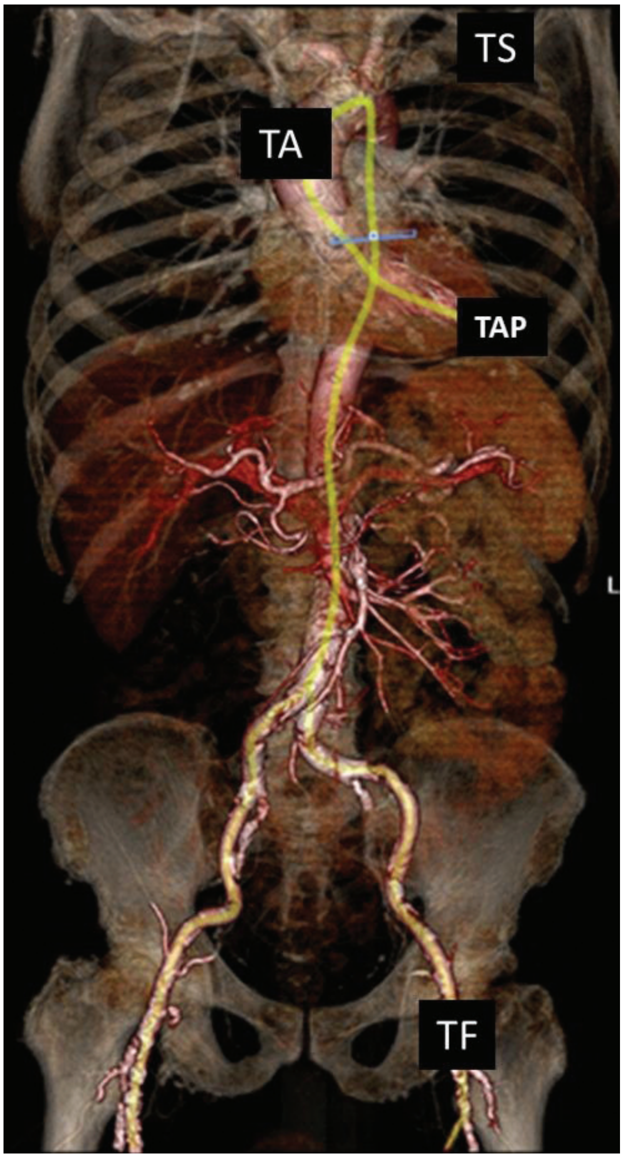


Fig. 6: The potential entry sites are demonstrated on the 3D CT image: transfemoral (TF), trans subclavian (TS), transaortic (TA), and transapical (TAP).

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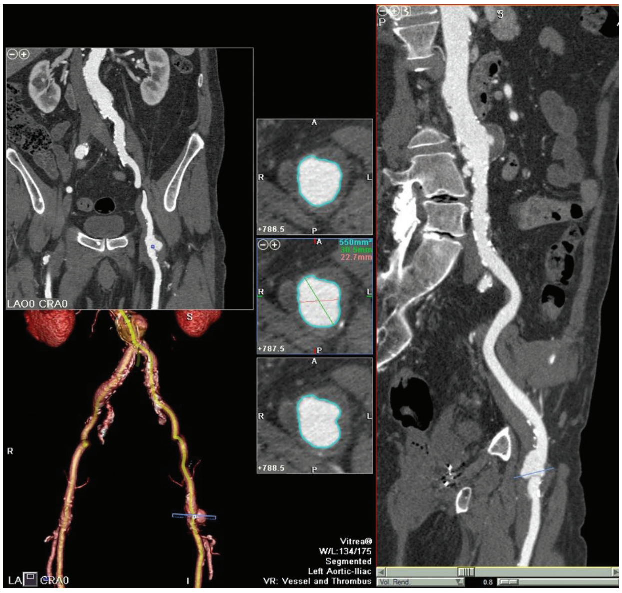

Fig. 7: *Aneurysms of the abdominal aorta and the left common femoral artery. The measurements are performed on derived axial images, orthogonally to the longitudinal vessel axis.*

Table 1. The required measurements and investigation from CT pre-TAVI

ANATOMY	
AORTIC VALVE	Cuspidity (bicuspid, tricuspid, other variants) Extent and distribution of calcifications
AORTIC ANNULUS	Short- and long-axis diameter (mm) Circumference (mm) Area (mm²) Optimum fluoroscopic projection angle (aortoventricular angle)
AORTIC ROOT	Height and width of sinus of Valsalva Distance from annular plane to coronary ostia (mm) Diameter sinotubular junction (mm)
AORTA	Anatomy, variants of the aortic arch Ascending aorta, aortic arch, and descending aorta diameters Tortuosity and elongation Dissections, aneurysms Intraluminal calcification, thrombi
SUBCLAVIAN ARTERIES	Minimal luminal diameters Tortuosity Calcifications, thrombi
ILIOFEMORAL ARTERIES	Minimal luminal diameters at several levels Tortuosity Calcifications, thrombi
LEFT VENTRICULAR APEX	Myocardium characteristics

(MPR). The measurements are performed on derived axial images, orthogonally to the longitudinal vessel axis of the common femoral, external iliac, and common iliac arteries (Fig. 7) as well as abdominal and thoracic aorta at several levels. Furthermore, left and right subclavian arteries may be used for endovascular access, and they should also be evaluated and included in the CT report. Minimal diameter of the inner lumen of the vessel of at least 5mm is required as the minimum vessel size should be larger than the outer diameter of the chosen delivery system (Fig.8) [11]. Medtronic and Edward Lifesciences bio-prosthesis have 14F sheaths for transfemoral delivery. Devices larger than 22–24F has been reported a higher incidence of vascular complications, from 23 to 31% [31] compared with smaller systems (1.9– 13.3%).

Additionally, the morphology of the vessels, such as the elongation, tortuosity, and angulation, or variations are associated with procedural complications and can be evaluated in 3D images.

The degree and extent of the atherosclerotic calcifications and the presence of thrombi in the vessels should be completely described, because of the high risk of complications [32]. For example, calcifications or thrombi in the aortic arch or the ascending aorta may lead to cerebrovascular microembolic events during or after the TAVI procedure [27]. Furthermore, severe circumferential calcifications of the ascending aorta are a contraindication for surgical aortic valve implantation and are one of the most serious indications for TAVI.

Although the retrograde via femoral artery approach should always be the first option, in case of severe arterial stenosis, occlusion, aneurysms with mural thrombus or aortofemoral bypass, optional access routes even more non- endovascular such as transapical or transaortic access should be selected [33].

For the transaortic approach, the entry site on the ascending aorta should be about 6 cm above the annular plane. This distance from the annular plane is required to accommodate the device length [15, 23] and is estimated on Volume-rendered CT images. At this entry site, possible calcifications plaques must be reported, to avoid complications during the device passage.

For transapical access, the angle between the left ventricular (LV) apex and the left ventricular outflow tract (LVOT) should be estimated, as the degree of angulation may complicate the procedure. A contraindication for the transapical approach is the myocardial apical infarct with apical thrombus [11].

The required measurements of the aortic root, aortic annulus, and access route are shown in Table 1.

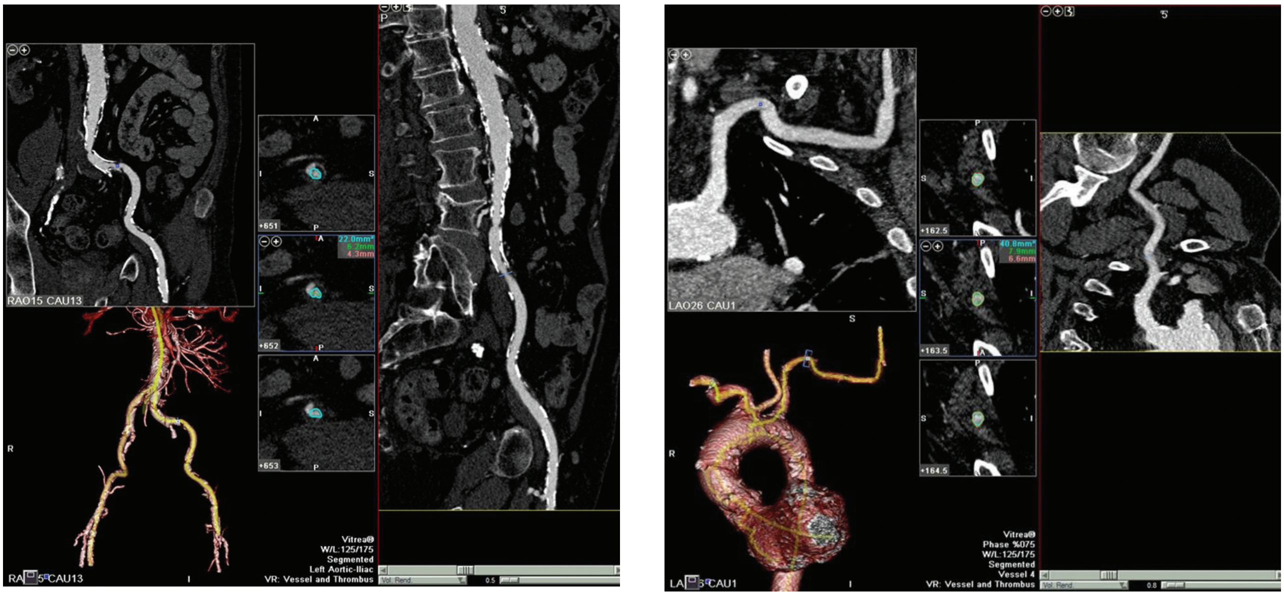

Fig. 8: ***a)*** *Porcelain calcification and stenosis of the left common iliac artery (inner diameter less than 5mm).* ***b)*** *Measurement of the lumen diameter of the subclavian artery.*

Incidental findings and comorbidities

Incidental findings in preprocedural CT are common in TAVI candidates, because of their advanced age and their physical condition. They may be detected in an incidence of about 34.3%, also including malignancies in 4.1% [34]. These findings must be reported and evaluated regarding their effect on the prognosis and the procedural success [11, 34, 35].

Additionally, during the CT an incomplete filling of the left atrial appendage may be shown. In such a case a second scan of the area 2 minutes after contrast injection should be performed to exclude a real thrombus, as this is a contraindication for TAVI due to the high risk of stroke.

As expected, coronary artery disease is common in patients undergoing TAVI [34, 35]. The evaluation of the coronary arteries performed using an invasive angiography and a CT-based evaluation is not recommended for these patients [35]. The reason is, that this population often shows coronary significant calcification and cardiac arrhythmia, which are limitations for coronary CT angiography. However, CT preprocedural TAVI may allow in the same examination, the evaluation of coronary arteries with using no more contrast material doses [36, 37].

Finally, the above-described measurements of the aortic root, aortic annulus, access route, and also incidental CT findings should be careful and systematically reported. For this reason, structured reports or otherwise known as templates are developed to include every related information from the CT pre-TAVI.

Conclusion

Transcatheter aortic valve implantation has rapidly gained preference in the treatment of symptomatic aortic valve stenosis for inoperable patients. CT preprocedural TAVI is absolutely necessary for the selection of the bio-prosthesis and the access route. Depending on the CT scanner and the specified demands of the CT examination (large anatomic scan range, high-quality images of at least 1mm reconstructed, minimal contrast agent amount) a suitable CT scanning protocol should be used. Great caution is required for the measurements of the aortic valvular complex and also for the investigation of endovascular or extravascular access routes. The CT results should be in a template reported. Finally, a collaboration between the radiologist and cardiologist is important for the success of the TAVI procedure. **R**

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