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CARDIAC RADIOLOGY

# Recommendations in pre-procedural imaging assessment for TAVI intervention: SIC-SIRM position paper part 2 (CT and MR angiography, standard medical reporting, future perspectives)

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**Abstract**
Non-invasive cardiovascular imaging owns a pivotal role in the preoperative assessment of patient candidates for transcatheter aortic valve implantation (TAVI), providing a wide range of crucial information to select the patients who will benefit the most and have the procedure done safely. This document has been developed by a joined group of experts of the Italian Society of Cardiology and the Italian Society of Medical and Interventional Radiology and aims to produce an updated consensus statement about the pre-procedural imaging assessment in candidate patients for TAVI intervention. The writing committee consisted of members and experts of both societies who worked jointly to develop a more integrated approach in the field of cardiac and vascular radiology. Part 2 of the document will cover CT and MR angiography, standard medical reporting, and future perspectives.

**Keywords** Aortic valve stenosis · TAVI · Imaging · Echocardiography · Computed tomography · Magnetic resonance

**Abbreviations**

| | |
|---|---|
| 2D/3D | Bi-three dimensional |
| AKI | Acute kidney injury |
| ATTR-CA | Transthyretin cardiac amyloidosis |
| BAV | Bicuspid aortic valve |
| CAD | Coronary artery disease |
| CABG | Coronary artery bypass graft |
| CM | Contrast material |
| CMR | Cardiac magnetic resonance |
| CT | Computed tomography |
| CTA | Computed tomography angiography |
| CCTA | Coronary computed tomography angiography |
| ECV | Extracellular volume |
| HR | Heart rate |
| ICA | Invasive coronary angiography |
| LGE | Late gadolinium enhancement |
| MR | Magnetic resonance |
| LVOT | Left ventricle outflow tract |
| SIC | Italian Society of Cardiology |
| SIRM | Italian Society of Medical and Interventional Radiology |
| SSFP | Steady-state-free-precession |
| TAVI | Transcatheter aortic valve implantation |
| VIV | Valve-in-valve |
| VTC | Virtual transcatheter aortic valve to coronary distance |
| VTSTJ | Valve-to-sinotubular junction distance |

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## Introduction

Advances in non-invasive imaging have occurred in parallel with the progression in the field of TAVI, refining patient selection, treatment planning, device selection and positioning. As described in Part 1 of this SIC-SIRM TAVI position paper, Echocardiography remains the first-line test for patients undergoing TAVI. However, Computed Tomography (CT) has become crucial in pre-procedural TAVI planning, representing the gold standard technique for the assessment of the aortic root, coronary ostia height, evaluation of the best access route, and prediction of appropriate fluoroscopy projection angles for prosthesis deployment. CT is also valuable to confirm the severity of the valvulopathy in the presence of low-flow, low-gradient, for an accurate quantification of the aortic valve calcium score and to calculate the aortic valve area with extreme precision. Magnetic Resonance (MR) may represent an alternative in patients unsuitable for CT given the availability of unenhanced cardiac MR (CMR) protocols. Moreover, MR is the gold standard for ventricular volumes and function and accurate in diagnosing myocardial fibrosis, an independent predictor of unfavourable post-operative left ventricle ejection fraction recovery and clinical outcome in TAVI patients. Part 2 of the SIC-SIRM TAVI position paper provides an updated guide for the use of CT-MR imaging and future perspectives in patients undergoing TAVI, reflecting both the opinions of cardiologists and radiologists involved in the diagnostic workflow providing recommendations on their use (Table 1).

## Cardiovascular CT angiography

### CT Technologies

The continuous evolution of CT technology, characterized by a progressive and constant increase in spatial and temporal resolution, the possibility of acquiring larger anatomical volumes with reduced scan-times, and the cardio-synchronization associated with a significant lower radiation dose, justifies the role of CT as standard of reference for the evaluation of patient candidates for TAVI. The available CT technology strongly influences the optimization of the scan protocols for pre-TAVI imaging, taking into account the need to acquire a large anatomical volume (from the subclavian to the common femoral arteries) together with the use of ECG-gating for the evaluation of the aortic root in order to perform the anatomical measurements, preferably in the systolic phase of the cardiac cycle. Patient candidates for TAVI are usually challenging, frequently elderly, with reduced respiratory compliance, often with coexisting tachyarrhythmias, and marked calcifications of the aortic valve. The scan protocols must include an image reconstruction thickness $\leq 1$ mm in order to obtain accurate 2D/3D reconstructions; therefore, it is mandatory to have at least a 64-multidetector-CT scanner. Moreover, in patients enrolled for TAVI who are generally fragile, it is essential to optimize the technical and image quality to avoid the need for repeat CT scanning, due to both radiation and iodinated contrast material (CM) dose damage, considering the high prevalence of renal dysfunction [1].

### Patient preparation

Respiratory motion artefacts degrade image quality, regardless of heart rate (HR), therefore, it is necessary to adequately instruct the patient before the scan to properly stop breathing. Even if beta-blockers are part of recommended treatment for severe acute stenosis, improving metabolic and hemodynamic impairment, [2] their administration prior to the examination should be avoided for the high risk of adverse effects, mainly due to reduced inotropy [3, 4]. Nitroglycerine is generally contra-indicated in severe aortic stenosis (risk of rapid hemodynamic collapse and hypotension) and therefore usually should not be administered prior to scanning [3, 4].

### CT scan acquisition

#### CT scan protocol

The CT scan should allow the acquisition of an angiographic phase with high image quality and extended from the subclavian to the common femoral arteries, with the need to use ECG-gating at the cardiac and aortic root levels to minimize/avoid cardiac movement artefacts and allow a multi- or at

**Table 1** Adopted Grading Score for recommendations

| | |
|---|---|
| (A) Strong recommendation | There is high certainty based on evidence that the net benefit is substantial |
| (B) Moderate recommendation | There is moderate certainty based on evidence that the net benefit is moderate to substantial, or there is high certainty that the net benefit is moderate |
| (C) Weak recommendation | There is at least moderate certainty based on evidence that there is a small net benefit |
| (D) Recommendation against | There is at least moderate certainty based on evidence that there is no net benefit or that risks/harms outweigh benefits |
| (E) Expert opinion | Net benefit is unclear. Balance of benefits and harms cannot be determined because of no evidence, insufficient evidence, unclear evidence, or conflicting evidence, but the Work Group thought it was important to provide clinical guidance and make a recommendation. Further research is recommended in this area |
| (N) No recommendation for or against | Net benefit is unclear. Balance of benefits and harms cannot be determined because of no evidence, insufficient evidence, unclear evidence, or conflicting evidence, and the Work Group thought no recommendation should be made. Further research is recommended in this area |

least biphasic (best diastole and best systole) assessment of the aortic root and coronary arteries. However, scanning and contrast material injection protocols should be optimized according to the available technology. Three are the main scanning strategies, all including the whole aorta from the subclavian arteries to the common femoral arteries: (a) ECG-gated (spiral or sequential) scan of the chest + ungated spiral scan of the whole abdomen; (b) wide detector ECG-gated scan of chest and abdomen, and finally (c) ECG-gated (spiral or sequential) scan of the heart + high pitch ungated spiral scan of chest and abdomen through a DSCT scanner. An accurate evaluation of the aortic root (left ventricle outflow tract—LVOT, annulus, sinus of Valsalva, sino-tubular junction, and coronary ostia) is crucial in order to avoid prosthetic valve under-/over-sizing, resulting in peri-procedural (annular rupture, valve embolization, coronary occlusion, etc.) and post-procedural complications (peri-prosthetic leak). The selection of the systolic cardiac phase generally allows the evaluation of the largest dimensions of the aortic annulus, because in this phase the annulus is slightly but significantly larger than in the diastole, with the exception of the case of interventricular septal hypertrophy [5]. The ECG-gated CT angiography can be reconstructed with a field of view (FoV) centered on the aortic root to increase spatial resolution, while a larger FoV is applied for the assessment of the subclavian arteries. Generally, a fast scan-speed and the use of low kVp (with iterative reconstruction algorithm) are strongly recommended to allow a reduction in the amount of CM and iodine concentration, respectively [6]. It is possible to perform a preliminary unenhanced ECG-gated CT scan of the aortic root with scan parameters identical to those used for the evaluation of the coronary artery calcium score (3 mm slice-thickness; tube voltage peak: 120 kVp) to calculate the calcium score of the aortic valve [7].

### Radiation exposure

The setting of the CT scan parameters should allow the radiation dose to be kept "as low as possible" while still ensuring adequate diagnostic quality of the examination acquired in accordance with the ALARA principle [8]. For this purpose, some strategies could be adopted: dose modulation with the peak tube-current applied during a single phase of the cardiac cycle, reduction of the phases of cardiac cycle acquired with focus mainly on the systolic phases, limiting the ECG-gated CT scan volume to the aortic root and coronary arteries [8].

### Contrast administration

Usually, a single intravenous (iv) injection of CM is recommended through an 18–20 gauge cannula, preferably in an antecubital vein and a bolus of at least 50 ml (up to 100 ml) at flow rates of 4–6 ml/s followed by a 50–60 ml of bolus chaser at the same flow-rate is often sufficient, but these parameters should always be adapted to the scanner technology available, iodine concentration, physical habitus and clinical conditions of the patient. Bolus-test or bolus-tracking techniques are applied to define the CT scan-delay, according to what is generally done in CT angiography (CTA) and coronary CTA (CCTA) exams. The volume of iodinated CM is of concern in many patients because candidates for TAVI frequently have an impaired renal function. Some recent evidences have shown the possibility to perform a CT scan for TAVI planning using low-dose (40 ml) or ultra-low dose (20–30 ml) CM injection protocol, particularly useful in specific clinical scenario such as in patients with chronic renal disease [9]. Acute kidney injury (AKI) subsequent to the TAVI procedure has been identified as a major predictor of mortality. In particular, the association between larger volumes of CM and the likelihood of contrast-induced nephropathy has been well described for coronary interventions, but only a few studies have reported a relationship between contrast volume and AKI occurrence in TAVI patients [10–13] Previous studies showed an association of prior chronic renal failure, peri-procedural bleeding and blood transfusion, transapical access route, peripheral vascular disease, and arterial hypertension with the occurrence of AKI following TAVI [14, 15]. A summary of the CT protocols and CT acquisition recommendations are provided in Tables 2 and 3.

## CT post-processing

### Aortic valve anatomy and cusp characteristics

The aortic valve is a complex structure and part of the aortic root, supported by a fibrous skeleton, extending from the ventricular-arterial junction to the sino-tubular junction. The aortic valve is generally constituted by the three valve leaflets or cusps named by the respective sinuses of Valsalva (right, left, and non-coronary) and anchored to the aortic wall by the outward semi-circular edges. The joining points between the valve cusp attachments and the annulus are called commissures. The assessment of the aortic root morphology should always include a description of the aortic valve morphology (number of cusps, thickness, calcification, and coaptation), and measurement of aortic lumen dimension at different levels (aortic annulus, sinuses of Valsalva, and sino-tubular junction) (Fig. 1). Since the anatomical conformation of the aortic root is variable between different subjects and its orientation does not respect the standard anatomical planes, its evaluation must be performed using specific oblique

**Table 2** CT scan protocols

| | |
|---|---|
| Scanner requirements | 64-Slices or higher (image reconstruction thickness ≤ 1 mm) |
| Scan range | From subclavian arteries to common femoral arteries |
| Scan protocol | Scan protocol according to the CT scanner used |
| | The coverage of the whole cardiac cycle is recommended (aortic annulus preferably assessed in systole) |
| | A pre-contrast scan of the aortic root can be added to assess calcium score of the aortic valve |
| Contrast material | Higher iodine concentration |
| | Flow rate: 4–6 mL/s |
| | Biphasic injection (50–100 mL of CM followed by 50–60 mL of bolus chaser) |
| | Start delay assessed by bolus test or bolus tracking techniques |
| Scan parameters | ALARA (as low as reasonably achievable) principles |
| | Fast scan speed and low-kVp (with iterative reconstruction algorithm) allow a reduction of the radiation dose, amount of CM and iodine concentration (useful in TAVI candidate patients, frequently with chronic kidney disease) |

CM, contrast media; CT, computed tomography; TAVI, transcatheter aortic valve implantation

**Table 3** Recommendations for CT and CMR use before TAVI

| | |
|---|---|
| CTA should be obtained in all patients before TAVI, unless contraindicated to assess the aortic annulus, aorta, peripheral access and fluoroscopic projection angle for the implantation procedure | A |
| Beta blockers and nitrates generally should not be used in patients with severe AS for the preparation to CTA | B |
| The report of a pre-TAVI CT or MR examination should include all information and measurements of the aortic root, thoracic-abdominal aorta and arterial access routes. The use of a structured report is strongly recommended to ensure that all relevant data is contained and to facilitate the communication of results | E |
| Aortic Valve Calcium score can be used in patients with discordant echocardiographic parameters to confirm the presence of severe AS | B |
| Scan protocols should be optimized according to the available technology and CT scan parameters should allow the radiation dose to be kept "as low as possible", at the same time obtaining high quality diagnostic images | E |
| In VIV with stented prosthesis, a VTC of less than 4 mm indicates a higher risk of coronary occlusion | B |
| The volume of iodinated CM should be kept as low as possible to reduce the likelihood of contrast-induced nephropathy (TAVI patients frequently have an impaired renal function at baseline) | B |
| In patients with contraindications to CM, pre-procedural CMR before TAVI can be used as an alternative method for the evaluation of the aortic root, thoraco-abdominal aorta and peripheral arterial accesses | B |
| In patients undergoing CMR before TAVI without contraindications to CM, LGE evaluation should be performed as it provides prognostic information | C |
| CMR can be used as a screening for subclinical amyloidosis associated with severe AS in patients candidate to TAVI | C |

AS, aortic stenosis; CM, contrast material; CMR, cardiovascular magnetic resonance; CT, computed tomography; CTA, computed tomography angiography; TAVI, transcatheter aortic valve implantation; VIV, valve-in-valve; VTC, virtual transcatheter aortic valve to coronary distance

bi-dimensional (2D) reformatted planes (Fig. 2). 2D/3D reconstruction tools provided in commercially available image analysis software obtains the specific aortic planes (long axis and orthogonal planes). These aortic planes can be automatically generated by dedicated software with a specific TAVI-module, able to extract the aortic centerline and create images oriented exactly orthogonal to the aortic root (cross sectional imaging) or may be manually reconstructed using a cross-sectional approach, guided by double oblique visualization. In patients with severely degenerated valves, as in TAVI candidates, the aortic valve is often heavily calcified and the assessment of the number of valve leaflets by echocardiography may be difficult; the ECG-gated CT-angiography with multiphasic or at least dual-phase (systole and diastole) reconstructions may be helpful and determine the morphology of the valve, in particular to distinguish congenital anatomical variants such as a bicuspid aortic valve (BAV). The BAV is associated with accelerated aortic valve degeneration with early and higher incidence of stenosis in comparison with the tricuspid valve, and is present in an increasing number of patient candidates for TAVI [16]. While BAV morphology is not a contra-indication for a TAVI procedure, it might affect procedural complexity because of the frequent association with bulky valve calcifications, larger annulus dimensions, increased annular ellipticity, asymmetric cusps and ascending aorta dilation [16]. Consequently, BAV subjects have an increased risk of procedural complications as device mal-positioning, high-residual gradient or significant residual aortic regurgitation (AR), annular rupture

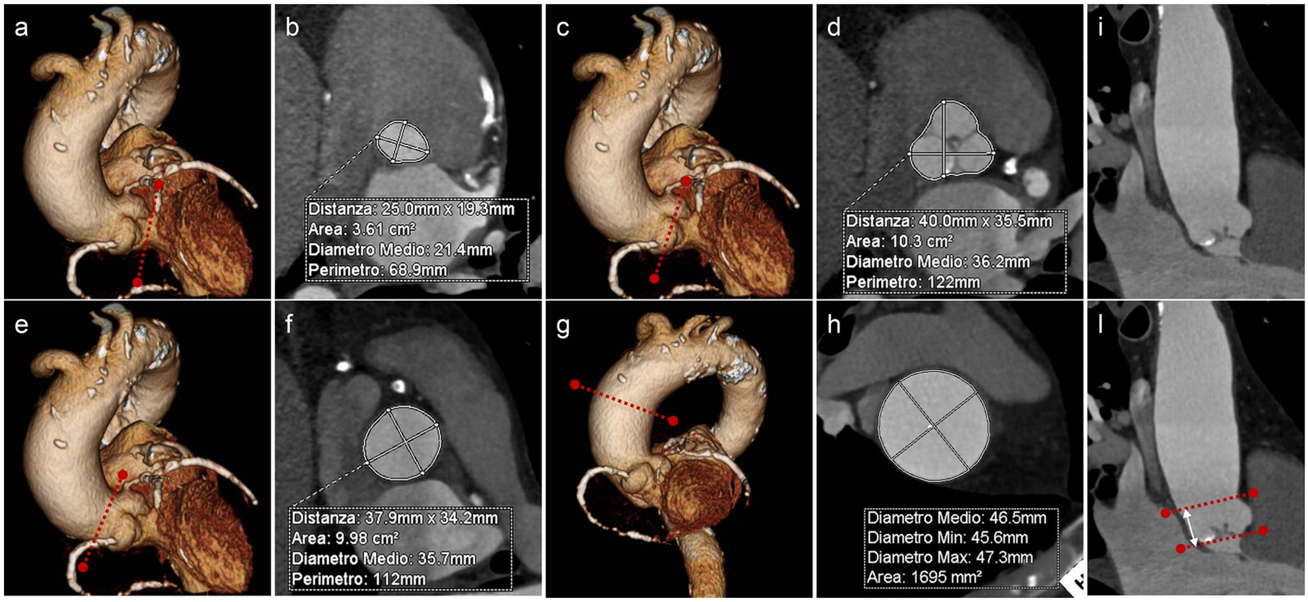


**Fig. 1** Measurement of the aortic lumen dimension at different anatomic levels as showed in the 3D VR images (**a**, **c**, **e**, **g**) through true orthogonal MPR images at the level of the aortic annulus (**a**, **b**), sinuses of Valsalva (**c**, **d**), sino-tubular junction (**e**, **f**), mid ascending thoracic aorta (**g**, **h**), with the assessment of the sino-tubular junction height (**i**, **l**)

or aortic dissection [17] and higher permanent pacemaker rate after TAVI implantation [17, 18].

## Aortic root size assessment

The aortic root connects the heart to the systemic circulation and is a highly sophisticated and complex structure, consisting of distinct entities: annulus, aortic valve, sinuses of Valsalva, and sino-tubular junction. On CT images, the aortic annulus is the anatomical site corresponding to the basal ring of the valve, perfectly aligned to the lowest insertion points (hinge points) of the aortic cusps, located just below the ventricular-arterial junction. An accurate assessment of the aortic annulus and aortic root measurements is a fundamental step in evaluating TAVI eligibility, for the correct pre-procedural planning and for proper device selection (prosthesis sizing and design). The use of the reconstructions along the conventional anatomical planes (coronal and sagittal) or single-oblique reconstruction to roughly measure the annular size is not acceptable. Optimal image quality and meticulous attention in properly orienting the reconstructed oblique planes are mandatory to provide reliable measurements, which are the basis of device selection. How to obtain the correct cross-sectional image of the aortic annulus with a double oblique approach starting from the conventional planes is shown in Fig. 2. The annulus sizing needs of a standardized and reproducible approach. In particular, the annular dimensions that should be measured and reported include the long- and short-axis diameters, the sectional area, and the perimeter (Fig. 3), all measurements obtainable through a (semi-)automatic attenuation/Hounsfield-unit-based contour detection. The area and circumference-derived effective diameter are calculated under the geometric assumption of a full circularity of the annulus after device deployment. However, these methods suffer from an intrinsic error and may be discrepant when the native annular shape is particularly eccentric, which in some cases can lead to under- or over-sizing of selected prosthesis with consequent risk of peri-prosthetic leak or incomplete device opening. The annulus is subject to conformational and dimensional changes during the cardiac cycle: its shape is more circular in systole and predominantly oval to ellipsoid in diastole. Short-axis diameter, sectional area and perimeter are larger during systole compared to diastole due to the increase of radial forces related to left ventricular ejection. Therefore, when a multiphase dataset is available, images reconstructed in the systolic phase should be preferred for the measurement of annulus sizes [19] as in subjects with wide changes between different phase, the use of diastolic measurements may result in undersizing TAVI prostheses and thus in increased risk of peri-prosthetic leak (Fig. 4) [19]. However, systolic images are more susceptible to cardiac motion artefacts in patients with high HR or arrhythmia and, if dose modulation is used during the scan acquisition, are typically characterized by increased image noise. In these cases, the diastolic images might offer a better motion-free image quality. Stenotic aortic valve disease is frequently characterized by a variable degree of calcium deposition on the valve leaflets, whose amount rises according to the stenosis degree and predicts worse prognosis [20]. The prevalence of calcific

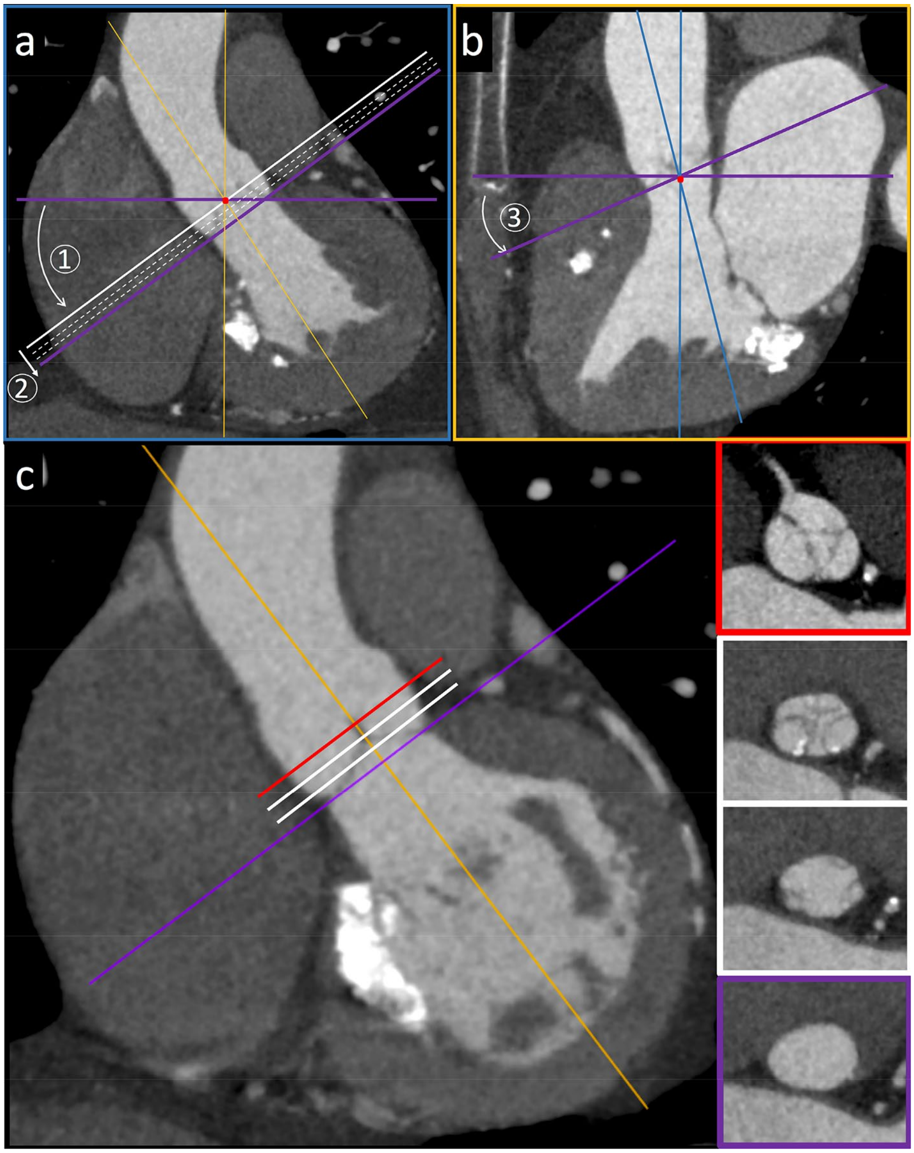


**Fig. 2** Instruction for multiplanar reconstruction of the aortic annular plane using a common viewer (generally with simultaneous vision of the triple projection). Once the CTA dataset is loaded, scroll the coronal images to the one passing through the center of the aortic root (**a**). In the coronal image, bring the axial viewing plane (horizontal purple line) to the level of the plane passing through the center of the aortic valve. By placing the center of rotation (red dot, meeting point between the rotation axes) at the center of the valve area, the axial plane is rotated (STEP 1) until it is perfectly parallel to the plane passing through the annulus (white line). Then move the reference line of the axial plane caudally (STEP 2) until it passes through the hinge points of the aortic cusps (inclined purple line). The sagittal plane (orange reference line), locked at 90° to the axial viewing plane, will be tilted accordingly. On the newly generated oblique sagittal plane (**b**), the axial reference line (horizontal purple line) will be rotated (STEP 3) until it passes through the lowest anterior and posterior insertion points of the aortic cusps. The scrolling of the new oblique axial plane just oriented (**c**) will enable the visualization of the plane passing through the annulus (purple box), the planes passing through the insertions of the cusps (white boxes) and the sinuses of Valsalva (red box)

aortic stenosis, in particular, increases with age with a sharp peak in patients aged > 65 years [21], which represents the population most frequently undergoing TAVI. Aortic valve calcification degree may be assessed by qualitative visual estimation (absent, mild, moderate, and severe, Fig. 5) on CTA images, even though a method based on the Agatston scoring system employed for the quantification of coronary calcium on unenhanced ECG-gated CT scan has been proposed for the quantitative assessment and pre-procedural risk stratification [22–24], with the most used cut-off value, which makes severe aortic stenosis likely, of 2000 for men and 1200 for women. Distribution of valvular calcium deposition should be routinely described based on pattern (symmetric versus asymmetric, diffuse versus focal) and location

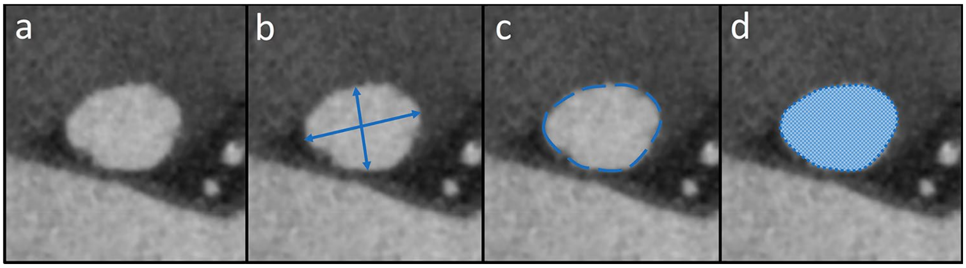


**Fig. 3** Once the MPR image passing through the aortic valve annulus has been reconstructed using the CTA dataset (**a**), the annular diameter can be measured with three strategies: direct measurement of maximum and minimum diameters (double-headed arrows, **b**) or indirect sizing starting from the measurement of the perimeter (**c**, dashed line) and the area (**d**, blue oval)

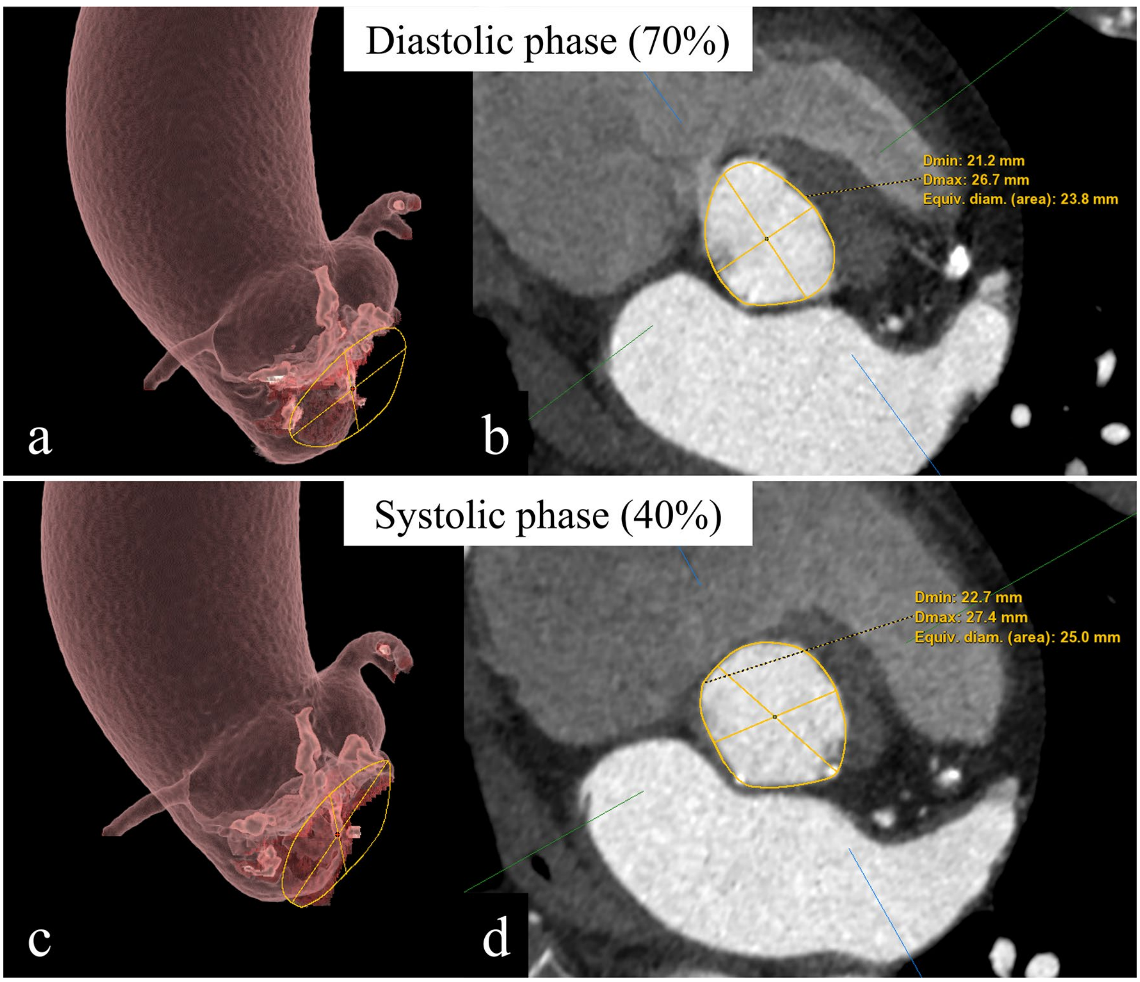


**Fig. 4** Measurement of aortic annulus in different phases of the cardiac cycle. Notice how the aortic annulus shape is more circular in systole and tends to be ellipsoid in diastole. Short-axis diameter and area are larger during systole compared to diastole

with respect to the cusps (leaflet edges, commissures, and attachment sites) and LVOT. When the delivery system opens, the calcified native valvular leaflets are squeezed onto the aortic walls. Many studies have demonstrated a significant impact of calcification degree and distribution of device landing zone on procedural outcome after TAVI with both self-expanding and balloon-expandable devices [25–27]. Bulky or eccentric calcifications of the aortic valve may hamper the complete opening of the device or hinder the correct anchoring of the prosthesis. Indeed, the mechanical obstacle constituted by the calcific nodules attached to the edge of the leaflets or the commissure can cause a residual

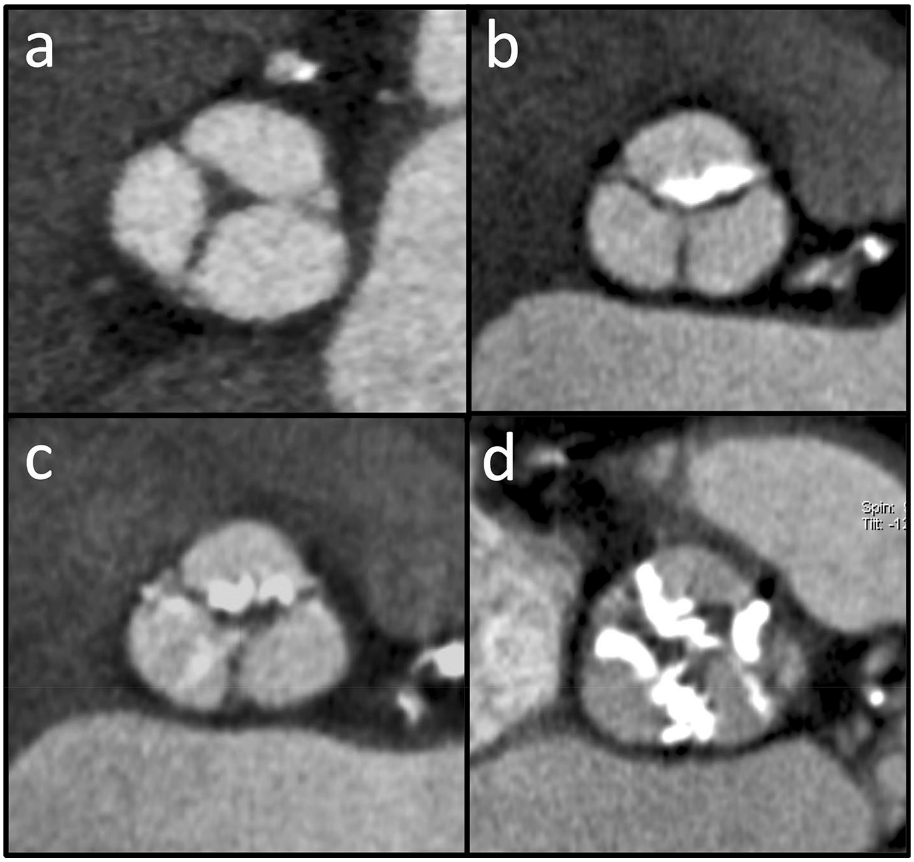


**Fig. 5** The aortic valve can be visually assessed according to four degrees of valvular calcification: absent (**a**, no calcification), mild (**b**, small and/or isolated calcification), moderate (**c**, large or multiple calcifications) and severe (**d**, extensive calcification of all leaflets/commissures)

gap between the prosthesis valve and the aortic root, which may affect the stability of the implanted prosthetic valve, the adherence to anchor sites or deform the section of the device. Severe valve calcification, in particular, increases risk of post-procedural regurgitation [21, 26, 27] or peri-prosthetic leak [27], leading to further pressure overload, which is poorly tolerated by these patients. Severe calcifications of the aortic valve are also known to be associated with other complications such as annular rupture with balloon expansion as aortic ring calcifications confer rigidity and reduced deformability to the annulus, conduction disturbances [25], or calcific embolism [28]. A further potential risk related to severe valve calcification is the coronary ostia obstruction by a voluminous calcific aortic cusp [22]. In TAVI, the native leaflets (including any adherent calcifications or vegetations) are not removed, as during surgical valve replacement, but are displaced and crushed against the native aortic walls by the prosthesis during system release. Obstruction of coronary ostia by the overlap of native valve leaflets is a life-threatening and fortunately rare complication of TAVI procedures, occurring in 0.35–0.8% of cases [29], most frequently reported in patients receiving a balloon-expandable valve, and generally involves the left coronary artery. It usually requires percutaneous coronary intervention and, despite the high rate of feasible and successful treatment reported in the literature, short- and long-term mortality still remains high [29]. Lower-lying coronary ostia, shallow sinus of Valsalva, heavily calcified and long native aortic valve leaflet are predisposing anatomical conditions [29], therefore a detailed pre-procedural anatomical evaluation is crucial to minimize the risk of this alarming complication. Measurement of longitudinal distances from the aortic annulus plane to the inferior margin of each coronary ostia on CT images is required, by applying appropriately oriented multi-planar reconstructions on the oblique coronal view during systole (Fig. 6). A distance between the coronary ostia and valve annulus greater than 10–14 mm is generally considered low risk of coronary obstruction, even though a shorter distance is not strictly assumed as an exclusion criterion for TAVI and those measures should be related to corresponding aortic cusp length [22]. However, the heavy and diffuse calcification of valve cusps should be taken into particular consideration, even more in cases of adequate distance between the coronary ostium and valve plane [22]. Evaluation should also include the measurement of the transverse diameters and the height of the aortic root at the level of the sinuses of Valsalva on a double-oblique projection, as specific TAVI devices require a minimum sinus width and height values for the correct deployment, which varies from model to model. The LVOT should be explored to verify the adequacy

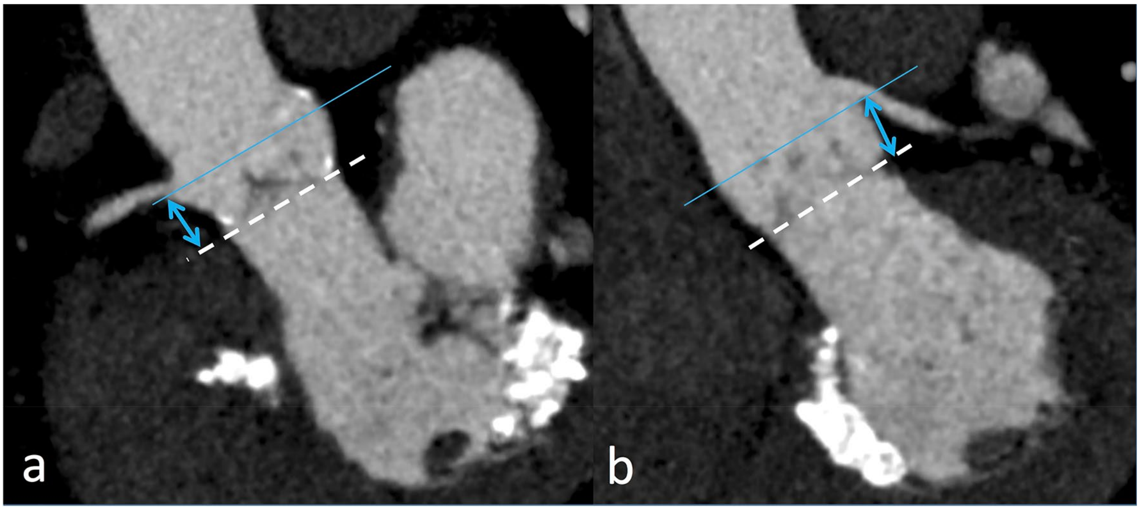


**Fig. 6** The distances between the annular plane and the ostia of right coronary artery (**a**) and left main artery (**b**) are assessed on dedicated MPR images, as the minimal distances between the lower border of the respective ostium to the attachment of the corresponding leaflet

of the landing zone and exclude the presence of sub-valvular obstructions, in particular in the case of a transapical approach, and to verify the presence of calcification; in this case it is preferable to use a self-expandable valve. Further routine measurements should include the assessment of the sino-tubular junction and ascending aorta maximum and minimum diameters (generally, 50 mm above the aortic annulus) [22].

## Coronary artery imaging

Degenerative aortic stenosis and coronary artery disease (CAD) share many risk factors, with obstructive CAD present in 52–65% of TAVI candidates [30]. During routine pre-TAVI assessment, CAD evaluation is recommended, and invasive coronary angiography (ICA) is frequently performed. Although controversial evidence exists on the prognostic value of CAD assessment [30] and on the preferable treatment strategy (before or after TAVI), it is common practice to favor percutaneous revascularization prior to TAVI, also because coronary hemodynamics are influenced by aortic valve stenosis removal. Considering that the pre-operative aortic CTA study generally includes the visualization of the coronary arteries in the same exam, coronary CT assessment could replace ICA to rule-out significant obstructive CAD, at least in the proximal and mid coronary arteries in a large number of TAVI candidates, avoiding additional CM or radiation dose. Nevertheless, it is common that TAVI patients often present with suboptimal image quality for an adequate assessment of coronary arteries due to the extensive calcifications, arrhythmias, reduced compliance in breath holding, and contraindication to beta-blockers and nitroglycerine [4]. However, given the wide heterogeneity of different clinical settings, the use of CTA for the exclusion of obstructive CAD should be modulated on the basis of centre-specific factors (technology available, staff experience) and a case-by-case basis [31]. However, in cases of previous coronary artery bypass graft (CABG), CTA assessment is recommended due to the high accuracy of the CT scan in the evaluation of graft patency [32].

## Aorta and peripheral vascular accesses

In pre-procedural TAVI evaluation, non-invasive imaging plays an important role in accurate evaluation of the vascular access. An accurate chosen access route is one of the most important components of procedural eligibility and success in order to minimize risk of peri- and post-procedural complications [33]. CT is more accurate than conventional single-plane angiography, allowing 2D and 3D reconstructions for the optimal assessment of the minimal vessel lumen diameter, vessel tortuosity, severity, extension and pattern of atherosclerosis, and identification of high-risk features, including dissections and complex atheroma (Fig. 7). Moreover, CT easily rules out congenital anatomic variants [34] (i.e., interrupted aortic arch, bovine aortic arch, double aortic arch, aortic coarctation, aberrant right or left subclavian artery, right arch mirror image) and other aortic anomalies (i.e., aneurysms, atherosclerosis/thrombosis) which could determine the best vascular access. Arterial transfemoral access is still the approach of preference for all devices. Subclavian, common carotid artery and brachiocephalic artery represents alternative accesses for both TAVI devices, while the left ventricular transapical approach is available only for the SAPIEN device. A further and more recent alternative for both devices is the minimally invasive

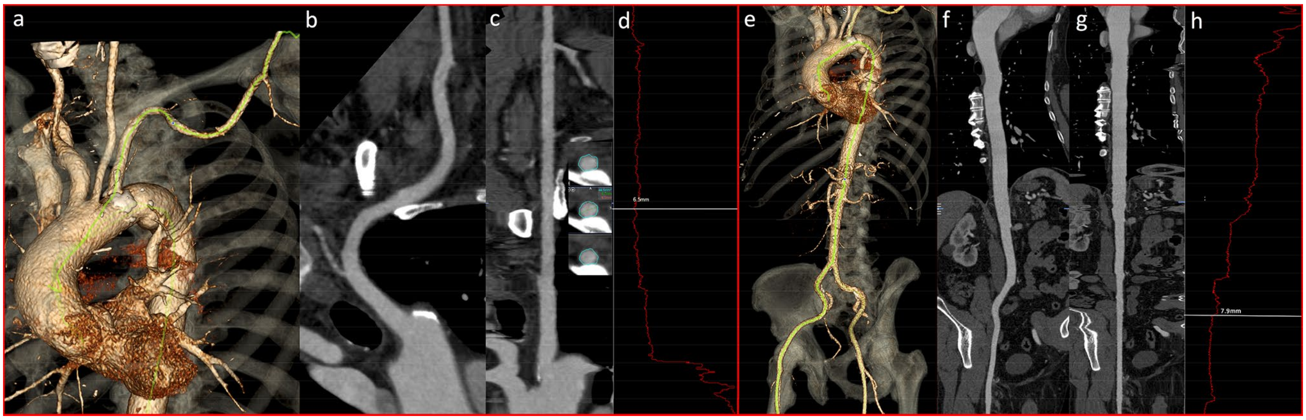


**Fig. 7** Assessment of the subclavian (**a**–**d**) and femoral (**e**–**h**) arterial accesses. The three-dimensional volume rendered CT images (**a**, **e**) offer an immediate visual evaluation of the tortuosity of the arterial tree, detecting any acute angulations. The curved planar reformations (CPR, **b**, **f**) and the straightened CPR (**c**, **g**) identify any stenosis or aneurysmal dilatations and identifies the tracts of vessels with minimum caliber. Some applications offer an automatic extrapolation of the average diameter of the vessel at each point throughout the course (**d**, **h**), therefore implementing and speeding up the identification of the point of minimum diameter

transaortic pathway through a mini sternotomy with an entry point approximately 6 cm above the annular plane. Available device delivery systems come with different sheath sizes depending on the manufacturer and the production version of the device [35]. Ideally, the minimum diameter of the native vessel should be larger than the outer diameter of the chosen delivery sheath [22]. Circumferential atherosclerotic wall calcifications (or horseshoe-like pattern), small native vessel diameters and marked tortuosity are risk factors for procedural complication [35] and if there are two or more of these features, other approaches (i.e. trans-apical, trans-aortic) must be considered [33]. Vascular complications are the most frequent complications of transfemoral TAVI (together with peri-prosthetic regurgitation and stroke) [35]. The CT analysis of peripheral access must be performed through a standardized approach that includes 3D imaging, curved MPR and MIP for calcifications, with all measurements taken in an orthogonal plane (cross section) to the vessel in order to obtain a more accurate evaluation [36]. CT is also valuable for the determination of optimal fluoroscopic angulation for the prosthesis implantation as showed in Fig. 8.

## Valve-in-valve implantation (VIV)

Transcatheter aortic valves can be used to treat patients with a degenerated bioprosthetic valves in a procedure named Valve-in-Valve implantation (VIV). Coronary occlusion risk is higher in patients undergoing VIV than TAVI in native AS, in particular with stented prostheses. The VTC (virtual transcatheter aortic valve to coronary distance) should be measured as it predicts the distance from the expanded transcatheter aortic valve frame to the coronary ostia. Post-processing software can simulate the presence of the transcatheter aortic valve as a cylinder with defined height and width. A VTC of less than 4 mm indicates a higher risk of coronary occlusion [37]. Moreover, as the new implanted prosthesis can determine the sequester of sinus of Valsalva at the level of sinotubular junction, a valve-to-sinotubular junction distance (VTSTJ) should also be measured (Fig. 9) [38].

## Cardiovascular MR angiography

In pre-TAVI evaluation, Magnetic Resonance (MR) has the advantage of associating the functional and quantitative assessment of the aortic valve with the anatomical evaluation of the aortic root, thoraco-abdominal aorta and peripheral arterial accesses, similar to CT but with the absence of radiation burden and use of iodinated CM [39] along with an accurate assessment of the impact of valvular disease on ventricular function. Another strong point of MR is the possibility to diagnose myocardial damage [40] associated with aortic valve disease by evaluating the late enhancement of macroscopic fibrosis using a gadolinium-based CM, characterized by a significant lower nephrotoxicity and associated with a lower incidence of adverse reactions in comparison with the iodinated CM used in CT. More recently, quantitative MR tissue characterization techniques such as T1 mapping and extracellular volume (ECV) provide insight into pathologies that result in diffuse myocardial fibrosis despite late gadolinium enhancement (LGE) being absent, making the use of CM potentially avoidable and reducing the risk of systemic nephrogenic fibrosis in patients with pre-existing severe renal dysfunction. Pre-contrast T1 values are typically increased in patients with severe aortic

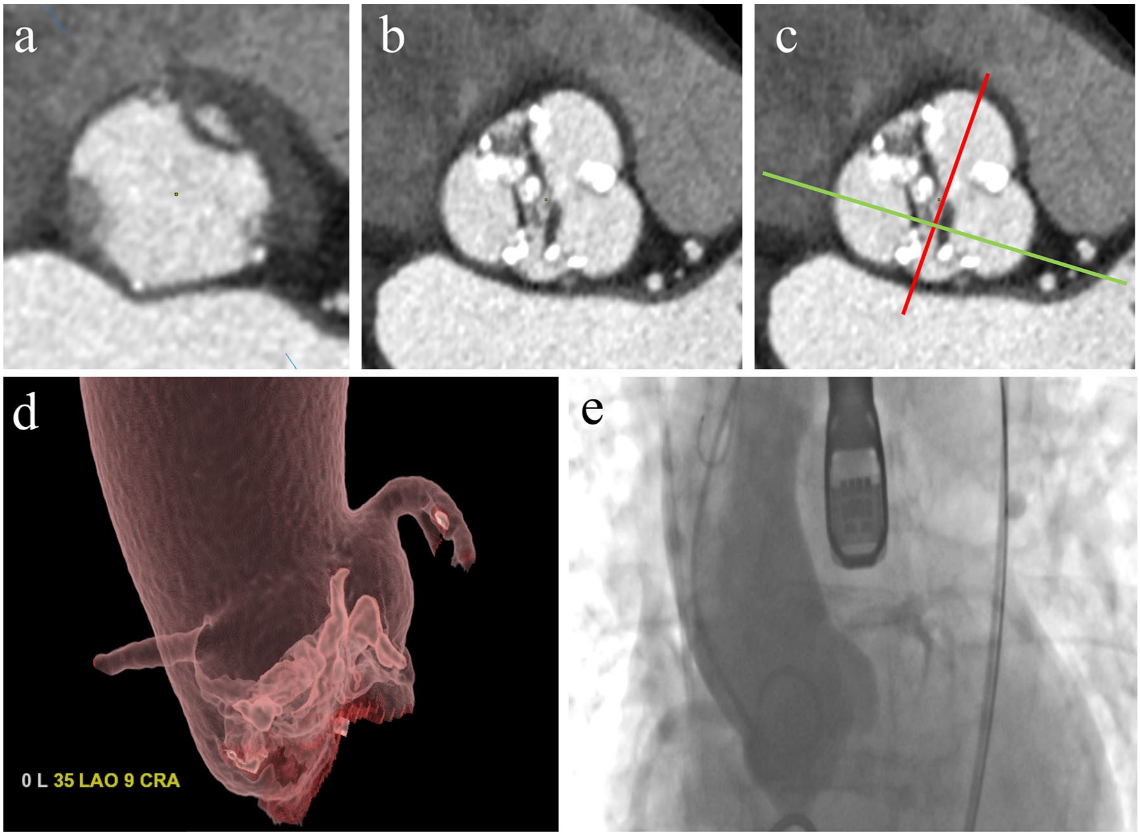


**Fig. 8** CT determination of optimal fluoroscopic angulation for TAVI procedure: **a** the cross-sectional plane of the aortic annulus is obtained (as already explained in Fig. 2). **b** the plane is shifted cranially to the level of the aortic valve. **c** The desired plane **d** is orthogonal both to the aortic annulus (red line) and to the commissural line (green line) between the left and non-coronary aortic cusps (**d**). The coordinates of the desired plane (in this case 35 LAO 9 CRA) are used in fluoroscopy during the TAVI procedure (**e**)

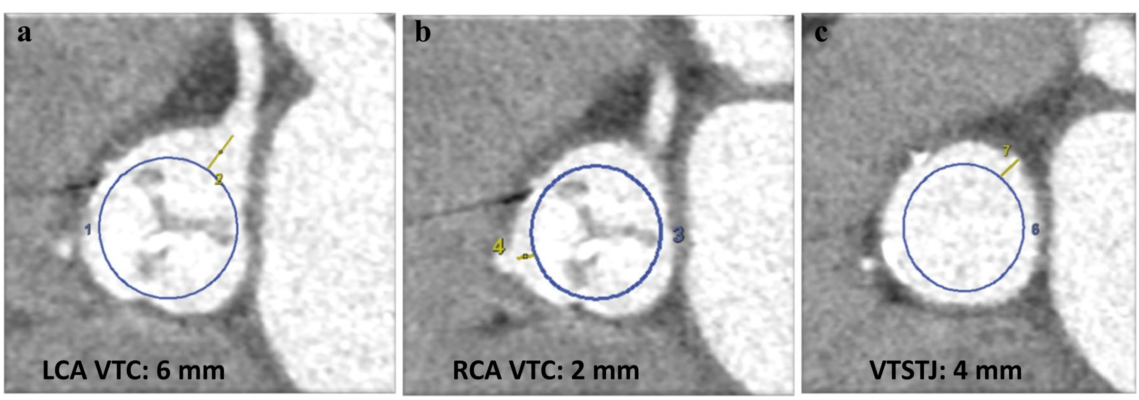


**Fig. 9** Simulation of TAVI Valve-in-Valve implantation: circular region of interest (**a**, **b**) with the dimension of the new prosthesis is traced (blue circle) for the measurement of virtual transcatheter aortic valve to coronary distance (VTC, yellow line) for left coronary artery (**a**) and right coronary artery (**b**). Notice that in this case, VTC for the right coronary artery is < 4 mm, with an increase in the risk of coronary obstruction post-TAVI deployment. The valve-to-sinotubular junction distance (VTSTJ) should also be measured (**c**, yellow line) to assess the risk of sinus of Valsalva sequester at the sinotubular junction. LCA: left coronary artery; RCA: right coronary artery

stenosis compared with control subjects and are even higher in symptomatic versus asymptomatic patients. Despite the setting of elderly patients, CMR is feasible in the majority of patients undergoing TAVI [41], except in those with an unsafe device, claustrophobia, poor clinical conditions, and severe arrhythmias. The limited use of MR in this setting is probably due to its greater technical complexity, longer study times, need for a greater degree of patient collaboration and by the inadequate assessment of valvular calcifications. However, in patients with severely depressed renal function, MR is a valid diagnostic alternative to CT.

The MRI protocol before TAVI requires adding to the classical cine steady-state-free-precession (SSFP) sequences used for the study of the heart, at least two cine images of the long axis of the aortic root, with the first obtained in an oblique coronal plane and the second obtained from the first along the passage of the plane through the aortic root and the ascending aorta. Moreover, a stack of cine images has to be acquired orthogonal to the previous two planes covering the entire aortic root. After these planes, thoracic and abdominal aorta and iliaco-femoral arteries can be assessed by two different approaches: (1) in patients with severe renal impairment and/or allergy to gadolinium chelates, a 3D-SSFP navigator-echo and ECG-gated sequence can be used for the thoracic aorta, while a non-contrast-enhanced MRA can be used for aorto-iliac evaluation [42]; (2) in patient without contraindication to contrast agents a contrast-enhanced MR angiography (CE-MRA) from aortic arch to proximal femoral arteries can be obtained [42]. Finally, T1 mapping sequences with evaluation of native T1 and extracellular volume as well LGE sequences are used for myocardial tissue characterization. Although MR is accurate for measuring aortic annulus diameters, the presence of voluminous calcifications can limit the accuracy of measurements due to the low signal associated with calcium [43] while it is able to provide an accurate and reproducible estimate of the height of coronary ostia and size of the aortic valve leaflet [44]. In addition, it must be considered that MR is the gold standard for ventricular volumes and function, particularly recommended in patients undergoing TAVI, given up to 50% of patients with severe aortic stenosis have evidence of focal fibrosis or unrecognized infarct by CMR at baseline [45]. Studies show that myocardial fibrosis is an independent predictor of unfavorable post-operative left ventricle ejection fraction recovery [46] and clinical outcome in TAVI patients and therefore, if possible, CMR LGE evaluation should be suggested in pre-operative assessment [47].

## Standard medical report in TAVI

The report of a pre-TAVI CT or MR examination should include all information and measurements of the aortic root, thoracic-abdominal aorta and arterial access routes [39, 48–52]. For this purpose, the use of a structured report is strongly recommended to ensure all the data are effectively reported and to facilitate the communication of results. A standardized pre-TAVI report should be generally provide and the Table 4 summarizes the main details/findings that should be included.

## Future perspective

### 3D printing

Three-dimensional (3D) printing is an emerging technique able to convert digital models into 3D objects. Its application in cardiovascular medicine is relatively recent [53]. The utility of 3D cardiovascular models is particularly felt in interventional cardiology, where a deep knowledge of patient-specific anatomy is fundamental to guide catheter-based procedures. The safety and efficacy of TAVI as aforementioned is strictly related to accurate aortic valve annulus sizing. At this aim, 3D printing allows the ability to create patient-specific 3D printed models of the aortic valve and aortic root complex, that have been proposed as a new tool for preoperative planning of TAVI, and even useful to predict which patients are more likely to develop peri-prosthetic regurgitation [54]. In particular, it could help simulate the implant, as in the operating room, evaluating the best operative approach. Moreover, it could be used during the Heart-Team discussion for decision making, also providing a tactile feedback of what the procedure will be like. Inter-manufacturer reproducibility is a basic requirement for 3D model generation and to improve diffusion of the technique for planning of endovascular procedure. Even if the process can be partly automated, it nevertheless requires great care for setting threshold values and when adjusting segmentation contours, but errors can be generated during any step of the process, including segmentation, post-processing and 3D printing [55]. To date, 3D printing has been used for the pre-treatment assessment of the aortic root in a small number of cases, demonstrating the capability of CT to allow the creation of 3D models of the aortic ring and surrounding structures for potentially safer valve deployment [56, 57].

### Role of CMR to screen subclinical transthyretin cardiac amyloidosis (ATTR-CA) in TAVI patients

Transthyretin cardiac amyloidosis (ATTR-CA) is the most common cause of restrictive cardiomyopathy in the elderly. It is usually wildtype (wtATTR) and acquired, characterized by a male preponderance and late onset; in fact it is formerly known as senile amyloid. Amyloid deposits from ATTR-CA are reported in 25% of histological specimen from surgically removed heart valves in adults > 80 years [58] and in up to 16% of patients with severe calcific aortic stenosis undergoing TAVI [59]. Patients suffering from severe aortic stenosis resulted to be associated with low-flow low-gradient pattern, severe diastolic dysfunction and

**Table 4** Main details/findings to be included in a standardized pre-TAVI report

| | | | |
|---|---|---|---|
| Scanner Type: | | | |
| Scan protocol (*main option strategies*): | Option a* | Option b# | Option c° |
| ECG-gating: | No | Yes: prospective | Yes: retrospective |
| Contrast agent: | Concentration | Total contrast volume | Flowrate |
| Cardiac cycle phase: | Systole | Diastole | |
| Aortic valve morphology: | Tricuspid | Bicuspid | Incomplete bicuspid |
| Aortic valve calcifications: | Absent | | |
| | Present | Localization and grading (qualitative/quantitative)<br>Extension to the aortic mitral curtain<br>Extension to the membranous septum | |
| Sub-valvular stenosis: | Absent | Present | |
| Aortic root: | | | |
| - Annulus | Diameters | Perimeter | Surface area |
| - Bulb | Diameters | | |
| - ST-junction | Diameters | Height | Wall atherosclerosis (y/n) |
| Coronary arteries ostia: | Location | Height (from annulus) | |
| Coronary arteries assessability (mid-proximal segments): | No | Yes: anomalies (*origin/course*) | Yes: calcification/stenosis |
| Left appendage thrombosis: | Absent | Present | Suspected (smoke-effect) |
| Thoracic aorta: | Diameters, lumen, course, atherosclerosis (characteristic/severity), disease extension | | |
| Abdominal aorta: | Diameters, lumen, course, atherosclerosis (characteristic/severity), disease extension | | |
| Subclavian arteries: | Course, patency, atherosclerosis, stenosis, minimal lumen diameter | | |
| Iliac-femoral axes: | Course, patency, atherosclerosis, stenosis, minimal lumen diameter | | |
| Recommended vascular access: | Subclavian/femoral/transapical/transaortic | | |
| Collateral findings: | Extra-/intra-vascular (± clinical indications) | | |

*ECG-gated (spiral or sequential) scan of the chest + ungated spiral scan of the whole abdomen

#Wide detector ECG-gated scan of chest and abdomen

°ECG-gated (spiral or sequential) scan of the heart + high pitch ungated spiral scan of chest and abdomen (DSCT)

mildly reduced ejection fraction [59]. The importance to screen subclinical ATTR-CA derived by its unfavourable prognostic impact: the 2-year mortality rate was reported to be similar between patients with and without aortic stenosis, suggesting that the mortality in patients with both diseases may be driven by ATTR-CA [60]. CMR offers the possibility to characterize the dual pathology of aortic stenosis and cardiac amyloidosis. In particular, ATTR-CA should be suspected in cases of diastolic heart failure, low QRS voltage, with a disproportionate increase in LV wall thickness detected with non-invasive imaging. CMR tissue characterization with late gadolinium enhancement (LGE) showed the characteristic difficulty in "nulling" the myocardium on post gadolinium images with global transmural LGE [61] due to diffuse increase of extracellular volume for amyloid deposit [61]. These conventional features are actually supported by newly introduced mapping techniques that allow to quantitatively measure the microstructural alteration occurring in the myocardium allowing a deeper characterization of myocyte and extracellular matrix alteration, with the promise of prompt characterization when conventional imaging techniques are still silent. Native T1 is a composite signal from both the interstitium and cells that is sensitive to the expansion of the extracellular volume even if not specific, potentially related to presence of amyloid, fibrosis and edema. However, in patients suffering from aortic stenosis a native T1 markedly elevated (also over 5 SD above normal) and a severe increase of the extracellular volume fraction (ECV > 50%) result have been associated to ATTR-CA [62], reflecting the huge expansion of the interstitial space from amyloid fibrils. Moreover, patients suffering from ATTR-CA showed a higher intracellular volume fraction (ICV) than healthy control and light chain amyloid, due to the presence of compensatory myocyte hypertrophy. Therefore, CMR reliably detects the presence of cardiac amyloidosis without recourse to biopsy. CMR findings could also be supported by nuclear imaging: cardiac scintigraphy with bone tracers such as technetium-99 m pyrophosphate (99mTc-PYP) have shown excellent diagnostic accuracy for ATTR-CA in patients with severe aortic stenosis and candidates for TAVI [59]. Recently, ECV derived from CT has been proposed as a method for ATTR-CA detection in patients with severe AS [63].

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## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethics approval** This article contains data extracted from published papers. All procedures were in accordance with the 1964 Helsinki Declaration and its later amendments.

**Ethical standards** This article does not contain any studies with human participants or animals performed by any of the authors.

**Informed consent** This article contains data extracted from published papers; informed consent was obtained from authors of included papers.

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