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Transcatheter Aortic Valve Replacement

Preprocedure and Postprocedure Imaging

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KEYWORDS
• Aortic stenosis • TAVR • Aortic valve disease therapy • Pre-TAVR imaging • Postoperative complications • PVL • Valve thrombosis

KEY POINTS
- Transcatheter aortic valve replacement (TAVR) has rapidly evolved as a percutaneous minimally invasive treatment of patients with severe, symptomatic aortic stenosis who are at very high risk for surgical aortic valve replacement (SAVR).
- Due to innovations in interventional cardiology with new devices, decreased size of access sheaths, better valve design, and delivery systems along with more operator experience, there is continued reduction in complication rates.
- Due to well-planned and robust clinical trials and registries along with maturation of multimodality structural cardiovascular imaging, TAVR has now been widely adopted.
- Multidetector CT (MDCT) in particular has emerged as the primary modality in preprocedural planning and postprocedural evaluation for valve thrombosis.
- Integration of a strong cardiovascular CT program is critical for a successful structural interventional program.

Video content accompanies this article at www.advancesinclinicalradiology.com.

INTRODUCTION

Transcatheter aortic valve replacement (TAVR) is the procedure of choice for inoperable and high-risk symptomatic patients with severe aortic stenosis. Preprocedure imaging with computed tomography (CT) is critical in appropriate valve sizing, best valve deployment angle, and optimal access route determination. CT is extremely useful in identifying several morphologic features associated with higher complications and poor outcome. In addition, CT provides information regarding post-TAVR valve thrombosis, which is often underdiagnosed in asymptomatic patients. With careful patient selection, decreased size of access sheaths, better valve design, and delivery systems along with more operator experience, there is continued reduction in complication rates expanding its suitability to intermediate and now even low-risk population. This review outlines the role of imaging especially CT in pre-TAVR and post-TAVR population, describes step-by-step image analysis and discusses its importance for a successful TAVR program.

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BACKGROUND

The semilunar aortic valve is normally comprised of 3 cusps forming the sinuses of Valsalva at the aortic root. The bicuspid congenital morphology, with fusion of the commissure between 2 cusps, occurs in less than 2% of the general population and is a common cause of aortic valve stenosis in sixth and seventh decades of life [1]. During the cardiac cycle, the aortic valve is exposed to high-pressure hemodynamics, and nonlaminar flow results in endothelial damage. Recent advances in our understanding of the pathogenesis of aortic valve stenosis reveals a complex hemodynamic and biochemical interplay of mechanical stress, inflammation, and osteoblast-like differentiation resulting in hydroxyapatite deposition with fibro-calcific remodeling [2]. Certain disease states that are associated with inflammation and atherosclerosis, such as hypertension, hyperlipidemia, and diabetes mellitus, also seem to overlap in association with valvular calcification [3].

The prevalence of aortic valve stenosis varies significantly with age with less than 0.5% affecting those under the age of 65 years. This increases to 2.8% to 3.4% affecting those over the age of 75 years [4,5]. The natural history of aortic valve stenosis was first reported in 1968 by Ross and Braunwald in a series of 12 patients in whom surgery was not performed for a variety of reasons [6]. They described a slow, insidious progression of disease with the onset of symptoms marking a precipitous decline in survival [6]. Recent studies focusing on the asymptomatic, severe aortic valve stenosis cohorts have shown an approximate 1% per year risk of sudden death, along with a 5-year risk of 25% for either death or symptomatic disease requiring surgery [7].

Surgical aortic valve replacement (SAVR) for predominantly stenotic valves have demonstrated a significant improvement in 3-year survival of 87% in operated versus 21% in unoperated patients [8]. Despite the good prognosis of surgery, up to a third of patients referred with severe, symptomatic aortic valve stenosis do not undergo surgery [9,10]. Irrespective of the debate on the rates of SAVR in severe aortic valve stenosis, the Society of Thoracic Surgeons (STS) had developed and updated the surgical risk models to predict mortality and morbidity from cardiac surgery based on the accumulated STS data [11–13]. Based on these prediction models, patients with the highest risks of mortality and morbidity were declined surgery. With the need for an alternative treatment approach, percutaneous methods of implanting prosthetic aortic valves were developed.

DEVELOPMENT OF TRANSCATHETER AORTIC VALVE REPLACEMENT

In 2002, the first ever percutaneously implanted aortic valve prosthesis in a human was described by Alain Cribier and his colleagues. They placed a bovine pericardial prosthesis inside a 23-mm balloon-expandable stainless steel stent and delivered via antegrade, transseptal approach in a 57-year-old man in cardiogenic shock with good results [14]. Percutaneous Valve Technologies, Inc, developed the original valve, but it was eventually acquired by Edwards Lifesciences in 2004. Edwards made further refinements and developed the Edwards-SAPIEN valve in 2005 [15]. Concurrently, another percutaneous aortic valve developed by CoreValve, in which a porcine pericardial tissue valve was placed inside a self-expanding nitinol frame. This device was delivered via smaller sheaths and with it also came the possibility of delivering the device via a subclavian approach [15,16]. The CoreValve, subsequently commercialized by Medtronic, also showed favorable outcomes in feasibility trials across Europe and Canada.

These early TAVR valves generated great interest as a viable option to treat patients deemed inoperable. European feasibility trials demonstrated favorable outcomes in high-risk, inoperable patients. National registries were developed across Europe culminating in a randomized clinical trial with Placement of AoRTic TraNscathetER Valve Trial (PARTNER) in the United States.

The PARTNER trial used the Edwards-SAPIEN valve in high-risk, inoperable patients, and compared them with standard, medical therapy including balloon aortic valvuloplasty. PARTNER showed a significant survival benefit in the TAVR arm. Deaths from cardiovascular causes were halved at 1 year [17]. Four years later, in 2014, the CoreValve Trial randomized high-risk, mean STS-predicted risk of mortality (STS-PROM) around 7.5%, between TAVR versus SAVR for treatment of severe, symptomatic aortic valve stenosis. This was the first trial to show superiority of TAVR over SAVR with 1-year mortality from any cause at 14.2% versus 19.1%, respectively [18].

Continued improvements in the TAVR valves and their delivery systems lead to reduced vascular complications, strokes, paravalvular regurgitation, and heart block. The original 2005 SAPIEN valve evolved into the second-generation SAPIEN-XT valve in 2009 and eventually into the third-generation and current-generation SAPIEN 3 in 2012 (Fig. 1; Table 1). The 2006 CoreValve evolved within the same CoreValve

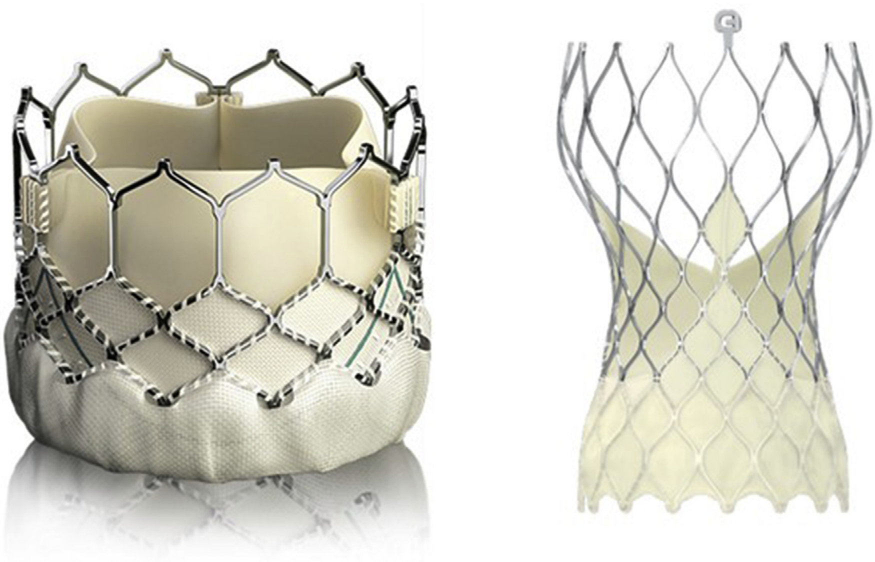

FIG. 1 Edwards Lifesciences SAPIEN 3 balloon-expandable TAVR valve (*left*) and Medtronic Evolut self-expanding TAVR valve (*right*). (*Courtesy of* Edwards LifeSciences LLC, Irvine, CA; and Medtronic, Minneapolis, MN.)

name over a span of 6 years until 2012, when the CoreValve Evolut R was released (see Fig. 1; Table 2) [15].

In the PARTNER-2 trial the intermediate-risk (mean STS-PROM of 5.8%) cohort were randomized between TAVR versus SAVR. Mortality from any causes or disabling stroke as the primary endpoint was similar between the 2 groups, 19.3% for TAVR and 21.1% for SAVR at the 2-year mark [18]. An observational study studying the SAPIEN 3 valve within the cohort of patients from the PARTNER-2 SAPIEN 3 and the PARTNER-2A showed that the 1-year mortality from any cause was significantly lower in TAVR 7.4% versus 13% in SAVR. Mortality from a cardiovascular cause was also significantly lower at 4.5% versus 8.1% [19]. With rapid advancement in technologies and clinical data supporting favorable outcomes along with the US Food and Drug Administration approval expansion for the intermediate-risk patient, the use of TAVR became widespread. Edwards Lifesciences and Medtronic have led the way in expanding the use of TAVR across the United States. However, in Europe, new TAVR valves from Saint Jude Medical, Boston Scientific, and Symetis, have received approval for clinical evaluation [15]. This rapid expansion in the treatment of severe aortic valve stenosis was made possible in part with cardiac imaging techniques, which have proved crucial in planning the TAVR procedures, none more so than cardiac CT angiography.

TABLE 1
Valve Area Sizing for Edwards Lifesciences SAPIEN 3 Valve

Edwards Lifesciences SAPIEN 3 Valve Sizes	20 mm	23 mm	26 mm	29 mm
Native annulus area (mm^2)	273–345	338–430	430–546	540–683
Area-derived diameter (mm)	18.6–21.0	20.7–23.4	23.4–26.4	26.2–29.5
Valve height (mm)	15.5	18	20	22.5
Iliofemoral vessel diameter (mm)	≥5.5			≥6.0
Edwards eSheath Introducer Set	14-F or equivalent			16-F or equivalent

TABLE 2
Valve Area Sizing for Medtronic Evolut R Valve

Medtronic Evolut R Valve Sizes	23 mm	26 mm	29 mm	34 mm
Annulus diameter (mm)	18–20	20–23	23–26	26–30
Annulus perimeter (mm)	56.5–62.8	62.8–72.3	72.3–81.7	81.7–94.2
Medtronic EnVeo R Delivery System	14-F or equivalent			16-F or equivalent

PRETRANSCATHETER AORTIC VALVE REPLACEMENT IMAGING

In traditional SAVR, an aortotomy is performed, and the aortic valve cusps are excised allowing for direct visualization of the aortic valve annulus. The annulus can then be directly measured for valve sizing intraoperatively [20]. However, the percutaneous approach of TAVR precludes direct visualization at the time of procedure. Annulus measurements must be performed before the procedure for valve sizing. In addition to valve sizing, cardiovascular imaging also allows for assessment of landing site anatomy to predict potential procedural challenges, degree of valvular calcification, access site measurements and suitability, and optimal fluoroscopic projection for valve deployment during the procedure [21].

ECHOCARDIOGRAPHY

Transthoracic echocardiography (TTE) is the primary initial imaging method in evaluation of suspected aortic stenosis. It provides morphologic and functional assessment of the aortic valve to determine the severity of aortic valve stenosis using peak systolic velocity of the continuous wave Doppler flow across the aortic valve, mean pressure gradient across the valve, and the calculated aortic valve area (Table 3).

In the PARTNER trial, inclusion criteria for severe aortic valve stenosis was defined as aortic valve area less than 0.8 cm^2, mean pressure gradient $\geq$40 mm Hg, and a peak velocity $\geq$4 m/s [17]. TTE or transesophageal echocardiography (TEE), however, provides a 2-dimensional (2D) imaging of the aortic valve and the sagittal plane measurements correspond to the shorter axis of the elliptical annulus as measured by the MDCT, and, hence, leads to under sizing of the annulus (Fig. 2). In addition, accurate analysis of heavy calcified aortic leaflets or root is limited due to acoustic shadowing.

In a comparative study between TEE and MDCT in a patient undergoing TAVR, the mean MDCT planimeteric annular area (4.65 $\pm$ 0.82 cm^2) was significantly higher than 2D TEE circular (3.89 $\pm$ 0.74

TABLE 3
2014 ACC/AHA Guideline for The Management of Patients with Valvular Heart Disease Criteria for The Diagnosis of Low-Flow, Low-Gradient Severe Aortic Valve Stenosis

2014 ACC/AHA Criteria for Severe Aortic Valve Stenosis	Aortic Valve V_{max} by Continuous Wave Doppler (m/s)	Mean Gradient (mm Hg)	Aortic Valve Area (cm^2)	Indexed Valve Area (cm^2/m^2)
Severe high-gradient	$\geq$4	$\geq$40	$\leq$1[a]	$\leq$0.6[a]
Severe low-flow low-gradient with reduced ejection fraction (EF)	<4 but $\geq$4 with dobutamine stress	<40	$\leq$1	$\leq$0.6
Severe low-gradient with normal EF, paradoxic low-flow	<4	<40	$\leq$1	$\leq$0.6[b]

[a] May be higher with mixed aortic valve disease.
[b] With concomitant calculated stroke volume index less than 35 mL/m^2 in a normotensive patient (systolic BP <140 mm Hg).
Adapted from Nishimura RA, Otto CM, Bonow RO, et al. 2014 AHA/ACC guideline for the management of patients with valvular heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. J Thorac Cardiovasc Surg 2014;148(1):e1–e132; with permission.

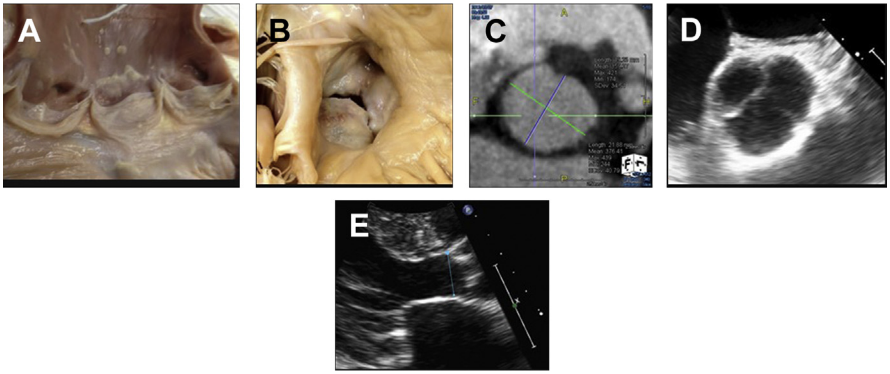

FIG. 2 (**A**) Specimen image of aortic root shows the semilunar cusps. The aortic annulus is oval-shaped structure as seen on (**B**) specimen, (**C**) CT, and (**D**) 3D TEE. (**E**) TTE annulus measurement in short plane is often smaller than CT and 3D TEE measurements.

cm^2, P<.001), 3D TEE circular (4.06 ± 0.79 cm^2, P<.001), and 3D TEE circular (4.06 ± 0.77 cm^2, P<.001) [22].

MULTIDETECTOR COMPUTED TOMOGRAPHY

MDCT allows isometric imaging of the aortic root with minimum image thickness of 0.6 mm or less, allowing oblique reconstructions without losing spatial resolution. It is now a well-validated tool, often cited as the gold standard in annular measurements. There are many scan protocols, but a minimum 64 detector scanner is recommended for TAVR imaging. Because of the severity of the aortic valve stenosis in these patients, heart-rate-lowering medications that could lower diastolic perfusion pressure of the coronaries are avoided to minimize potential complications of severe hypotension that could lead to acute cardiogenic shock.

IMAGE ACQUISITION

At the authors' institutions, an electrocardiographic (ECG)-gated, noncontrast-enhanced CT of the heart is first obtained for quantification of aortic valve calcification. Studies have shown that the degree of aortic valve calcification correlated to the severity of aortic valve stenosis [23].

A second scan of the chest is done with intravenous contrast, and breath-held images are acquired with retrospective ECG gating. Retrospective ECG gating is favored for reconstruction of cine images that allow for selection of the optimal phase of the cardiac cycle, in which the most accurate measurements can be performed. The ECG pulsing is either turned on, optimized to systolic phase imaging, or is turned off for best resolution throughout the entire cardiac cycle. The contrast medium typically used is Iohexol-350 and the contrast dose and rate of injection varies based on patient's body mass index and type of scanner, although usually between 80 and 100 mL at 4 to 5 mL/s followed by the same amount of saline chaser. The volume of acquisition begins just above the thoracic inlet and spans to the lesser trochanter to include the peripheral vasculature. In patients with renal insufficiency, the contrast dose is often reduced to 30 to 40 mL, with 70 mL saline chaser, and adjustments are made to the CT technique with lowering threshold to 100 HU for bolus tracking, decreasing rate of injection to 3 to 3.5 mL/s and increasing the pitch to maximum allowed for gated study.

MEASUREMENTS

After obtaining the 3D dataset, measurements are performed using dedicated postprocessing software. Aortic valve calcium scoring is first performed from the noncontrast-enhanced dataset using the Agatston method. From the contrast-enhanced images, a stepwise approach is pursued from measurements of the fluoroscopic angle, aortic valve annulus area, left ventricular outflow tract area, sinus of Valsalva dimensions, annulus to coronary artery ostia distance, annulus to brachiocephalic artery distance, and the peripheral vasculature luminal diameters.

To obtain the optimal fluoroscopic angle, the lowest points of each of the coronary cusps are marked on the 3D software, and the volume is rotated to a plane where all 3 points are visible en face in a single annular plane. The software then calculates the virtual fluoroscopic angles in the anterior oblique plane with a craniocaudal tilt (Fig. 3).

The most crucial of measurements is the aortic valve annulus area, which leads to determination of appropriate prosthetic valve sizing. As with the determination of the optimal fluoroscopic angle, the lowest points of the coronary cusps determine the annular plane, where the valve connects to the wall of the left ventricular outflow tract. This annular plane is the target area for the landing site of the TAVR prosthetic valves. This annular plane should ideally be measured at maximal valvular opening during ventricular systole. Once the optimal phase of the cardiac cycle has been determined, double oblique projections near the level of the annular plane are first obtained. The annular plane should be at the level where it lies just at the level of the lowest points of the coronary cusps. The lowest points of all 3 coronary cusps should be viewed on the 2 double oblique projections. Following this, the annular plane could be rotated to assess that it does not cross above lowest points of insertion of the coronary cusps to the wall of the left ventricular outflow tract. Once this has been determined, the annulus could be traced around the perimeter via planimetry method. The aortic valve annulus is typically not circular, but rather ellipsoid, and tracing around the perimeter is preferred for accurate area and perimeter measurements. This method will generate the shortest and longest distances along with an average diameter, perimeter, and area (Fig. 4). As is frequently the case with severe aortic valve stenosis, there is significant calcification that may involve the left ventricular outflow tract. Calcification may be crescentic or bulky, but the annular perimeter should be traced where the true annulus is formed, rather than selecting either inside or outside the calcification. This may involve tracing through the area of calcification for the annular measurement. It is also important to characterize the pattern of calcification in the left ventricular outflow tract for the proceduralist to be aware.

A

B

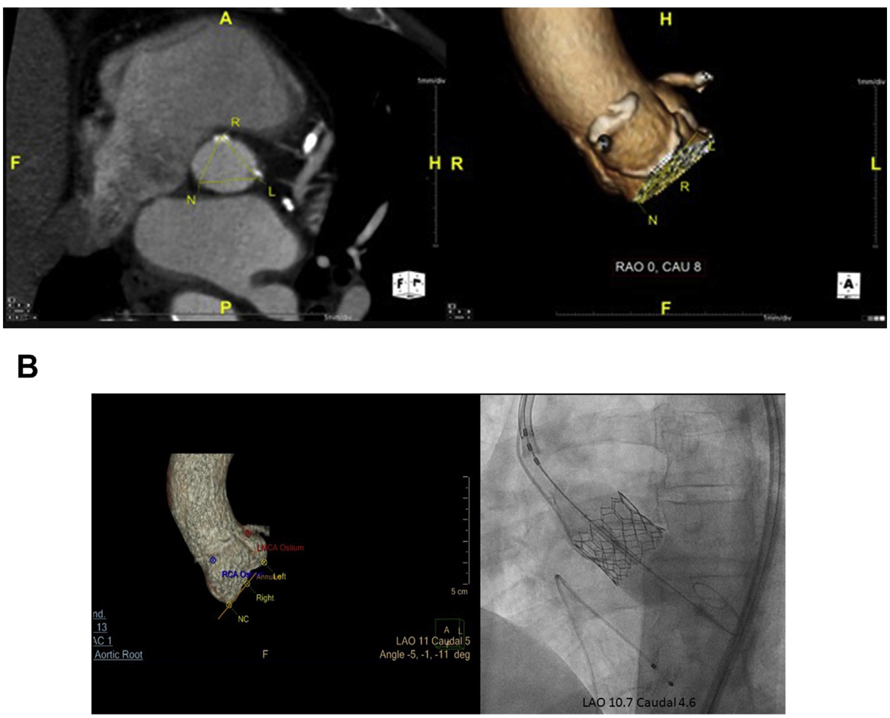

FIG. 3 (**A**) Determining optimal fluoroscopic valve deployment angle. (**B**) Good correlation between CT suggested and flouroscopic valve deployment angle. Due to the high accuracy of the provided projection angle from CT data, only 1 injection of 15 to 20 mL of contrast is used during the procedure.

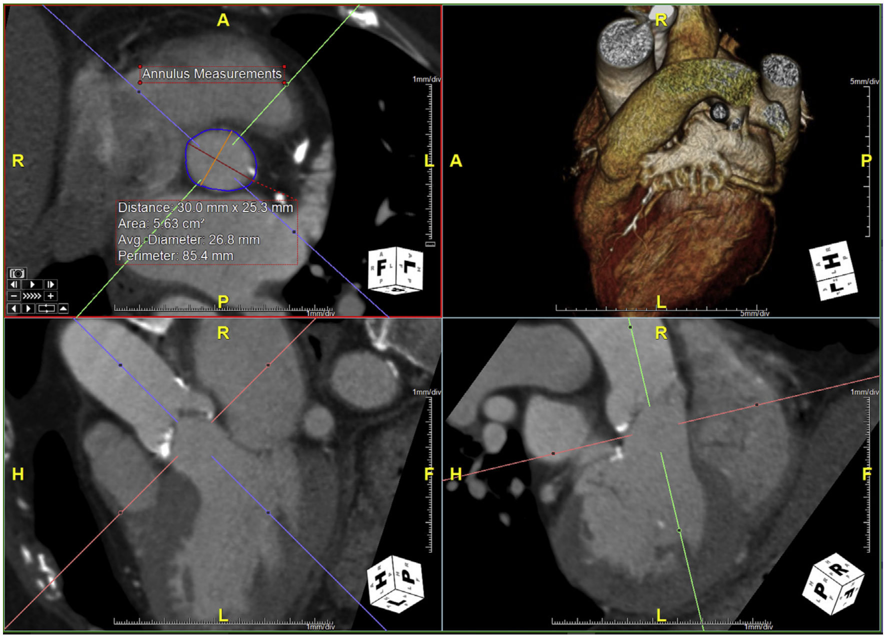

FIG. 4 Aortic annulus measurements done in systolic phase using the double oblique method.

For measurement of the left ventricular outflow tract, staying in same systolic phase, a 4-mm distance should be measured from the annular plane in one of the double oblique projections toward the left ventricle (Fig. 5). A similar perimeter method is used at this level to generate the shortest and longest distances along with average diameter, perimeter, and area. The SAPIEN 3 valve is cylindrical structure, and if the area in the left ventricular outflow tract significantly narrows, this valve may not be appropriate for the patient owing to the lack of clearance on the ventricular side of the prosthesis. Other TAVR valves that extend significantly into the left ventricular outflow tract may also be excluded from use based on the left ventricular outflow tract (LVOT) measurements. A qualitative degree of calcification in the LVOT should also be reported to inform the proceduralist of the potential risks for rupture or conduction abnormalities with balloon expansion (Fig. 6). Thickness of the basal anterior ventricular septum is not routinely reported. However, if this is noted visually, measurements of the basal anteroseptal thickness in diastole should be reported for potential risks of LVOT obstruction following valve deployment.

The next step is to measure the heights of coronary ostia from the annulus plane. This allows for assessment of the coronary artery ostial clearance on the aortic side of the prosthesis. At the level of the annulus, the imaging plane of the annulus could be rotated to bring the right and left main coronary ostia into view. Once these are in view, the distance from the coronary ostium to the annular plane could be measured as right and left main coronary heights (Fig. 7). Unlike SAVR, the percutaneous method is more of an implantation rather than a replacement, in which the native aortic valve is resected. When the native aortic valve cusps are displaced with the TAVR valve, there is risk for potential occlusion of coronary ostia. This makes the coronary ostial height measurement important in avoiding procedural complications. The required optimum coronary artery to annulus distance is 10 mm [24].

Following measurements of the coronary ostial heights, the imaging plane can be moved to the level of the sinuses of Valsalva. The phase of the cardiac cycle can be changed to end of diastole when the valve is closed for standardization of measurements of the aorta. At this point, aortic valve cusp to cusp distances can be measured at the apices. Although this may not be the greatest distance between the cusps, the standardization of TAVR protocol requires cusp apex to cusp apex measurements. Apex of the coronary cusp to opposite coronary commissure may also be measured for additional information. The imaging plane can be moved further up the aorta to the level of the

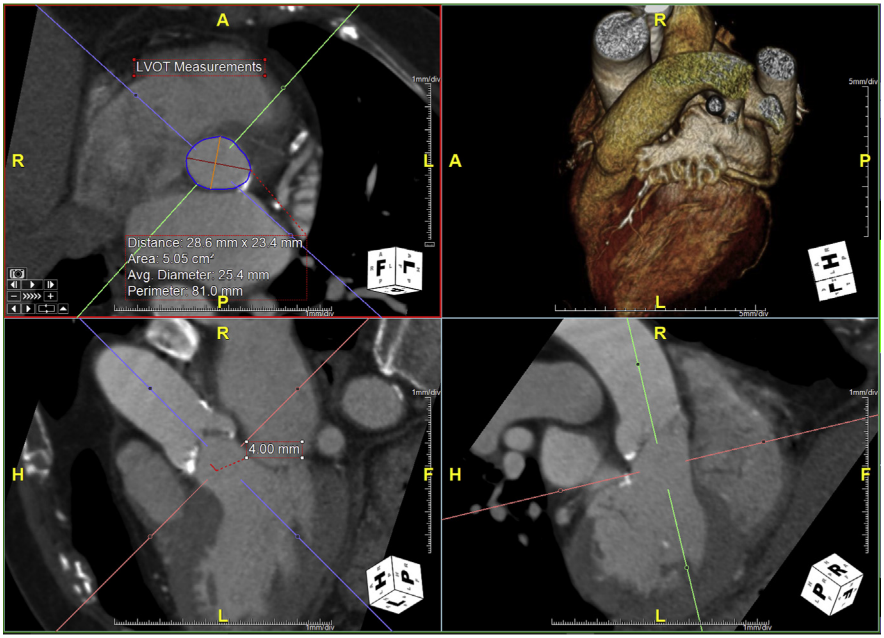

FIG. 5 Measurement of the left ventricular outflow tract. It is important to mention the severity of LVOT calcification when present. In patients with basal interventricular septal thickening, it is advised to measure the septal thickness as well as LVOT measurements in systole and diastole.

sinotubular junction. Measurement of the sinotubular junction diameter is also important in avoiding aortic damage during implantation of the CoreValve where the superior portion of the valve apposes to the wall of the aorta.

ACCESS SITE MEASUREMENTS

Transfemoral

Vessel diameter measurements can be done manually using the double oblique method or using the automated centerline of the bilateral common iliac arteries, bilateral external iliac arteries, and bilateral common femoral arteries to assess for minimum diameter (Fig. 8). In the early days of TAVR, the sheath sizes ranged from 21-Fr to 24-Fr, but, with subsequent technological advances, the valves can now be crimped into smaller sizes. Currently, the SAPIEN 3 valves can be delivered via 14-Fr to 16-Fr sheaths, and the CoreValve Evolut R can be delivered via a 14-Fr sheath. The new CoreValve Evolut R 34 mm, however, requires a 16-Fr sheath (see Tables 1 and 2). Thus, the modern generation of TAVR valve can be delivered through sheaths with outer diameters ranging from 4.67 to 5.33 mm. Qualitative assessment of the tortuosity of the iliofemoral system is also important to make the proceduralist aware of favorable laterality in access sites.

Measurements of the descending thoracic and abdominal aorta are not typically necessary unless if there is severe narrowing. Qualitative description of the abdominal aortic atherosclerosis, calcification, and mural thrombus is, however, important to build into the report for the proceduralist to be made aware of potential embolic complications.

Transapical

This approach is less favored due to associated prolonged morbidity. Qualitative description of the left ventricular apex is important to exclude thrombi or other potential masses, which may preclude access via transapical approach. CT can be used to localize and mark the skin surface for optimal entry site of left ventricle apex without intervening lung (Fig. 9).

Other Access Sites

Development of smaller sheath sizes have also allowed for access from less-conventional peripheral vasculature such as the axillary or subclavian arteries. These are not

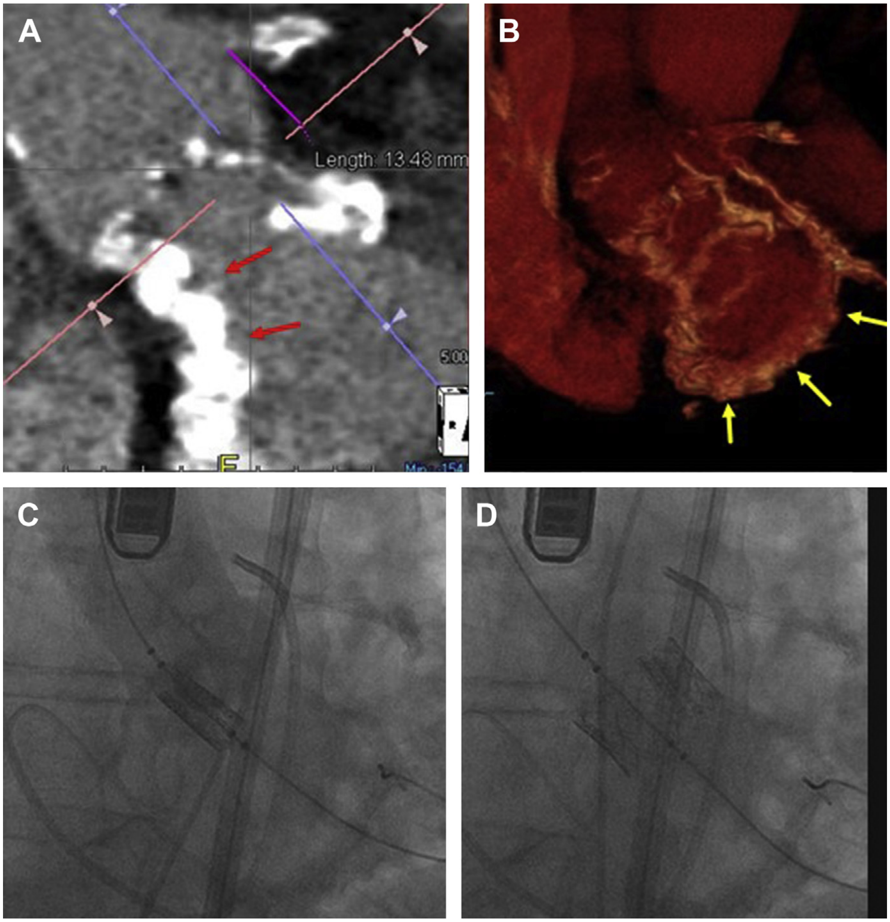

FIG. 6 A 91-year-old man with (**A**) LVOT calcification (*red arrows*) and (**B**) extensive mitral annular (*yellow arrows*) underwent successful transfemoral TAVR with (**C**, **D**) a 26-mm valve implantation without any conduction issues after the procedure. The presence of LVOT and severe mitral annulus calcification increases the risk of conduction disturbances as well as increased risk for annular rupture. Oversizing should be avoided in such situations.

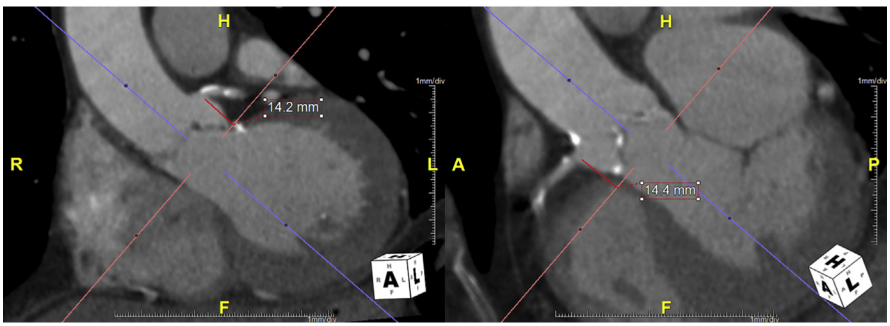

FIG. 7 Coronary ostia to aortic annulus distance.

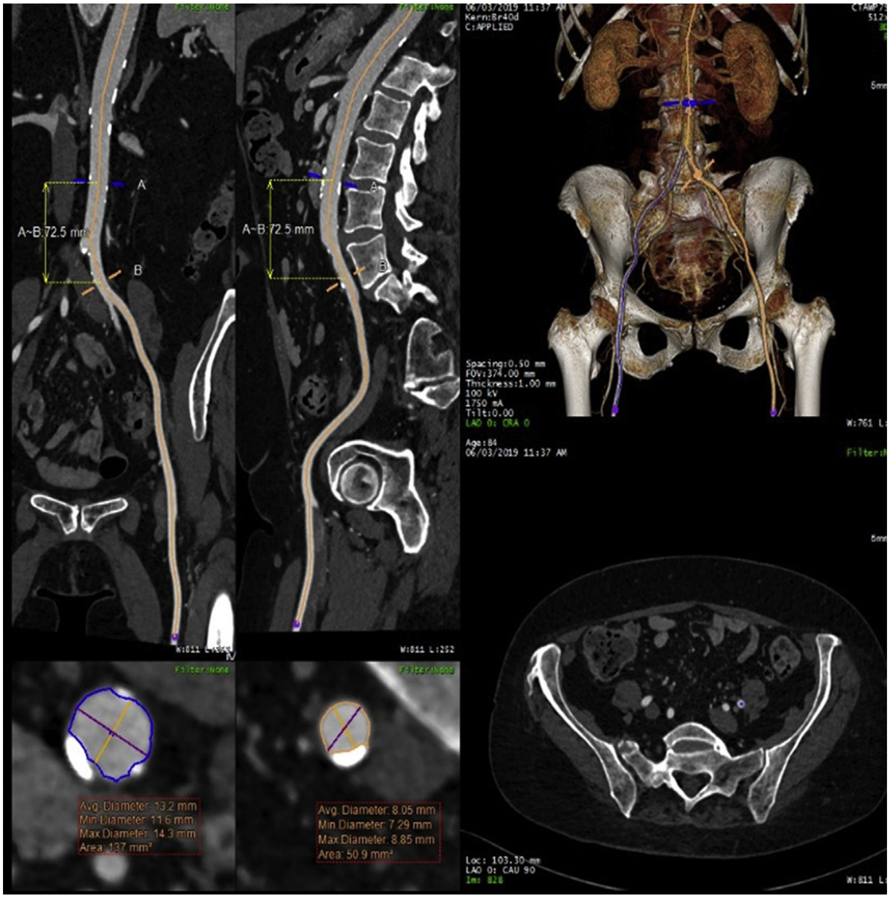

FIG. 8 Iliofemoral access measurements from cardiac CT angiography (CTA) using the automated centerline, as shown here, to assess for minimum diameter. In addition, degree of calcification (circumferential or horseshoe calcification), vessel tortuosity, and aneurysmal dilatation with any mural thrombus should be included in the report.

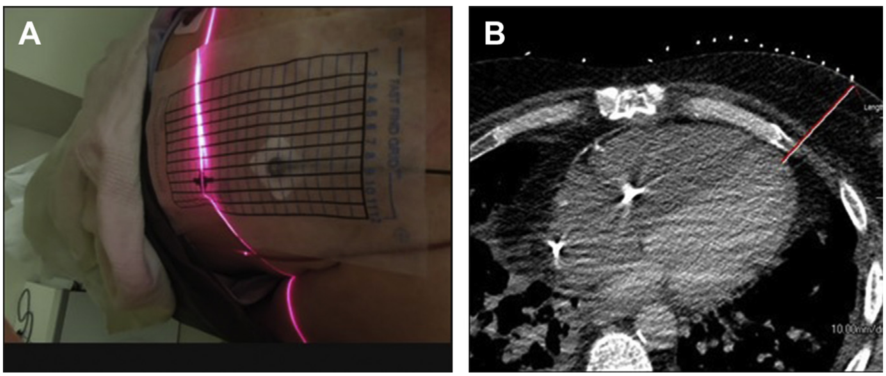

FIG. 9 LV apex localization with CT. (**A**) A limited CT with 15 to 20 mL contrast or without contrast is done with arms beside patient, with a lung biopsy grid on skin surface. (**B**) The best CT image demonstrating the LV apex is selected and (**A**) using the CT laser marker light the skin surface is marked corresponding to the chosen image position.

measured routinely, but similar double oblique or automated centerline measurements can be performed to assess minimum diameter.

With the transcaval approach, the optimal site of crossing from the inferior vena cava to the abdominal aorta needs to be identified via imaging (Fig. 10). From an imaging standpoint, identifying the aortic site with the least amount of calcifications, and the absence of intervening structures between the inferior vena cava and the abdominal aorta, such as bowel and small arterial or venous structures, needs to be reported. This is not typically included in the report routinely, but this can be discussed through multidisciplinary team approach to plan a transcaval approach [25].

Regarding the transcarotid approach, routine pre-TAVR CTs do not typically incorporate the internal carotids, but common carotid measurements can be performed from the scan using the double oblique or automated centerline method [26]. Again, this is not commonly reported, but measurements can be performed retrospectively (Box 1).

ALTERNATIVE IMAGING MODALITIES

If the patient cannot receive intravenous iodinated contrast because of allergic reaction or renal failure, noncontrast CT could be performed for degree of calcification assessment, as well as measuring vascular structures. However, differentiating blood pool from myocardium may lead to some challenges in accurate measurements of the aortic valve annulus. Combinations with 3D TEE may add to increased diagnostic yield. Noncontrast-enhanced magnetic resonance imaging could be a second alternative to measure annular measurements along with access site assessment [27]. However, spatial resolution is lower than in contrast-enhanced CT and, thus, there is slightly increased interobserver variability in measurements. Large-field intravascular ultrasonography (IVUS) with measurements can also be performed. However, this will have to be performed intraoperatively, and this limits the assessment of access sites as well as valve sizing preprocedurally. Data comparing annulus measurements using transesophageal echocardiography and large-field IVUS with multidetector CT showed that large-field IVUS outperformed TEE and correlated better to CT measurements and IVUS and CT predicted perivalvular leak similarly [28].

SPECIAL CASES

Currently, percutaneous transcatheter aortic valve implantation/replacement is approved for patients with aortic valve stenosis in a tricuspid aortic valve who are high risk or intermediate risk for SAVR. The trials that have been carried out have excluded bicuspid aortic valves, aortic valve regurgitation, and patients with bioprosthetic aortic valves that have degenerated. However, off-label use has been performed in special circumstances to alleviate patient symptoms.

The placement of a TAVR valve inside a degenerated bioprosthetic aortic valve is not uncommon given the advanced age of patients with increased risks for redo sternotomy. Measurements for the most part are similar to a routine pre-TAVR study, especially with vascular access sites. However, measurements in the aortic root are quite different. Instead of measuring the aortic valve annulus, the area inside the bioprosthetic aortic valve is measured, excluding the calcifications and pannus

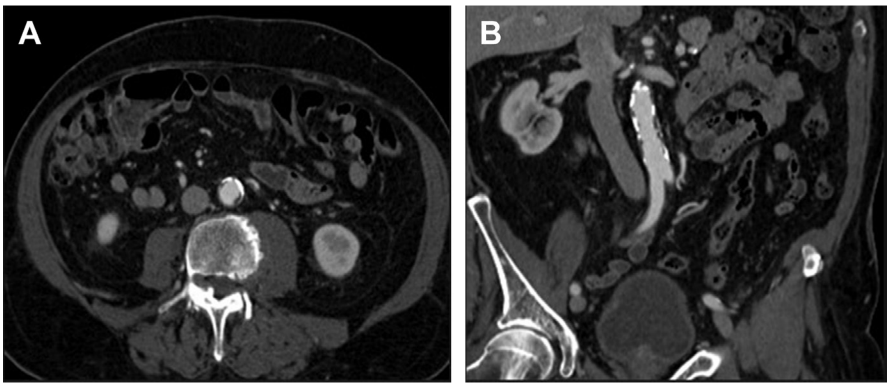

FIG. 10 Optimal site selection for transcaval approach. The presence of atheroma (*A*, *B*) and any focal dissection should be noted and communicated with the TAVR team.

BOX 1
Access Site Limitations (MDCT Used Exclusively)

- Transfemoral:
    - Small size, extreme calcification, tortuosity
    - If common femoral arterysmall, can do high cut down.
- Transaortic:
    - Extensive calcification
    - Left internal mammary arteryor saphenous vein graft graft too close and behind the sternum
    - Scarring from mediastinal fibrosis or previous radiation
- Transapical:
    - Previous radiation or thoracic surgery
    - Previous chronic granulomatous infection with extensive scarring
    - Previous LV apex aneurysm, thrombus
    - Extreme obesity: LV apex too deep from skin surface (relative contraindication)

or thrombi. Following this measurement, the virtual TAVR valve to coronary ostia measurements needs to be performed. A virtual ring as the basal aspect of the surgical prosthesis needs to be identified at the 3 lowest point of the prosthesis. Following this, this vertical plane has to be shifted to the level of the coronary ostia. The distance from this virtual ring to the ostia is subsequently measured and reported.

COMPLICATIONS

Despite the extensive amount of preprocedural planning, complications do arise from percutaneous aortic valve implantation (Table 4). Some complications may present acutely during the procedure with at times catastrophic consequences.

Aortic annular ruptures (Videos 1–3) with resultant hemopericardium and tamponade are quite impressive, but fortunately rare with less than 1% in all TAVR procedures [29]. Errors in measurements of the aortic valve annulus area and diameter with resultant valve sizing errors or failure to report significant LVOT calcification may result in such dreaded complications.

Coronary artery obstruction can rarely happen and is usually due to displaced native calcified leaflets and less likely from stent itself (Videos 4–6)

Paravalvular leak (PVL) (Video 7; Fig. 11) is related to valve malpositioning, eccentric severe valve calcification and undersizing or underexpansion. Balloon postdilatation is helpful in the case of underexpansion, and percutaneous plugging is another option to treat PVL. Newer devices with more flexible cuffs allowing more complete seal over the retained native valve will decrease PVL.

Valve malpositioning, embolization or migration (Fig. 12) incidence is slightly higher with self-expanding than balloon dilated valve. In the PARTNER trial, valve embolization was observed in 1% with 30 day mortality of 27% [17]. Causes of malpositioning include erroneous assessment of annulus size, improper or inadequate valve plane visualization, and inadequate balloon dilatation. Other predisposing factors include hypertrophied interventricular septum, severe annular calcification extending into the LVOT and anterior mitral leaflet, the presence of mitral valve prosthesis and insufficient rapid ventricular pacing. TAVR valve migration is rare and the data from reviewing the TVT Registry has shown a less than 1% rate of device migration in the CoreValve with the rate of device migration in the new Evolut R at about 0.2% [30].

Vascular access complications (Fig. 13; Videos 8–14) were more frequent with earlier generation of TAVR valves due to the larger sheath size requirement. However, despite the advances, vascular complications

TABLE 4
An Abbreviated List of Common Complications Following TAVR Placement

30-Day Clinical Outcomes	Edwards Lifesciences SAPIEN 3	Medtronic Evolut R
All-cause mortality	1.1	3.7
Any stroke	2.7	3.1
Transient ischemic attack	0.4	0.7
Myocardial infarction	0.3	0.2
Life-threatening or major bleeding	4.6	7.3
Vascular complication	6.1	5.6
New pacemaker or ICD	10.2	18.3
Aortic valve reintervention	0.1	0.3

Adapted from Thourani VH, Kodali S, Makkar RR, et al. Transcatheter aortic valve replacement versus surgical valve replacement in intermediate-risk patients: a propensity score analysis. Lancet 2016;387(10034):2222; and Sorajja P, Kodali S, Reardon MJ, et al. Outcomes for the commercial use of self-expanding prostheses in transcatheter aortic valve replacement: a report from the STS/ACC TVT registry. JACC Cardiovasc Interv 2017;10(20):2096.

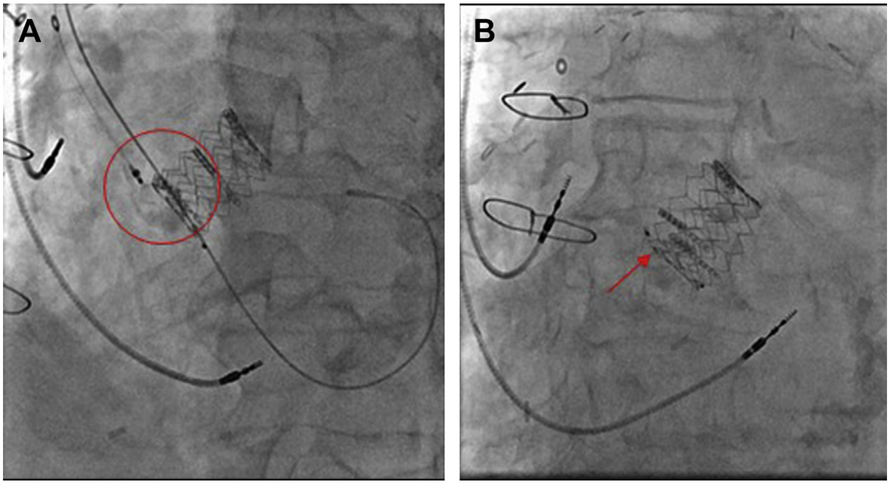

FIG. 11 Paravalvular leak (PVL). (**A**, **B**) This patient required percutaneous plugging with occlude device (*circle* and *arrow*).

continued to occur at about 5% with major vascular complications at 1.4% in the core valve registry [30]. Pseudoaneurysm at the entry site in transapical approach is a rare complication (see Videos 8–14). It can be detected with echocardiography, but computed tomographic angiography often provides a more precise information for further management.

The rate of acute strokes also have remained stable around 2.7% in both the Evolut R (procedural and in-hospital) and the SAPIEN 3 (30 days) [19,30].

Conduction abnormality is one of the most common complications following TAVR due to close proximity of the aortic valve and intraventricular conduction system in LVOT. It usually results from

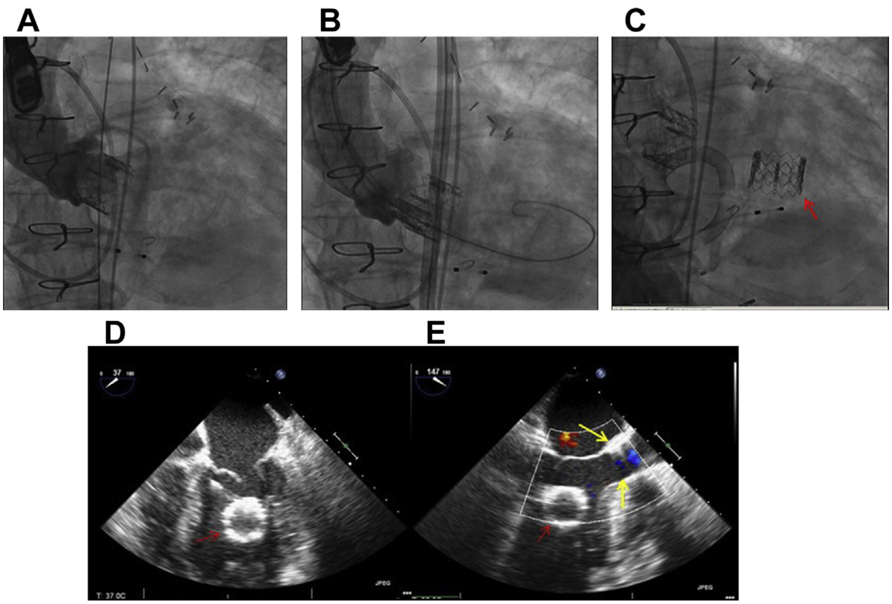

FIG. 12 Low valve deployment and migration. (**A**) The first valve was deployed low. (**B**) While attempting to deploy second valve the first valve is already displaced into the LVOT and (**C**) eventually into LV cavity (*arrow*). TEE shows the displaced valve in (**D**) LVOT and (**E**) subsequently in the LV cavity (*red arrow*). (**E**) The second deployed valve is well seated (*yellow arrows*).

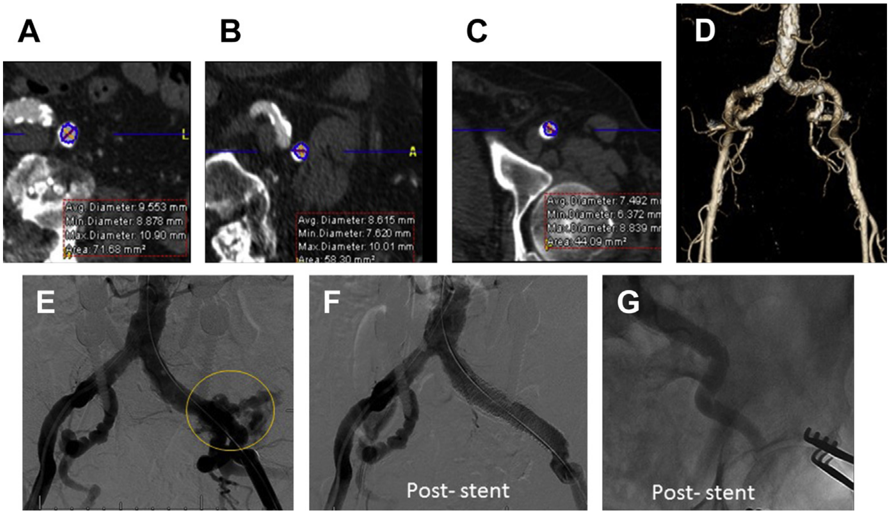

FIG. 13 Vascular injury. (**A–D**) An 88-year-old woman with extensive atherosclerotic calcification and tortuosity of iliofemoral arteries underwent left tranfemoral TAVR. Advancement of 24-Fr sheath was difficult but successful after several dilatations. A 26-mm valve was deployed successfully. (**E**) Postprocedure iliac angiogram showed extravasation of contrast from the left external iliac artery (*circle*). (**F**, **G**) Two stents were positioned in the external iliac and inflated to 14 atm with good results.

mechanical trauma of valve implantation or balloon angioplasty causing tissue edema, local inflammation, or pressure necrosis. It is seen more commonly with self-expanding valves due to deeper extension of the stent frame into the LVOT and self-expanding property, which maintains a steady radial force on annular and subendocardial tissue. Preprocedural predictors includes preexisting right bundle branch block, narrow LVOT, septal wall thickness, and calcification. Procedural predictors include low more ventricular implantation of the valve. Pacemaker rates in the Evolut R are around 17% in-procedure or in-hospital, but the rates for the SAPIEN 3 are slightly lower at 10.2% and 12.4% at 30 days and at 1 year, respectively [19,30].

Valve Thrombosis

A relatively common late complication that typically presents with elevated valve gradients compared with the intraprocedural gradients in an asymptomatic patient. This is usually first detected on follow-up transthoracic echocardiography with elevated Doppler gradient across the prosthetic valve. Transthoracic echocardiography, however, is limited in assessing the motion of the prosthetic valve cusps due to acoustic shadowing from the metallic stents surrounding the bioprosthesis. ECG-gated cardiovascular CT has a high sensitivity of detecting valve thrombosis given the high spatial resolution and minimal effects from the blooming artifact of the metallic stents. Valve thrombus is usually seen as leaflet thickening with hypoattenuated filling defects in the cusps without evidence of destruction or vegetations along with absence of clinical symptoms of endocarditis (Videos 15–17). In a series of patients undergoing ECG-gated cardiovascular CT following TAVR the hypoattenuating leaflet thickening occurred in about 1.4% at discharge and at about 10% at 6 months [31]. The 2017 ACC/AHA focused update of the 2014 guideline for management of patients with valvular heart disease touch specifically on this issue, and it may be reasonable for the patient to be on anticoagulation with a vitamin K antagonist for 3 months following TAVR with low bleeding risk [32].

Postprocedural imaging with ECG-gated cardiovascular CT may use the same protocols as the pre-TAVR imaging. However, if there are concerns for valve thrombosis, it may be reasonable to turn ECG pulsing off to increase spatial resolution throughout the cardiac cycle. When a paravalvular leak is considered, pulsing may be turned on to minimize radiation dose. Cardiac MRI may also be beneficial in patients with concern of paravalvular leak with the ability of phase contrast sequences allowing for flow measurements in the aorta.

SUMMARY

TAVR has become standard of care over the last 2 decades in management of patients with severe, symptomatic aortic valve stenosis. With the 2017 ACC/AHA focused update, it is now a class I recommendation in patients with prohibitive risk for SAVR, as well as in those with high surgical risk as an alternative to SAVR. It is now a class IIa recommendation in intermediate surgical risk patients with severe aortic valve stenosis [32]. Cardiovascular CT has played a crucial role in planning these TAVR procedures as well as predicting outcomes and diagnosing complications. This review highlights the importance of a step-by-step approach to obtaining accurate CT measurements for successful procedural outcomes and minimizing procedural and postprocedural complications. A strong cardiovascular CT program will be complementary and assist in building a strong structural interventional program.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found online at https://doi.org/10.1016/j.yacr.2019.04.001.

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