Journal of Cardiovascular Computed Tomography (2012) 6, 366–380

Journal of
Cardiovascular
Computed Tomography

Guidelines

SCCT expert consensus document on computed tomography imaging before transcatheter aortic valve implantation (TAVI)/transcatheter aortic valve replacement (TAVR)

Stephan Achenbach, MD, FSCCT[a,*], **Victoria Delgado, MD**[b], **Jörg Hausleiter, MD**[c], **Paul Schoenhagen, MD**[d], **James K. Min, FSCCT**[e], **Jonathon A. Leipsic, MD, FSCCT**[f]

[a]Department of Cardiology, University of Erlangen, Ulmenweg 18, 91054 Erlangen, Germany; [b]Department of Cardiology, Leiden University Medical Center, Leiden, The Netherlands; [c]Department of Cardiology, Klinikum Grosshadern, Munich, Germany; [d]Imaging Institute and Heart & Vascular Institute, Cleveland Clinic Foundation, Cleveland, OH, USA; [e]Cedars-Sinai Heart Institute, David Geffen UCLA School of Medicine, Los Angeles, CA, USA and [f]Department of Radiology, St Paul's Hospital, Vancouver, BC, Canada

KEYWORDS:
Transcatheter aortic valve replacement;
TAVR;
Transcatheter aortic valve implantation;
TAVI;
Guidelines;
Compute tomography

Abstract. Computed tomography (CT) plays an important role in the workup of patients who are candidates for implantation of a catheter-based aortic valve, a procedure referred to as transcatheter aortic valve implantation (TAVI) or transcatheter aortic valve replacement (TAVR). Contrast-enhanced CT imaging provides information on the suitability of the peripheral access vessels to accommodate the relatively large sheaths necessary to introduce the prosthesis. CT imaging also provides accurate dimensions of the ascending aorta, aortic root, and aortic annulus which are of importance for prosthesis sizing, and initial data indicate that compared with echocardiographic sizing, CT-based sizing of the prosthesis may lead to better results for postprocedural aortic valve regurgitation. Finally, CT permits one to predict appropriate fluoroscopic projections which are oriented orthogonal to the aortic valve plane. This consensus document provides recommendations about the use of CT imaging in patients scheduled for TAVR/TAVI, including data acquisition, interpretation, and reporting.

Introduction to transcatheter aortic valve replacement/transcatheter aortic valve implantation

Aortic valve stenosis

Aortic valve stenosis is a common disease and frequently affects patients of older age. When symptoms are present, and in selected situations even for asymptomatic

---

Conflict of interest: S. Achenbach has received speaker honoraria from Siemens and Edwards Lifesciences, research grants from Siemens and Bayer Schering Pharma, and serves as a consultant to Servier and Guerbet. V. Delgado has received consulting fees from Medtronic and St. Jude Medical. J. Hausleiter has received speaker honoraria from Abbott Vascular and Siemens Medical Solutions. P. Schoenhagen has no conflict of interest. J.K. Min has received research support from and served on the medical advisory board of GE Healthcare. J.A. Leipsic has received speaker honoraria from Edwards Lifesciences.

* Corresponding author.
E-mail address: stephan.achenbach@uk-erlangen.de

Submitted September 19, 2012. Accepted for publication November 6, 2012.

1934-5925/$ - see front matter © 2012 Society of Cardiovascular Computed Tomography. All rights reserved.
http://dx.doi.org/10.1016/j.jcct.2012.11.002

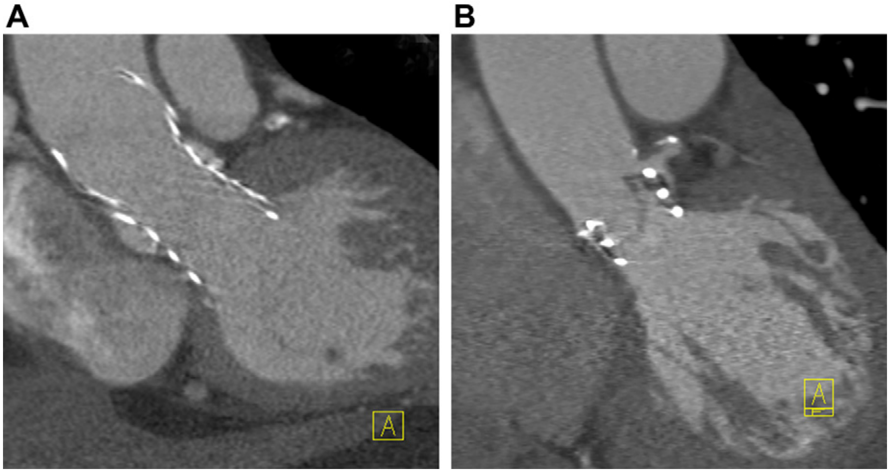

Figure 1 Implanted CoreValve (**A**) and Edwards Sapien valve (**B**) in contrast-enhanced, multiplanar reformatted CT.

persons, aortic valve replacement is indicated.[1–3] Although surgery for aortic valve replacement can usually be performed at relatively low risk, some conditions substantially increase the risk of conventional surgery. The conditions include, among others, frailty, prior radiation therapy that caused significant damage to the chest, "porcelain aorta," severe pulmonary or hepatic disease, and chest deformities. In addition, other comorbidities, for example, renal impairment, prior stroke and peripheral vascular disease, reduced left ventricular (LV) function, and older age can increase surgical risk. The presence of multiple such circumstances is not infrequent in older patients with aortic valve stenosis and may prompt the surgeon or patient to decline surgery because of a high perioperative mortality risk. In 2002, the first catheter-based aortic valve implantation was performed in a human.[4] In the past years, this procedure has become increasingly common and is an accepted alternative to surgical aortic valve replacement in patients with contraindications to surgery or high surgical risk.[1]

Transcatheter aortic valve replacement/transcatheter aortic valve implantation

Catheter-based implantation of a bioprosthetic aortic valve is referred to as transcatheter aortic valve replacement (TAVR) or transcatheter aortic valve implantation (TAVI), sometimes as percutaneous aortic valve replacement. Several prosthesis types are available, and by far the most commonly used are the self-expandable Medtronic CoreValve (Medtronic Inc, Minneapolis, MN, USA), available in the sizes 23 mm, 26 mm, 29 mm, and 31 mm, as well as the balloon-expandable Edwards Sapien valve (Edwards Lifesciences Inc, Irvine, CA, USA), available in multiple models and sizes of 20 mm, 23 mm, 26 mm, and 29 mm (Fig. 1). In the United States, only 23 mm and 26 mm Edwards Sapien valve prostheses are currently available. Typically, the preferred implantation route is transfemoral. If this is not possible because of patient characteristics, both valve types can be implanted via the subclavian artery, and the Edwards Sapien valve can be implanted via a transapical route. An aortic approach (entry into the ascending aorta after mini-thoracotomy, eg, in the second intercostal space) is also possible.[5] Transcatheter aortic valve prostheses are anchored in the aortic annulus and displace the native aortic wall cusps toward the aortic wall.

Table 1 Recommendations about CT before TAVI/TAVR

CT imaging should be performed in the evaluation process of patients who are under consideration for TAVI/TAVR unless there is a contraindication.
CT datasets should be interpreted jointly with a member of the TAVI/TAVR procedural team or reviewed with the operator before the procedure.

TAVI, transcatheter aortic valve implantation; TAVR, transcatheter aortic valve replacement.

CT imaging before TAVI/TAVR

As opposed to conventional aortic valve replacement, direct visualization of the valve and annulus is lacking during the TAVI/TAVR procedure. As a result, imaging is necessary to allow for appropriate valve sizing. This needs to be performed before the procedure because for some patients, no suitable valve is available (eg, patients with an aortic annulus diameter of <18 mm). Imaging is also necessary to evaluate the best access pathway (transfemoral vs apical, subclavian, or aortic). Other information that computed tomography (CT) can provide and that are potentially helpful for the procedure are the extent of aortic valve calcification and appropriate fluoroscopic projection angles that permit exactly orthogonal views onto the valve.

CT imaging is a highly valuable diagnostic tool in the workup of patients who are being considered for TAVI/TAVR.[6] Image acquisition remains challenging, however, as

Table 2 Recommendations for CT image acquisition before TAVI/TAVR

Imaging of the aortic root must use ECG-synchronization.
Motion artifacts should be minimized.
Slice thickness should be ≤1.0 mm.
Multiphase ("cine") imaging is in general not necessary.
Imaging of the aorta and peripheral vessels should extend from aortic arch (and potentially subclavian artery) to below the groin.
Imaging of the abdominal aorta and peripheral vessels does not need to be ECG gated.
Contrast agent exposure may be an issue in the patients who are often of advanced age and may have renal impairment. Contrast reduction and adherence to protocols for prevention of contrast-induced nephropathy is recommended.
Two separate acquisitions (ECG-synchronized for the aortic root and nongated for the aorta and peripheral vessels) may be preferable over an ECG-synchronized acquisition of the entire volume to reduce the amount of contrast agent. If ECG-triggered high-pitch spiral acquisition is available, its use may be advantageous.

ECG, electrocardiogram; TAVI, transcatheter aortic valve implantation; TAVR, transcatheter aortic valve replacement.

a large imaging volume needs to be covered from the aortic arch to the lesser trochanters. A substantial amount of clinically relevant information can and should be obtained from the dataset, and interpretation requires knowledge of the TAVI/TAVR procedure and potential complications. Image interpretation should be performed jointly by an expert reader and a member of the team who performs the TAVI/TAVR procedure, or the image dataset should be reviewed with the responsible operator. The ability to review the CT image dataset in the room used for the TAVI/TAVR intervention is ideal (Table 1).

Although CT can determine the aortic valve orifice area and provide a measure of aortic valve stenosis severity,[7,8] this is typically not the primary indication to perform CT before TAVI/TAVR. The main indications relate to the evaluation of the access route (peripheral, transapical, subclavian, transaortic), aortic root and aortic annulus dimensions, as well as aortic valve structure and calcification. The volume of iodinated contrast medium is of concern in many patients because candidates for TAVI/TAVR frequently have impaired renal function. Given the commonly advanced age of patients being considered for TAVI/TAVR, radiation exposure is of lesser concern. Finally, current practice suggests that CT evaluation should also include competent evaluation of extracardiac and extravascular pathology for relevant findings.

Table 3 Minimum recommended vessel lumen diameters depending on the device considered for TAVI/TAVR

Device and valve size	Introducer profile, F	Recommended minimum vessel lumen diameter, mm
Edwards Sapien Transcatheter Heart Valve with Retroflex 3 Delivery System*		
23 mm	22	≥7
26 mm	24	≥8
Edwards Sapien XT Transcatheter Heart Valve with NovaFlex Delivery System and eSheath		
23 mm	16	≥6
26 mm	18	≥6.5
29 mm	20	≥7.0
Medtronic CoreValve Revalving System		
26 mm	18	≥6
29 mm	18	≥6
31 mm	18	≥6

TAVI, transcatheter aortic valve implantation; TAVR, transcatheter aortic valve replacement.

*Available in the United States.

Data acquisition protocols

CT imaging in the evaluation for TAVI/TAVR should include imaging of the aortic root, aorta, and iliac, as well as common femoral arteries. Hence, a large volume must be covered. To achieve the desired accuracy, imaging of the aortic root must be synchronized to the electrocardiogram (ECG) either by retrospective ECG gating or through the use of prospective ECG triggering. Spatial resolution must be high to provide adequate imaging, especially of the aortic root and of the iliofemoral arteries, because in both regions detailed dimensions must be obtained to adequately plan the procedure.

Image acquisition protocols vary and depend on the scanner platform that is used. In general, it is desirable to choose an acquisition protocol that obtains a reconstructed slice width of ≤1.0 mm throughout the entire imaging volume. Imaging should be performed in supine position and during suspended respiration. The aortic root must be imaged with retrospective ECG gating or prospective ECG triggering (depending on patient characteristics and scanner capabilities) to allow for adequate motion-free imaging. However, it is not necessary to image the entire aorta and iliofemoral arteries with ECG synchronization. For these sections, nongated acquisitions may be preferable because of lower radiation exposure (because of the higher helical pitch than with retrospective ECG-gated techniques) and because of faster volume coverage that requires lower volumes of iodinated contrast medium. As a result, several strategies are possible. With wide detector systems, it is feasible to image the entire volume with an

Table 4 Recommendations for assessment of the access route by CT before TAVI/TAVR

CT imaging should be performed for vascular access assessment (pelvic arteries and aorta) when not contraindicated;

CT examinations should be performed with iodinated contrast medium.

Manual multiplanar reformation or semiautomated centerline reconstruction should be used to achieve cross-sectional visualization for measurement of vessel dimensions. From these reconstructed images, the minimal luminal diameter along the course of the vascular access should be determined.

Qualitative assessment of vascular tortuosity should be performed.

Qualitative assessment of vascular calcification should be performed.

Consideration to varied thresholds of vessel size (sheath/femoral artery ratio) should be contemplated, depending on the presence and extent of vascular calcification.

The left ventricle should be evaluated for the presence of thrombus and, if a transapical access route is planned, for geometry and position of the apex.

TAVI, transcatheter aortic valve implantation; TAVR, transcatheter aortic valve replacement.

Table 5 Recommendations for assessment of the aorta

The entire aorta should be imaged and evaluated, unless a transapical access is planned.

Severe elongation and kinking of the aorta, dissection, and obstructions caused by thrombus or other material should be reported.

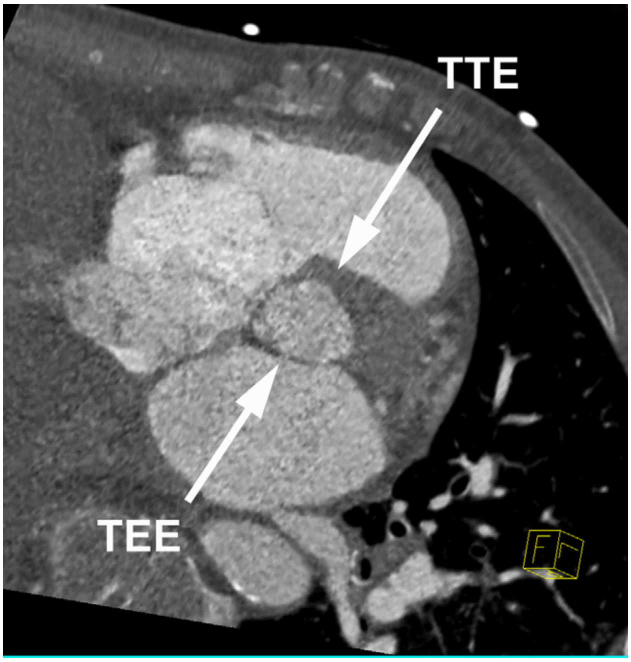

Figure 2 The aortic annulus has an oval shape in most patients. On the basis of their viewing angle, both transthoracic echocardiography (TTE; parasternal long-axis view) and transesophageal echocardiography (TEE; 120-degree left ventricular outflow tract view) usually show the smaller diameter of the left ventricular outflow tract and aortic annulus (see *arrows*).

ECG-synchronized approach. ECG-triggered high-pitch spiral acquisitions may be advantageous because they allow the required z-axis coverage to be obtained rapidly.[9] With systems that have limited detector width (eg, 64 simultaneously acquired slices or less), it may be better to acquire an ECG-gated dataset that contains the heart and aortic root and to cover the remaining volume with a second nongated acquisition (potentially even on a second day if contrast exposure is problematic). Recent data indicate that imaging of the aortic root and annulus in systole may be preferable over diastole because of the dynamic changes of the annulus and slightly larger annular sizes noted in systole.[10,11] However, it is important to ensure adequate image quality even if systolic imaging is used. Because CT is typically not used to determine the severity of aortic valve stenosis, datasets do not need to cover the entire cardiac cycle, which allows for reduction of radiation exposure.

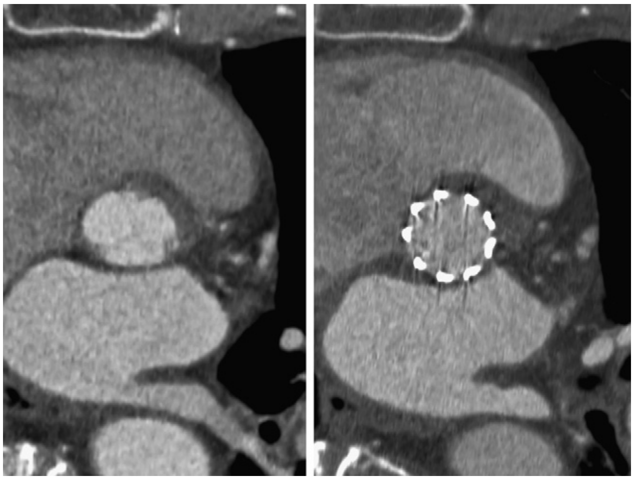

Figure 3 The oval shape of the aortic annulus will typically change to a more circular geometry after a catheter-based valve is implanted. Shown here are CT cross-sections in identical position and orientation in a patient before and after catheter-based implantation of a balloon-expandable valve.

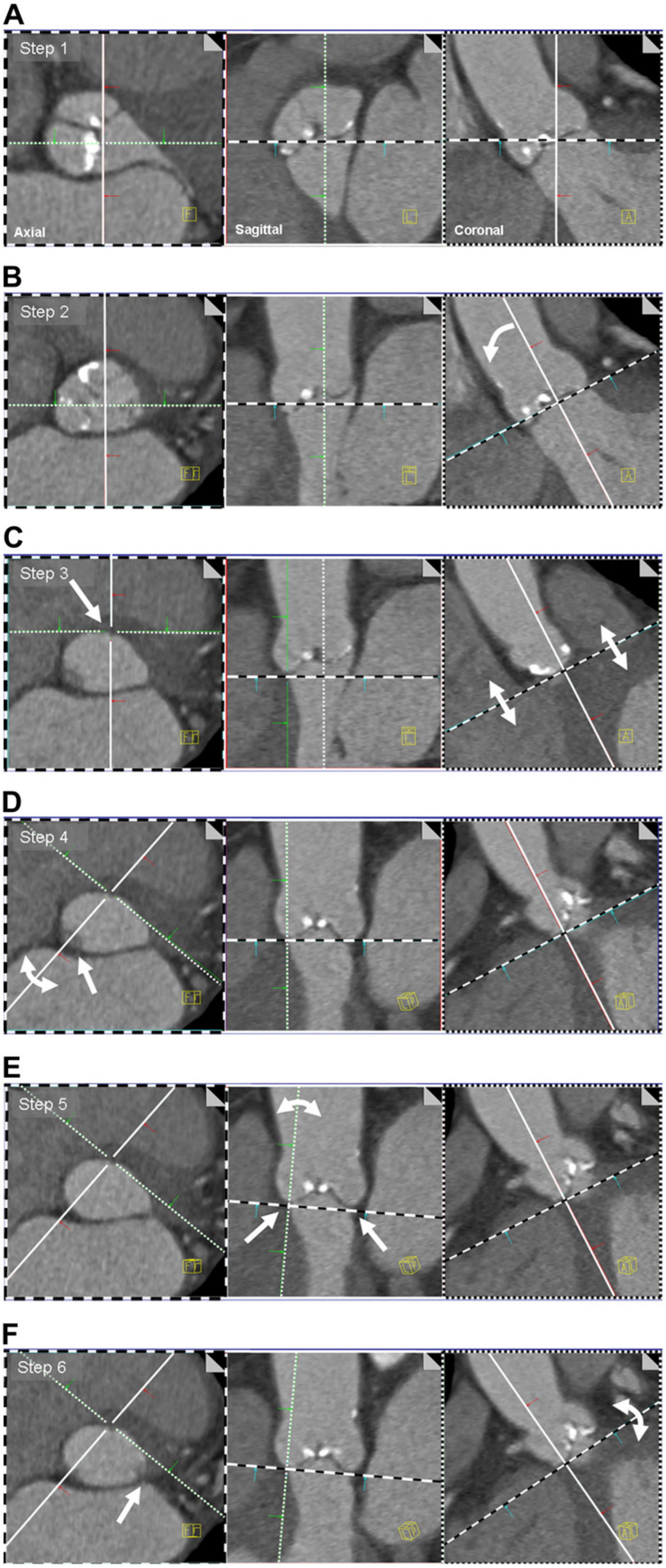

Figure 4 This sequence describes a method of creating a plane that precisely corresponds to the aortic annulus/basal ring. A multiplanar reconstruction will be rendered which includes all 3 lowest insertion points of the aortic valve cusps (hinge points). This approach can be

According to recommendations on radiation protection in cardiovascular CT by the Society of Cardiovascular Computed Tomography (SCCT),[12] a tube potential of 100 kV should be considered for patients weighing ≤ 90 kg or with a body mass index (BMI; calculated as weight in kg divided by height in m^2) ≤ 30; whereas a tube potential of 120 kV is usually indicated for patients weighing >90 kg and with a BMI > 30. Choice of tube current strongly depends on the CT hardware as well as chosen slice collimation. It should be adjusted, based on each individual patient's size, to the lowest setting that guarantees acceptable image noise.[12]

To maximize the information obtained by CT, imaging needs to be performed with intravenous contrast injection.

Timing of the image acquisition procedure can occur through a separate test bolus or by bolus triggering. Limiting the amount of contrast agent is an important concern in TAVI/TAVR candidates. Choice of an appropriate imaging strategy (ECG gated vs nongated) is therefore important to limit contrast volumes. Reduction of contrast volumes can be achieved by using lower flow rates than for coronary CT angiography. Although 5 mL/s is typically recommended for coronary imaging,[13] 3 mL/s and in some cases even less may be sufficient for imaging patients in the workup for TAVI/TAVR (Table 2).[7] Dual-energy techniques with low monochromatic energy imaging may also be helpful to reduce contrast volume and are expected to be generally available in the near-term future.[14] Direct aortic injection with extremely low volumes of contrast has been reported by some groups.[15,16]

Assessment of the access route

The iliofemoral axis remains the most common route of access for TAVI/TAVR. Ongoing refinements have resulted in progressive reduction of the profile of the delivery systems for transfemoral TAVI/TAVR, and the required sheath sizes can be expected to decrease further in the future. Current delivery profiles, as well as the corresponding vendor recommendations for minimal vessel diameters, are listed in Table 3. Single-plane angiography, which is typically performed at the time of coronary artery assessment, was considered a minimum requirement for evaluation of the iliofemoral system in the early days of TAVI/TAVR, but this yields limited information about true vessel lumen, calcification, and tortuosity. Vascular complications have emerged as a main cause of mortality and morbidity in transfemoral TAVI/TAVR.[17–19] The large 22- to 24-F sheaths required for the first-generation valves were associated with vascular complication rates of 30.7% in the North American PARTNER 1B trial.[18] Better patient selection and smaller sheaths have been associated with lower reported vascular complication rates, ranging from 1.9% to 13% for 18-F sheaths. Vascular complications are largely attributable to the large device size, significant atherosclerosis, vessel tortuosity, and kinking that are often present.[20,21] Risk factors for vascular complications are an external sheath diameter that exceeds the minimal artery diameter, moderate or severe calcification, and peripheral vascular disease.[20,21] CT can consistently identify the presence of these risk factors. Along with better vascular closure techniques, CT imaging has improved patient selection for the transfemoral access. Some centers have recently reported improved outcomes, decreasing major vascular complications from 8% to 1% and minor vascular complications from 24% to 8% between 2009 and 2010.[21]

CT Predictors of vascular injury

Moderate-to-severe arterial calcification is associated with a 3-fold increase in vascular complications (29% vs 9%), and the presence of a minimal arterial lumen diameter

◀

followed with any image processing software that allows free multiplanar reconstruction and in which the reference lines can be "locked" in orthogonal position. In this way, it is possible to ensure that all planes will remain orthogonal to each other during manipulation of other imaging planes. The principle of this approach is to create a double-oblique plane (the formerly axial plane) which contains all 3 cusp insertion points. (**A**) Step 1, start out with multiplanar images in axial, sagittal, and coronal orientation. (**B**) Step 2, use the reference line in the coronal image to rotate the *former axial plane* in a way so that it crudely approximates the plane of the aortic valve. (**C**) Step 3: in the coronal image, move the reference line that controls the *former axial plane* up and down to identify the lowest insertion point of the right coronary cusp which is usually located at about the 1 o'clock position. Position the formerly axial plane exactly at the level of that cusp insertion point. Then, move the crosshair in the formerly axial plane exactly onto the right coronary cusp insertion point. (**D**) Step 4, rotate (without moving up and down or left and right) the reference lines in the formerly axial plane in a way so that the line that controls the *former sagittal plane* crosses the lowest insertion point of the noncoronary cusp, which is located at approximately the 8 o'clock position (note: it is not shown here that this may require to interactively change the level of the formerly axial plane by moving it up and down with the use of the reference line in the formerly coronal image, without rotating it so that the orientation remains unchanged). (**E**) Step 5, the formerly sagittal plane will now show the lowest insertion point both of the right coronary cusp and the noncoronary cusp. In this window, move and rotate the reference line of the *former axial plane* so that it very exactly crosses both of these insertion points. Once this is achieved, the formerly axial plane will contain 2 of the 3 lowest cusp insertion points. (**F**) Step 6, in the former coronal plane, rotate (without moving it) the reference line of the *former axial plane* until the lowest insertion point of the left coronary cusp just barely appears in the formerly axial window (*arrow*). Now, the former axial plane is exactly aligned with the lowest cusp insertion points of all 3 aortic cusps and represents both the orientation as well as the level of the "aortic annulus" (image on *left*). Measurements of aortic annulus dimensions should be performed in this plane.

less than that of the external sheath showed a 4-fold increase (23% vs 5%).[22] A sheath-to-femoral artery ratio (SFAR) of ≥ 1.05 is predictive of vascular access–related complications and 30-day mortality.[21] It has been shown that this threshold is more lenient (SFAR = 1.10) in the absence of calcification of the iliofemoral vessels, and a stricter threshold (SFAR = 1.00) is required in the presence of moderate-to-severe calcification. Special caution is indicated if calcification is circumferential or nearly circumferential and/or located at vessel bifurcations.

CT is a helpful adjunct for the evaluation of other access routes for TAVI/TAVR. CT can identify bulky atheroma or eccentric calcifications in the aortic arch,[22] which might cause stroke when dislodged by mechanic manipulation during an intervention.[23] In the setting of unfavorable vascular pelvic anatomy, a transapical, subclavian, or transaortic approach may be selected. CT can provide similar anatomic detail for the subclavian system and provide preprocedural localization of the LV apex to assist with transapical puncture as well as the angle at which to advance the device.

Image processing and evaluation

In addition to assessment of transaxial images, multiplanar reconstructions, curved multiplanar reformats, maximum intensity projection images, and 3-dimensional (3D) volume-rendered images can be used for evaluation of the peripheral vessels. The most important parameter to be reported is the minimal luminal diameter along the entire course of the iliac arteries on either side. Transverse source images allow no more than a preliminary assessment of vessel size. Careful multiplanar reconstruction, either manual or with the use of automated software algorithms, must be used to create images oriented exactly orthogonal to the vessel course. These images must be used to measure luminal diameter. Otherwise, the risk of overestimation of the vessel diameter is substantial. Modern workstations can automatically extract vessel centerlines and display the orthogonal planes that allow manual or automated measurements orthogonal to the vessel at every point regardless of vessel obliquity. Pronounced arterial wall calcifications can lead to underestimation of the lumen diameter because of partial volume effects that make calcification seem larger than they actually are ("blooming").

Tortuosity of vascular structures can be assessed on transverse source images, but evaluation is facilitated with 3D display from multiple viewing angles. Anterior-posterior and 45-degree right anterior oblique as well as 45-degree left anterior oblique projections are the minimum required to allow for a qualitative visual assessment of iliac tortuosity. In the absence of calcification, iliofemoral arterial tortuosity, even with angles of 90 degrees or slightly more, is not necessarily a contraindication for femoral access. Noncalcified, but tortuous vessel segments can usually be straightened to introduce the sheath. However, calcified tortuous segments carry a substantial risk of access failure, and the operator should be advised about this situation.

Assessment of the left ventricle and chest wall

LV thrombi can be a source of embolic complications both for the transapical approach and, because of the stiff guide wire that needs to be advanced through the aortic valve into the LV cavity, also for the transfemoral approach. Hence, CT datasets should be evaluated for the presence of LV thrombi. Position of the LV apex relative to the chest wall and alignment of the LV axis with LV outflow tract (OT) orientation may be useful information in the case of transapical access. Similarly, chest deformities are of relevance and should be reported (Table 4).

Assessment of the aorta

In addition to the iliac and femoral arteries, the entire aorta should be evaluated by CT angiography before a TAVI/TAVR procedure if a transfemoral approach is considered. Transverse axial images and multiplanar reconstructions are commonly used. Contraindications to a femoral access include massive elongation with kinking of the aorta, dissection, or large thrombi protruding into the lumen or other obstacles that may prevent advancing the valve through the aortic lumen. If a transaortic approach is considered, the position of the ascending aorta relative to the chest wall is of importance. If coronary bypass grafts are present, their position and potential adhesion to the sternum may be of relevance if emergency conversion to open heart surgery is required (Table 5).

Aortic annulus

Choosing the appropriate prosthesis size requires accurate measurement of the dimensions of the aortic annulus. If the prosthesis size is too small, embolization may occur, and paravalvular regurgitation is more frequent, with negative clinical outcome.[24–26] If the prosthesis is too large relative to the aortic annulus, rupture may occur which is often fatal.

The aortic annulus is not a separate anatomic structure. Much rather, it is formed by the 3 lowest points of the aortic valve cusps ("hinge points") as they connect to the wall of the LVOT.[27] The virtual ring that connects these 3 hinge points, the "virtual basal ring," is the target structure for sizing transcatheter aortic valve prostheses.

Measurements of aortic annulus size for TAVI/TAVR preparation have historically been performed with calibrated aortic angiography, transthoracic echocardiography (TTE), or transesophageal echocardiography (TEE). Discordance between these measurements is common.[28–30] Substantial

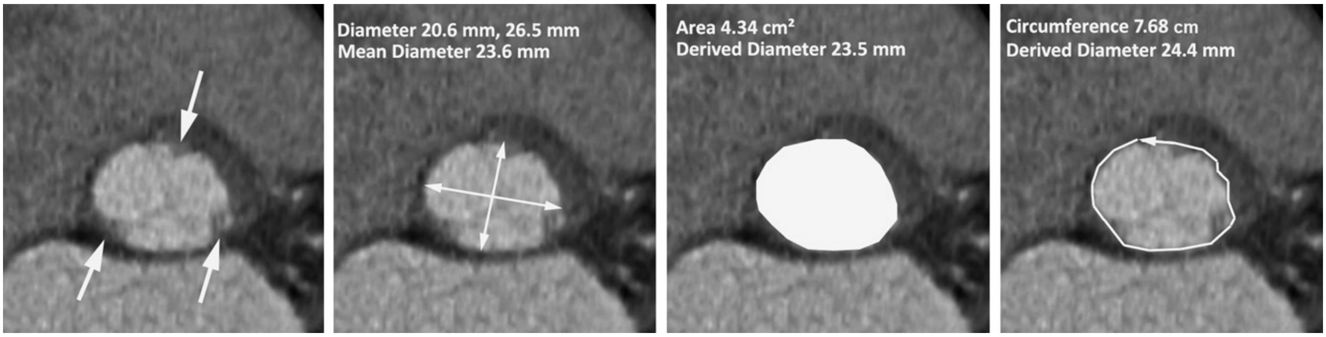

Figure 5 Determination of aortic annulus dimensions in CT. After an appropriate plane that exactly contains the 3 lowest insertion points of the coronary cusps has been created, 3 different methods of determining aortic annulus size have been proposed. The long and short diameter can be measured to calculate the mean diameter. The area can be measured and the diameter can be deducted under the assumption that this area changes to a circle when a valve is implanted. Finally, it can be assumed that the circumference will stay constant during the implantation, and the diameter can be derived from the circumference, again assuming that the annulus will achieve a perfectly circular shape. The more eccentric the aortic annulus, the more these 3 measurements will differ from one another, with the circumference-based method yielding the largest results.

limitations of these 2-dimensional (2D) techniques arise from the fact that the annulus has an oval, not a circular, shape.[28,29] Two-dimensional echocardiography, whether transthoracic or transesophageal, will typically measure the shorter diameter of the oval aortic annulus (Fig. 2). It is important to note that the oval aortic annulus will reshape to a more circular geometry after catheter-based implantation of prosthesis (Fig. 3). This effect is probably more pronounced in balloon-expandable prostheses than in self-expanding prostheses.[31]

In most experienced sites, sizing of the aortic valve prosthesis is achieved in a multifactorial process that is based on ≥1 imaging technique and does not rely on a single echocardiographic measurement alone. Growing evidence suggests that CT offers valuable information about prosthesis sizing in TAVI/TAVR and that incorporating CT-derived dimensions of the aortic annulus may improve outcome of the procedure. For example, aortic annulus dimensions obtained by magnetic resonance (MR) and CT correlate closely, without systematic difference between the 2 methods (bias, 0.4 mm).[32] In this trial, both MR (bias, 4.5 mm) and CT (bias, 4.1 mm) yielded significantly larger aortic annulus dimensions than TTE. Similar results have consistently been reported in other studies.[10,28–31,33] It is therefore well accepted that 3D imaging techniques, with a particular amount of evidence for CT, yield larger aortic annulus dimensions than echocardiography. This is not because echocardiography measures incorrectly, but because the diameter seen and reported in echocardiography will usually be comparable with the smaller of the 2 diameters reported by 3D techniques. This emphasizes the often oval shape of the annulus.

Evaluation of aortic annulus dimensions

Measurement of aortic annulus dimensions by CT requires the manipulation of image data to create an image that exactly corresponds to the basal ring of the aortic valve,[34] as defined by the level immediately below the 3 lowest insertion points of the aortic cusps. Coronal, sagittal, or single-oblique reconstructions to approximate the short and long axis of the noncircular annulus are not considered acceptable.

Because of the double-oblique position of the aortic valve it is not trivial to render a plane in exactly the same orientation as defined by the 3 lowest insertion points of the aortic valve leaflets. The plane formed by the 3 insertion

Table 6 Manufacturer-suggested aortic annulus and aortic root dimensions for TAVI/TAVR

	Aortic annulus diameter, mm	Distance aortic annulus to left main ostium, mm	Ascending aorta diameter, mm	Sinus of Valsalva width, mm	Sinus of Valsalva height, mm
Edwards Sapien XT 23 mm	18–22	≥10			
Edwards Sapien XT 26 mm	21–25	≥10			
Edwards Sapien XT 29 mm	24–27	≥10			
Medtronic CoreValve 26 mm	20–23		≤40	≥27	≥15
Medtronic CoreValve 29 mm	23–27		≤43	≥29	≥15
Medtronic CoreValve 31 mm	26–29		≤43	≥29	≥15

TAVI, transcatheter aortic valve implantation; TAVR, transcatheter aortic valve replacement.

Table 7 Manufacturer recommendations for CT-based sizing of the self-expanding Medtronic CoreValve

	Mean diameter, mm	Perimeter/circumference, mm	Area, mm^2
Medtronic CoreValve 23 mm	18–20	56.5–62.8	254.5–314.2
Medtronic CoreValve 26 mm	20–23	62.8–72.3	314.2–415.5
Medtronic CoreValve 29 mm	23–27	72.3–84.8	415.5–572.6
Medtronic CoreValve 31 mm	26–29	81.7–91.1	530.9–660.5

points is often not orthogonal to the LVOT. Frequently, the insertion of the right coronary cusp leaflet is inferior to the left and noncoronary cusp leaflets. Figure 4 suggests a possible approach for creating a plane which exactly corresponds to the aortic annulus.

When a plane that corresponds precisely to the basal ring/aortic annulus has been generated, 3 measurements have been proposed as the most appropriate for annular sizing and prosthesis selection. These 3 commonly proposed measurements are displayed in Figure 5. They are as follows. (1) Measurement of the long and short diameters (D_L and D_S) of the oval aortic annulus. The mean diameter D is calculated by averaging the 2 values [$D = (D_L + D_S)/2$]. (2) Planimetry of the area A of the aortic annulus and calculation of the diameter D that corresponds to this area under the assumption of full circularity [$D = 2*\sqrt{(A/\pi)}$]. (3) Measurement of the circumference C of the aortic annulus and calculation of the diameter D that corresponds to this area under the assumption of full circularity ($D = C/\pi$)

Preliminary data suggest that it may be preferable to measure aortic annulus dimensions in systole (as is done in echocardiography). The planimetered annular area and mean diameters are larger in systole than in diastole.[20,21] Measurement of the circumference may be more stable throughout the cardiac cycle,[35,36] and it also appears to undergo a lesser degree of dynamic change throughout the cardiac cycle. However, the mean diameter obtained by averaging the short and long diameter, and the aortic annular area have been suggested to offer better interobserver agreement than circumference measurements across operators and workstation platforms.[30] This is potentially due to interobserver variability as well as a lack of standardization across workstations to generate a perimeter/circumference measurement. Many platforms lack adequate smoothing algorithms at present which results in perimeter values that are significantly larger than they are in reality.

Prosthesis sizing

Manufacturer suggested thresholds of aortic annulus dimensions for transcatheter heart valve selection are provided in Tables 6 and 7. These recommendations have typically been used on the basis of echocardiographic measurements, and the use of CT-based measurements without adaptation of the sizing thresholds may lead to the choice of different prosthesis sizes in approximately 25%–45% of cases.[10,11,33] No CT-specific guidelines for prosthesis sizing have been developed and sufficiently validated yet for the balloon-expandable prosthesis. They are more firmly entrenched for the self-expanding prosthesis[34] (Table 7). However, evidence is growing that for both valve types CT-based dimensions permits better prediction of paravalvular regurgitation than TEE-derived annular dimensions.[33,36–38] These data have led many to believe that selection of prosthesis size with CT may yield better clinical results. In fact, in a study of 133 patients who underwent CT before TAVI/TAVR, it was reported that, in comparison with TEE-based sizing, the use of CT-based aortic annulus dimensions led to a significantly lower rate of "worse-than-mild" paravalvular regurgitation after implantation of a balloon-expandable Edwards Sapien valve (7.5% vs 21.9%).[33] The investigators aimed to use a prosthesis diameter <4 mm smaller than the maximum diameter of the aortic annulus in CT and <1.5 mm smaller than the circumference-derived diameter of the aortic annulus.[33] Manufacturer suggestions for CT-specific sizing thresholds for the self-expanding CoreValve prosthesis are listed in Table 7. They include an approximate oversizing of the annular perimeter by 10%–15%.[34]

Table 8 Recommendations for measurement of aortic annulus dimensions

For measurement of aortic annulus dimensions, an imaging plane must be created which is exactly aligned with the 3 most caudal insertion points of the aortic cusps (hinge points).

If available, systolic measurements may be preferable to diastolic measurements of aortic annulus size.

Dimensions that should be obtained include small and large diameter, area, and circumference (and for all 3 the derived mean diameter).

Measurements in a coronal or sagittal reconstruction or in a 3-chamber view are not acceptable.

Choice of prosthesis size should be multifactorial and multimodality based, with the recognition that echocardiography may underestimate the true dimension of the aortic annulus.

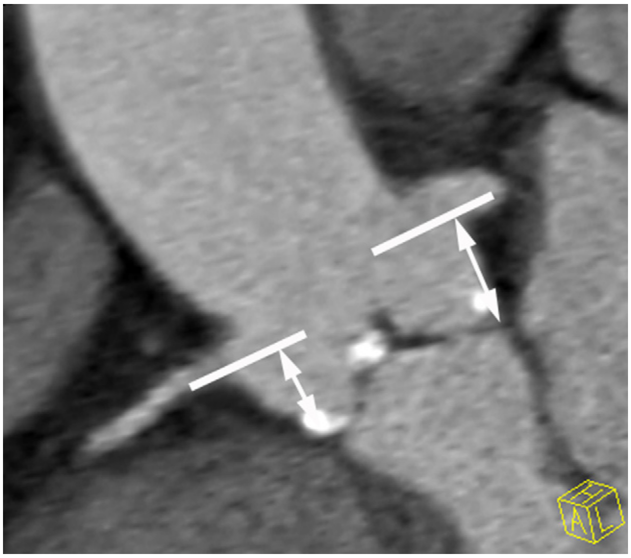

Figure 6 Measurement of the distance of the coronary ostia from the aortic annulus plane.

Despite that the results of recent studies uniformly indicate that CT-based sizing may be superior to TEE-based sizing of the prosthesis, it has currently not been fully clarified in clinical trials that CT-derived dimension permits optimal guidance of prosthesis selection and which thresholds should be used. It is therefore currently recommended that a multidisciplinary and multimodality approach should be used for prosthesis selection. Despite recognition that echocardiography is supported by a large body of literature, including randomized data,[18,38] modifying sizing may be advisable in the setting of discordance between echocardiography and appropriately determined dimensions on the basis of CT. This is of particular relevance when CT clearly shows a noncircular annulus, suggesting that in this particular patient, 2D echocardiography underestimates the true annulus size (Table 8).

Other aortic root dimensions

Besides aortic annulus size, other anatomic measures of the aortic root have relevance for TAVI/TAVR planning. They include distance of the coronary ostia to the aortic valve plane, aortic cusp length, width of the aortic sinus, width of the sinotubular junction, and width of the ascending aorta. These measurements are important to avoid potentially catastrophic complications such as coronary occlusion and root injury.[39] CT is well suited to provide these measures because of its multiplanar imaging capabilities and high spatial resolution.

Unlike in surgical aortic valve replacement whereby the native valve leaflets and the majority of annular calcification is resected, with TAVI/TAVR the native leaflets and calcifications are displaced and at times crushed by the prosthesis. With this is the risk of potential coronary occlusion, particularly when associated with shallow sinuses and heavily calcified and long cusps. Distance from the aortic annulus plane to the coronary ostia can easily be assessed by CT with the use appropriately oriented multiplanar reconstructions (Fig. 6). In a study of 100 patients with aortic stenosis undergoing CT, the average distance of left coronary ostium and right coronary ostium was found to be 15.5 ± 2.9 mm and 17.3 ± 3.6 mm, respectively.[40] However, reported average distances vary and may depend on the measurement technique used (eg, oblique from depicted hinge point to coronary ostia vs parallel to the aortic root axis).[40] Currently, there are no strict exclusion criteria about a minimum distance of the coronary ostia from the aortic annulus to avoid coronary obstruction. Risk is assumed less with the CoreValve prosthesis than with the Edwards Sapien prosthesis. For the latter, minimum distance values of 10–14 mm between the coronary ostia and leaflet insertion are usually suggested.[39] In addition to the distance to the coronary ostia, the length of the aortic valve cusps and the extent of calcification should be taken into consideration. Concern about coronary occlusion is much greater in the setting of heavily and diffusely calcified cusps than in the absence of calcification or when the calcification is isolated to the cusp insertion. Other features that may be predictive of risk of coronary occlusion are shallow sinuses of Valsalva, long aortic valve cusps, and a narrow sinotubular junction.

While the Edwards Sapien prostheses are between 15 and 19 mm in height and do not extend beyond the aortic sinus, the self-expandable CoreValve is between 52 and 55 mm in length and, when implanted, extends beyond the sinotubular junction into the ascending aorta (Fig. 1). Manufacturer specifications for CoreValve require a minimum sinus of Valsalva width of 27 mm for the 29-mm prosthesis and 29 mm for the 26-mm and 31-mm prostheses, as well as minimum sinus of Valsalva height of 15 mm. Maximum diameter of the proximal ascending aorta

Table 9 Recommendations for measurements of aortic root dimensions

The distance of the aortic annular plane to the lower point of the left and right coronary ostium should be measured if a balloon-expandable prosthesis is considered.
The length of aortic leaflets and presence of severe leaflet calcification that may obstruct a coronary ostium after valve implantation should be determined.
Heavily and diffusely calcified aortic valve cusps particularly in the setting of shallow sinuses of Valsalva should be noted.
Sinus of Valsalva height and width should be measured if a self-expandable prosthesis is considered.
The ascending aorta diameter should be measured if a self-expandable prosthesis is considered.

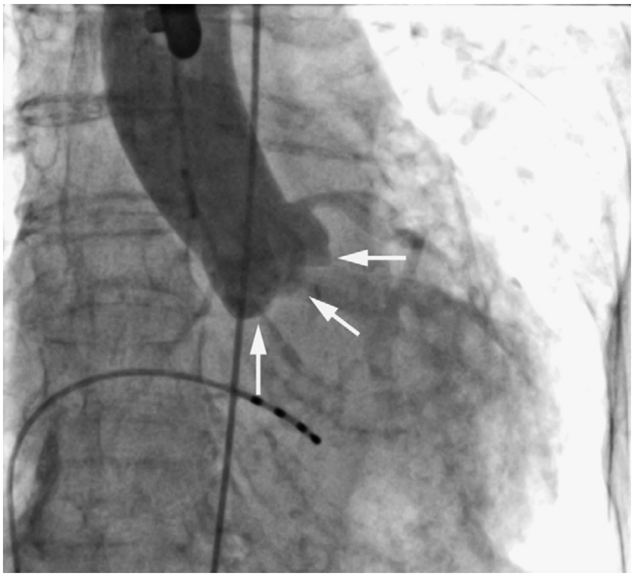

Figure 7 Ideal projection for implantation of a catheter-based aortic valve in fluoroscopy. All tree coronary cusps are in the same plane, with the right coronary cusp in the middle and the left and noncoronary cusp symmetrically to the left and right.

should not exceed 40–43 mm at 40 mm from the annulus for the 3 prosthesis sizes (Table 6). These dimensions can easily be extracted from contrast-enhanced CT datasets (Table 9).

Aortic annulus plane for fluoroscopy

During catheter-based implantation especially of the balloon-expandable prosthesis, it is important to use a fluoroscopic projection that provides an exact orthogonal view onto the aortic annular plane. Theoretically, an unlimited number of projections exist which will provide such a view, but most operators prefer a projection whereby the right coronary cusp is central and closest to the image intensifier, whereas the left and noncoronary cusps are positioned symmetrically to either side of the right coronary cusp (Fig. 7). Because CT offers a 3D dataset, it allows identification of appropriate projection angles that will provide an orthogonal view onto the aortic valve plane.[41–43] Recently, appropriate angles predicted from preprocedural CT have been shown to correlate well with 3D rotational angiography at the time of the procedure when patients are positioned in a similar fashion.[44] Dedicated, automated software programs are available, but manual evaluation is possible. If the exact plane of the aortic annulus has been defined in CT (a multiplanar reconstruction that exactly contains the 3 lowest cusp insertion points; Fig. 4), most image processing software products will permit to place a further multiplanar reconstruction that is both orthogonal to the aortic annulus plane and orthogonal to the commissure between the left coronary cusp and noncoronary cusp (Fig. 8). The angulation of this plane is often displayed in the image. It corresponds to the angulation of the C-arm which will provide the desired view during the implantation procedure. Another approach is the use of thick maximum intensity projections that are manually angulated to align aortic valve calcifications.[45]

If the patient is positioned differently during CT acquisition and the TAVI/TAVR procedure (eg, patients may be turned toward their right side for easier access during transapical implantation, whereas they were positioned on their back during the CT acquisition), corrections need to be made to account for the difference in patient orientation (Table 10).

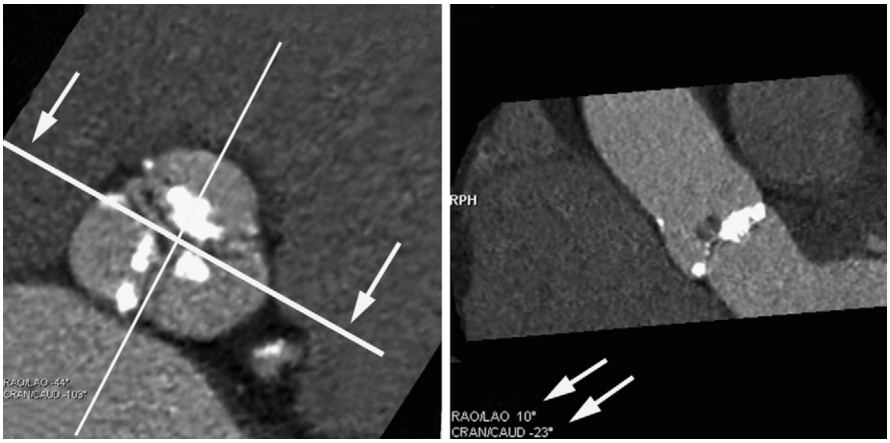

Figure 8 Determination of an appropriate projection on the basis of the CT dataset. First, the exact plane of the aortic annulus needs to be identified as explained in Fig. 4. Then the plane is moved to a more cranial position (without changing its orientation) to show the commissures of the aortic valve. Multiplanar reconstructions are rendered orthogonal to the aortic annulus plane and, in the reference image, orthogonal to the commissure between the left coronary cusp and noncoronary cusp (*thicker white reference line* than in the left image). The obtained image (*right*, corresponds to the *thicker white reference line*) is exactly in the desired plane. Most software programs will display the angulation of that image (*arrows*). The displayed values can be used to angulate the C-arm.

Table 10 Recommendations about determination of an appropriate fluoroscopic projection for valve implantation

Automated software tools or manual evaluation permit determination of suitable angulations of the C-arm that provide a projection orthogonal to the aortic annular plane.
Potential differences in patient position between CT data acquisition and the fluoroscopically guided TAVI/TAVR procedure may result in discordance

TAVI, transcatheter aortic valve implantation; TAVR, transcatheter aortic valve replacement.

Aortic valve calcification

Calcific aortic valve stenosis is pathologically characterized by thickening of the aortic valve cusps with large calcific nodules that protrude on the aortic surface of the cusps. Unlike surgical aortic valve replacement, the diseased aortic cusps are not removed in TAVI/TAVR. The presence of valvular calcifications may be of importance to ensure prosthesis anchorage and avoid dislodgement.[46] By contrast, excessive calcification may hamper the apposition of the prosthesis to the irregular surface of the aortic root and may leave gaps between the prosthetic frame and the native aortic root that favor the occurrence of paravalvular aortic regurgitation after implantation.[47,48] However, evidence about the presence of aortic valve calcification and the occurrence of paravalvular aortic regurgitation is controversial.[44] The severity and location or aortic ring calcification may be related to annular rupture. Aortic valve calcification has also been speculated to be associated with increased risk for prosthesis dislodgement,[46] reported in 4%–18% of several series.[46,49,50] Possibly, calcification has a greater effect on postimplant paravalvular regurgitation with self-expanding prostheses than with balloon-expandable prostheses.

A further potential consequence of severe aortic calcification may be obstruction of coronary ostia during TAVI/TAVR. Displacement of an extremely bulky calcified aortic cusp over the coronary ostia is the most frequent reported cause.[16,17,51,52] As detailed above, a distance from the coronary ostia to the aortic valve annulus of $\geq$10–14 mm is recommended for the Edwards Sapien valve and the width of the sinuses of Valsalva should be $\geq$30 mm, particularly for Medtronic CoreValve, to minimize the risk of this complication. These recommendations are not based on scientific data. Furthermore, these parameters alone are not sufficient. The length of the aortic valve cusps and the presence of bulky calcification at the commissures must be individually evaluated and considered in every case.

Atheroembolism from the ascending aorta or aortic arch is assumed to be the most common cause of periprocedural stroke during TAVI/TAVR.[39] In addition, the occurrence of calcific embolism from the aortic valve after aggressive balloon valvuloplasty has been reported.[53] The extent of aortic valve calcification may therefore be of relevance for stroke risk, especially when the use of embolic protection devices

Table 11 Recommendations about aortic valve calcification

The extent and severity of aortic valve calcification should be mentioned in descriptive terms in the report.

Table 12 Data elements included in the report

- Data acquisition mode
- Timing of images in the cardiac cycle (systolic vs diastolic)
- Contrast volume
- Image quality
- Aorta
  - Presence of kinking
  - Presence of intraluminal obstruction
  - Presence of intraluminal thrombi
- Ascending aorta
  - Width at 40 mm from annulus
  - Position relative to sternum
- Aortic arch
  - Width
  - Branch anatomy (for embolic protection device purposes)
- Descending aorta
  - Width
- Iliofemoral arteries
  - Minimal width on both sides
  - Tortuosity
  - Calcification
- Aortic root
  - Sinotubular junction aortic diameter*
  - Sinus of Valsalva width*
  - Sinus of Valsalva height*
  - Distance of coronary ostia from aortic annular plane
- Aortic valve
  - Cuspidity
  - Qualitative extent of aortic valve calcification, separately for commissures and annulus
  - Presence of a severely calcified cusp which may obstruct a coronary ostium
- Aortic Annulus
  - Aortic annulus short diameter
  - Aortic annulus long diameter
  - Aortic annulus area and area-derived diameter
  - Aortic annulus circumference and circumference-derived diameter
  - Appropriate fluoroscopic projection angle to obtain an orthogonal view onto the aortic valve plane (if the reader feels competent to report this)
- Left Ventricle
  - Presence of thrombi

*For self-expanding valves.

Disclosure of conflicts of interest: External Peer Review Group

Name	Disclosure
Suhny Abbara	None
Helmut Baumgartner	Consultant, speakers fees: Edwards Life Sciences, Actelion, AGA (St Jude Medical)
Milind Desai	None
Stephan Ensminger	Proctor, Europe and US: Edwards Lifesciences Proctor, Scientific Advisory Board: Jenavalve Research Grant Support : Novartis
Frank Flachskampf	Speaker honoraria: GE Healthcare
Tobias Pflederer	Speaker honoraria: Siemens
Murat Tuzcu	None
Todd Villines	None

is considered. However, no clinical data exist in this regard (Table 11).

Quantification of aortic valve calcification in CT can be achieved on a continuous scale through the Agatston score, calcified volume, or calcified mass.[46,47] Semiquantitative scores consider, for example, the circularity of calcium or the number of affected cusps.[48]

Data elements to be included in the report

The data elements included in the report are shown in Table 12.

Summary

CT imaging plays an important role in procedural planning for TAVI/TAVR and should be a fully integrated component of any TAVI/TAVR program. The use of CT in TAVI/TAVR is multifaceted and should include the assessment of vascular access of the aortic valve, annulus, and root and of the orientation of the annulus plane. Importantly, the person responsible for the interpretation of the CT examination should be integrated in the TAVI/TAVR team to ensure appropriate incorporation into the patient selection process and procedure planning.

Disclosure of Conflicts of Interest: SCCT Guidelines Committee

Name	Disclosure
Stephan Achenbach	Grant research: Siemens Healthcare, Bayer Schering Pharma Speaker honoraria: Edwards Lifesciences, Siemens Healthcare Consultant: Servier, Guerbet
J. Jeffrey Carr	None
Mario Garcia	None
Jeffrey Hellinger	None
Kheng-Thye Ho	None
Scott Jerome	None
GB John Mancini	None
Gilbert Raff	Grant research: Siemens Healthcare, Bayer Schering Pharma
Allen Taylor	None
Javed Tunio	None
Uma Valeti	None

References

1. Holmes DR Jr., Mack MJ, Kaul S, Agnihotri A, Alexander KP, Bailey SR, Calhoon JH, Carabello BA, Desai MY, Edwards FH, Francis GS, Gardner TJ, Kappetein AP, Linderbaum JA, Mukherjee C, Mukherjee D, Otto CM, Ruiz CE, Sacco RL, Smith D, Thomas JD: 2012 ACCF/AATS/SCAI/STS expert consensus document on transcatheter aortic valve replacement. J Am Coll Cardiol. 2012;59:1200–54.
2. Authors/Task Force Members, Vahanian A, Alfieri O, Andreotti F, Antunes MJ, Barón-Esquivias G, Baumgartner H, Borger MA, Carrel TP, De Bonis M, Evangelista A, Falk V, Iung B, Lancellotti P, Pierard L, Price S, Schäfers HJ, Schuler G, Stepinska J, Swedberg K, Takkenberg J, Von Oppell UO, Windecker S, Zamorano JL, Zembala M, ESC Committee for Practice Guidelines (CPG); Bax JJ, Baumgartner H, Ceconi C, Dean V, Deaton C, Fagard R, Funck-Brentano C, Hasdai D, Hoes A, Kirchhof P, Knuuti J, Kolh P, McDonagh T, Moulin C, Popescu BA, Reiner Z, Sechtem U, Simes PA, endera M, Torbicki A, Vahanian A, Windecker S; Document Reviews: Popescu BA, Von Segesser L, Badano LP, Bunc M, Claeys MJ, Drinkovic N, Filippatos G, Habib G, Kappetein AP, Kassab R, Lip GY, Moat N, Nickening G, Otto CM, Pepper J, Piazza N, Pieper PG, Rosenhek R, Shuka N, Schwammenthal E, Schwitter J, Mas PT, Trindade PT, Walther T: Guidelines on the management of valvular heart disease (version 2012): The Joint Task Force on the Management of Valvular Heart Disease of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS). Eur Heart J. 2012;33:2451–96.
3. Webb JG, Wood DA: Current status of transcatheter aortic valve replacement. J Am Coll Cardiol. 2012;60:483–92.
4. Cribier A, Eltchaninoff H, Bash A, Borenstein N, Tron C, Bauer F, Derumeaux G, Anselme F, Laborde F, Leon MB: Percutaneous transcatheter implantation of an aortic valve prosthesis for calcific aortic stenosis: first human case description. Circulation. 2002;106:3006–8.
5. Bruschi G, de Marco F, Botta L, Cannata A, Oreglia J, Colombo P, Barosi A, Colombo T, Nonini S, Paino R, Klugmann S, Martinelli L: Direct aortic access for transcatheter self-expanding aortic bioprosthetic valves implantation. Ann Thorac Surg. 2001;94: 497–503.

6. Ropers D, Ropers U, Marwan M, Schepis T, Pflederer T, Wechsel M, Klinghammer L, Flachskampf FA, Daniel WG, Achenbach S: Comparison of dual-source computed tomography for the quantification of the aortic valve area in patients with aortic stenosis versus transthoracic echocardiography and invasive hemodynamic assessment. Am J Cardiol. 2009;104:1561–7.
7. Schoenhagen P, Hausleiter J, Achenbach S, Y. Desai M, Tuzcu EM: Computed tomography in the evaluation for transcatheter aortic valve implantation (TAVI). Cardiovasc Diagn Ther. 2011;1:44–56.
8. Pflederer T, Achenbach S: Aortic valve stenosis: CT contributions to diagnosis and therapy. J Cardiovasc Comput Tomogr. 2010;4:355–64.
9. Wuest W, Anders K, Schuhbaeck A, May MS, Gauss S, Marwan M, Arnold M, Ensminger S, Muschiol G, Daniel WG, Uder M, Achenbach S: Dual source multidetector CT-angiography before transcatheter aortic valve implantation (TAVI) using a high-pitch spiral acquisition mode. Eur Radiol. 2012;22:51–8.
10. Willson AB, Webb JG, LaBounty TM, Achenbach S, Moss R, Wheeler M, Thompson C, Min JK, Gurvitch R, Norgard BL, Hague C, Toggweiler S, Binder RK, Freeman M, Poulson S, Wood DA, Leipsic J: 3-dimensional aortic annular assessment by multidetector computed tomography predicts moderate or severe paravalvular regurgitation after transcatheter aortic valve replacement: implications for sizing of transcatheter heart valves. J Am Coll Cardiol. 2012;59:1287–94.
11. Blanke P, Reinöhl J, Schlensak C, Siepe M, Pache G, Euringer W, Geibel-Zehender A, Bode C, Langer M, Beyersdorf F, Zehender M: Prosthesis oversizing in balloon-expandable transcatheter aortic valve implantation is associated with contained rupture of the aortic root. Circ Cardiovasc Interv. 2012;5:540–38.
12. Halliburton SS, Abbara S, Chen MY, Gentry R, Mahesh M, Raff GL, Shaw LJ, Hausleiter J; Society of Cardiovascular Computed Tomography: SCCT guidelines on radiation dose and dose-optimization strategies in cardiovascular CT. J Cardiovasc Comput Tomogr. 2011;5: 198–224.
13. Abbara S, Arbab-Zadeh A, Callister TQ, Desai MY, Mamuya W, Thomson L, Weigold WG: SCCT guidelines for performance of coronary computed tomographic angiography: a report of the Society of Cardiovascular Computed Tomography Guidelines Committee. J Cardiovasc Comput Tomogr. 2009;3:190–204.
14. Yuan R, Shuman WP, Earls JP, Hague CJ, Mumtaz HA, Scott-Moncrieff A, Ellis JD, Mayo JR, Leipsic JA: Reduced iodine load at CT pulmonary angiography with dual-energy monochromatic imaging: comparison with standard CT pulmonary angiography–a prospective randomized trial. Radiology. 2012;262:290–7.
15. Joshi SB, Mendoza DD, Steinberg DH, Goldstein MA, Lopez CF, Raizon A, Weissman G, Satler LF, Pichard AD, Weigold WG: Ultra--low-dose intra-arterial contrast injection for iliofemoral computed tomographic angiography. JACC Cardiovasc Imaging. 2009;2:1404–11.
16. Nietlispach F, Leipsic J, Al-Bugami S, Masson JB, Carere RG, Webb JG: CT of the ilio-femoral arteries using direct aortic contrast injection: proof of feasibility in patients screened towards percutaneous aortic valve replacement. Swiss Med Wkly. 2009;139:458–62.
17. Genereux P, Head SJ, Van Mieghem NM, Kodali S, Kirtane AJ, Xu K, Smith C, Serruys PW, Kappetein AP, Leon MB: Clinical outcomes after transcatheter aortic valve replacement using valve academic research consortium definitions: a weighted meta-analysis of 3,519 patients from 16 studies. J Am Coll Cardiol. 2012;59:2317–26.
18. Leon MB, Smith CR, Mack M, Miller DC, Moses JW, Svensson LG, Tuzcu EM, Webb JG, Fontana GP, Makkar RR, Brown DL, Block PC, Guyton RA, Pichard AD, Bavaria JE, Herrmann HC, Douglas PS, Petersen JL, Akin JJ, Anderson WN, Wang D, Pocock S; PARTNER Trial Invstigators: Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. N Engl J Med. 2010;363:1597–607.
19. Leon MB, Piazza N, Nikolsky E, Blackstone EH, Cutlip DE, Kappetein AP, Krucoff MW, Mack M, Mehran R, Miller C, Morel MA, Petersen J, Popma JJ, Takkenberg JJ, Vahanian A, van Es GA, Vranckx P, Webb JG, Windecker S, Serruys PW: Standardized endpoint definitions for Transcatheter Aortic Valve Implantation clinical trials: a consensus report from the Valve Academic Research Consortium. J Am Coll Cardiol. 2011;57:253–69.
20. Hayashida K, Lefevre T, Chevalier B, Hovasse T, Romano M, Garot P, Mylotte D, Uribe J, Farge A, Donzeau-Gouge P, Bouvier E, Cormier B, Morice MD: Transfemoral aortic valve implantation new criteria to predict vascular complications. JACC Cardiovasc Interv. 2011;4:851–8.
21. Toggweiler S, Gurvitch R, Leipsic J, Wood DA, Willson AB, Binder RK, Cheung A, Ye J, Webb JG: Percutaneous aortic valve replacement: vascular outcomes with a fully percutaneous procedure. J Am Coll Cardiol. 2012;59:113–8.
22. Rodes-Cabau J, Webb JG, Cheung A, Ye J, Dumont E, Feindel CM, Osten M, Natarajan MK, Velianou JL, Martucci G, DeVarennes B, Chisholm R, Peterson MD, Lichtenstein SV, Nietlispach F, Doyle D, DeLarochellière R, Reoh K, Chu V, Dancea A, Lachapelle K, Cheema A, Latter D, Horlick E: Transcatheter aortic valve implantation for the treatment of severe symptomatic aortic stenosis in patients at very high or prohibitive surgical risk: acute and late outcomes of the multicenter Canadian experience. J Am Coll Cardiol. 2010;55: 1080–90.
23. Tamburino C, Capodanno D, Ramondo A, Petronio AS, Ettori F, Santoro G, Klugmann S, Bedogni F, Maisano F, Marzocchi A, Poli A, Antoniucci D, Napodano M, De Carlo M, Fiorina C, Ussia GP: Incidence and predictors of early and late mortality after transcatheter aortic valve implantation in 663 patients with severe aortic stenosis. Circulation. 2011;123:299–308.
24. Gilard M, Eltchaninoff H, Iung B, Donzeau-Gouge P, Chevreul K, Fajadet J, Leprince P, Leguerrier A, Lievre M, Prat A, Teiger E, Lefevre T, Himbert D, Tchetche D, Carrié D, Albat B, Cribier A, Rioufol G, Sudre A, Blanchard D, Collet F, Dos Santos P, Meneveau N, Tirouvanziam A, Caussin C, Guyon P, Boschat J, Le Breton H, Collart F, Houel R, Delpine S, Souteyrand G, Favereau X, Ohlmann P, Doisy V, Grollier G, Gommeaux A, Claudel JP, Bourlon F, Bertrand B, Van Belle E, Laskar M; FRANCE 2 Investigators: Registry of transcatheter aortic-valve implantation in high-risk patients. N Engl J Med. 2012;366:1705–15.
25. Sinning JM, Hammerstingl C, Vasa-Nicotera M, Adenauer V, Lema Cachiguango SJ, Scheer AC, Hausen S, Sedaghat A, Ghanem A, Müller C, Grube E, Nickenig G, Werner N: Aortic regurgitation index defines severity of peri-prosthetic regurgitation and predicts outcome in patients after transcatheter aortic valve implantation. J Am Coll Cardiol. 2012;59:1134–41.
26. Kodali SK, Williams MR, Smith CR, Svensson LG, Webb JG, Makkar RR, Fontana GP, Dewey TM, Thourani VH, Pichard AD, Fischbein M, Szeto WY, Lim S, Greason KL, Teirstein PS, Malaisrie SC, Douglas PS, Hahn RT, Whisenant B, Zajarias A, Wang D, Akin JJ, Anderson WN, Leon MB; PARTNER Trial Investigators: Two-year outcomes after transcatheter or surgical aortic-valve replacement. N Engl J Med. 2012;366:1686–95.
27. Piazza N, de Jaegere P, Schultz C, Becker AE, Serruys PW, Anderson RH: Anatomy of the aortic valvar complex and its implications for transcatheter implantation of the aortic valve. Circ Cardiovasc Interv. 2008;1:74–81.
28. Altiok E, Koos R, Schröder J, Brehmer K, Hamada S, Becker M, Mahnken AH, Almalla M, Dohmen G, Autschbach R, Marx N, Hoffmann R: Comparison of two-dimensional and three-dimensional imaging techniques for measurement of aortic annulus diameters before transcatheter aortic valve implantation. Heart. 2011;97:1578–84.
29. Ng AC, Delgado V, van der Kley F, Shanks M, van de Veire NR, Bertini M, Nucifora G, van Bommel RJ, Tops LF, de Weger A, Tavilla G, de Roos A, Kroft LJ, Leung DY, Schuijf J, Schalij MJ, Bax JJ: Comparison of aortic root dimensions and geometries before and after transcatheter aortic valve implantation by 2- and 3-dimensional transesophageal echocardiography and multislice computed tomography. Circ Cardiovasc Imaging. 2010;3:94–102.

30. Gurvitch R, Webb JG, Yuan R, Johnson M, Hague C, Willson AB, Toggweiler S, Wood DA, Ye J, Moss R, Thompson CR, Achenbach S, Min JK, Labounty TM, Cury R, Leipsic J: Aortic annulus diameter determination by multidetector computed tomography: reproducibility, applicability, and implications for transcatheter aortic valve implantation. JACC Cardiovasc Interv. 2011;4:1235–45.
31. Willson AB, Webb JG, Gurvitch R, Wood DA, Toggweiler S, Binder R, Freeman M, Madden M, Hague C, Leipsic J: Structural integrity of balloon-expandable stents after transcatheter aortic valve replacement: assessment by multidetector computed tomography. JACC Cardiovasc Interv. 2012;5:525–32.
32. Jabbour A, Ismail TF, Moat N, Gulati A, Roussin I, Alpendurada F, Park B, Okoroafor F, Asgar A, Barker S, Davies S, Prasad SK, Rubens M, Mohiaddin RH: Multimodality imaging in transcatheter aortic valve implantation and post-procedural aortic regurgitation: comparison among cardiovascular magnetic resonance, cardiac computed tomography, and echocardiography. J Am Coll Cardiol. 2011; 58:2165–73.
33. Jilaihawi H, Kashif M, Fontana G, Furugen A, Shiota T, Friede G, Makhija R, Doctor N, Leon MB, Makkar RR: Cross-sectional computed tomographic assessment improves accuracy of aortic annular sizing for transcatheter aortic valve replacement and reduces the incidence of paravalvular aortic regurgitation. J Am Coll Cardiol. 2012; 59:1275–86.
34. Piazza N, Lange R: Imaging of valvular heart disease: I can see clearly now. Anatomy of the aortic valve. Available at: http://org.crsti.dliv2010.s3.amazonaws.com/pdfs/034_Ovality_of_the_aortic_valve_annulus.pdf. Accessed April 15, 2011.
35. Leipsic J, Gurvitch R, Labounty TM, Min JK, Wood D, Johnson M, Ailan AM, Wijesinghe N, Webb JG: Multidetector computed tomography in transcatheter aortic valve implantation. JACC Cardiovasc Imaging. 2011;4:416–29.
36. Hamdan A, Guetta V, Konen E, Goitein O, Segev A, Raanani E, Spiegelstein D, Hay I, Di Segni E, Eldar M, Schwammenthal E: Deformation dynamics and mechanical properties of the aortic annulus by 4-dimensional computed tomography: insights into the functional anatomy of the aortic valve complex and implications for transcatheter aortic valve therapy. J Am Coll Cardiol. 2012;59:119–27.
37. Schultz CJ, Tzikas A, Moelker A, Rossi A, Nuis RJ, Geleijnse MM, van Mieghem N, Krestin GP, de Feyter P, Serruys PW, de Jaegere PP: Correlates on MSCT of paravalvular aortic regurgitation after transcatheter aortic valve implantation using the Medtronic CoreValve prosthesis. Catheter Cardiovasc Interv. 2011;78:446–55.
38. Smith CR, Leon MB, Mack MJ, Miller DC, Moses JW, Svensson LG, Tuzcu EM, Webb JG, Fontana GP, Makkar RR, Williams M, Dewey T, Kapadia S, Babaliaros V, Thourani VH, Corso P, Pichard AD, Bavaria JE, Herrmann HC, Akin JJ, Anderson WN, Wang D, Pocock SJ; PARTNER Trial Investigators: Transcatheter versus surgical aortic-valve replacement in high-risk patients. N Engl J Med. 2011;364:2187–98.
39. Masson JB, Kovac J, Schuler G, Ye J, Cheung A, Kapadia S, Tuzcu ME, Kodali S, Leon MB, Webb JG: Transcatheter aortic valve implantation: review of the nature, management, and avoidance of procedural complications. JACC Cardiovasc Interv. 2009;2:811–920.
40. Tops LF, Wood DA, Delgado V, Schuijf JD, Mayo JR, Pasupati S, Lamers FP, van der Wall EE, Schalij MJ, Webb JG, Bax JJ: Noninvasive evaluation of the aortic root with multislice computed tomography. Implications for transcatheter aortic valve replacement. JACC Cardiovasc Imaging. 2008;1:321–30.
41. Tzikas A, Schultz C, Van Mieghem NM, de Jaegere PP, Serruys PW: Optimal projection estimation for transcatheter aortic valve implantation based on contrast-aortography: validation of a Prototype Software. Catheter Cardiovasc Interv. 2010;76:602–7.
42. Gurvitch R, Wood DA, Leipsic J, Tay E, Johnson M, Ye J, Nietlispach F, Wijesinghe N, Cheung A, Webb JG: Multislice computed tomography for prediction of optimal angiographic deployment projections during transcatheter aortic valve implantation. JACC Cardiovasc Interv. 2010;3:1157–65.
43. Kurra V, Kapadia SR, Tuzcu EM, Halliburton SS, Svensson L, Roselli EE, Schoenhagen P: Pre-procedural imaging of aortic root orientation and dimensions: comparison between X-ray angiographic planar imaging and 3-dimensional multidetector row computed tomography. JACC Cardiovasc Interv. 2010;3:105–13.
44. Binder RK, Leipsic J, Wood D, Moore T, Toggweiler S, Willson A, Gurvitch R, Freeman M, Webb JG: Prediction of optimal deployment projection for transcatheter aortic valve replacement: angiographic 3-dimensional reconstruction of the aortic root versus multidetector computed tomography. Circ Cardiovasc Interv. 2012; 5:247–52.
45. Arnold M, Achenbach S, Pfeiffer I, Ensminger S, Marwan M, Einhaus F, Pflederer T, Ropers D, Schuhbaeck A, Anders K, Lell M, Uder M, Ludwig J, Weyand M, Daniel WG, Feyrer R: A method to determine suitable fluoroscopic projections for transcatheter aortic valve implantation by computed tomography. J Cardiovasc Comput Tomogr. 2013;7: xxx–xxx.
46. Van Mieghem NM, Schultz CJ, van der Boon RM, Nuis RJ, Tzikas A, Geleijnse ML, van Domburg RT, Serruys PW, de Jaegere PP: Incidence, timing, and predictors of valve dislodgment during TAVI with the medtronic corevalve system. Catheter Cardiovasc Interv. 2012;79:726–32.
47. Delgado V, Ng AC, van de Veire NR, van der Kley F, Schuijf JD, Tops LF, de Weger A, Tavilla G, de Roos A, Kroft LJ, Schalij MJ, Bax JJ: Transcatheter aortic valve implantation: role of multi-detector row computed tomography to evaluate prosthesis positioning and deployment in relation to valve function. Eur Heart J. 2010;31:1114–23.
48. John D, Buellesfeld L, Yuecel S, Mueller R, Latsios G, Beucher H, Gerckens U, Grube E: Correlation of device landing zone calcification and acute procedural success in patients undergoing transcatheter aortic valve implantations with the self-expanding CoreValve prosthesis. JACC Cardiovasc Interv. 2010;3:233–43.
49. Geisbusch S, Bleiziffer S, Mazzitelli D, Ruge H, Bauernschmitt R, Lange R: Incidence and management of CoreValve dislocation during transcatheter aortic valve implantation. Circ Cardiovasc Interv. 2010; 3:531–6.
50. Webb JG, Pasupati S, Humphries K, Thompson C, Altwegg L, Moss R, Sinhal A, Carere RG, Munt B, Ricci D, Ye J, Cheung A, Lichtenstein SV: Percutaneous transarterial aortic valve replacement in selected high-risk patients with aortic stenosis. Circulation. 2007; 116:755–63.
51. Treede H, Tubler T, Reichenspurner H, Grube E, Pascotto A, Franzen O, Mueller R, Low R, Bolling SF, Meinertz T, Schofer J: Six-month results of a repositionable and retrievable pericardial valve for transcatheter aortic valve replacement: the Direct Flow Medical aortic valve. J Thorac Cardiovasc Surg. 2010;140:897–903.
52. Webb JG, Harnek J, Munt BI, Kimblad PO, Chandavimol M, Thompson CR, Mayo JR, Solem JO: Percutaneous transvenous mitral annuloplasty: initial human experience with device implantation in the coronary sinus. Circulation. 2006;113:851–5.
53. Isner JM: Acute catastrophic complications of balloon aortic valvuloplasty. The Mansfield Scientific Aortic Valvuloplasty Registry Investigators. J Am Coll Cardiol. 1991;17:1436–44.