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# Role of Computed Tomography in Transcatheter Aortic Valve Replacement

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**ABSTRACT**
The rapid development of transcatheter aortic valve replacement (TAVR) and its widespread adoption has heavily relied on rapid innovations in interventional cardiology and cardiovascular imaging. With a furious pace of evolution of data in recent years, the field has moved dramatically forward to a point of widespread acceptance and routine performance in an outpatient setting or a non-urgent inpatient setting. From its earliest iteration, it was recognized that a "heart team," which comprised of cardiologists (valve specialists, imaging specialists and interventionalists) and cardiac surgeons was crucial for successful execution of a TAVR procedure. Additionally, it was also recognized that careful pre-procedural planning was also imperative in its success. This has led to the burgeoning field of multimodality structural and interventional imaging, which coincided with the maturation of modern imaging techniques such as 3D echocardiography, ECG gated multi-detector computed tomography (MDCT) and cardiac magnetic resonance imaging (CMR). Of these, MDCT has gained particular importance in the context of preprocedural planning in the setting of TAVR and its integration has been critical for its success. The current article is a state-of-the-art review of the role of MDCT in the context of TAVR. With the emergence of valve-in-valve TAVR, there will be evolution of newer details to be reported on a preprocedural MDCT; however these are beyond the scope of this article.

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**KEYWORDS** Multi-detector computed tomography; transcatheter aortic valve replacement

## Introduction

The rapid development of transcatheter aortic valve replacement (TAVR) and its widespread adoption has heavily relied on rapid innovations in interventional cardiology and cardiovascular imaging. With a furious pace of evolution of data in recent years, the field has moved dramatically forward to a point of widespread acceptance and routine performance in an outpatient setting or a non-urgent inpatient setting. From its earliest iteration, it was recognized that a "heart team," which comprised of cardiologists (valve specialists, imaging specialists and interventionalists) and cardiac surgeons was crucial for successful execution of a TAVR procedure. Additionally, it was also recognized that careful pre-procedural planning was also imperative in its success. This has led to the burgeoning field of multimodality structural and interventional imaging, which coincided with the maturation of modern imaging techniques such as 3D echocardiography, ECG gated multi-detector computed tomography (MDCT) and cardiac magnetic resonance imaging (CMR). Of these, MDCT has gained particular importance in the context of preprocedural planning in the setting of TAVR and its integration has been critical for its success. The current article is a state-of-the-art review of the role of MDCT in the context of TAVR. With the emergence of valve-in-valve TAVR, there will be evolution of newer details to be reported on a preprocedural MDCT; however these are beyond the scope of this article.

## Discussion

### Rational for preprocedural imaging

The first major multicenter trial for TAVR with a surgical comparison was the Placement of Aortic Transcatheter Valves (PARTNER I) trial, which studied an early generation balloon expandable transcatheter bioprosthetic valve.[1] At the time of the study, valve sizing was performed based on transthoracic echocardiography (TTE) assessment of the aortic annulus. In this trial, although TAVR compared favorably to SAVR, overall mortality was high with many of the adverse events driven by paravalvular aortic regurgitation and vascular access complications.[2] Paravalvular leak in particular was proportionally related to increased mortality.[3] It is notable then, that the parallel CoreValve US Pivotal trial, which evaluated a self-expanding nitinol TAVR valve, incorporated the routine use of MDCT to visualize the aortic annulus, thoracic vasculature, and iliofemoral vasculature. The rates of moderate or severe paravalvular regurgitation were only 6.1% compared to the 12.2% seen PARTNER I,[4] which may be attributed to the integrative use of MDCT for annular measurements. Due to the increased amount of supportive evidence, all modern TAVR trials now routinely incorporate annular sizing performed with 3D MDCT (or less frequently using 3D echocardiography or CMR). Reports from the intermediate risk cohort has seen lower rates of major vascular access complications of 7.9% vs 5.0% in SAVR.[5] More contemporary data

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with much lower rates of moderate to severe paravalvular regurgitation. Experience from these clinical trials has therefore informed the need for improved 3D imaging integration for structural heart disease.

## Emergence of computed tomography in TAVR

The evolution of TAVR has produced a standard imaging pathway that utilizes a multimodality approach to imaging (including MDCT), as highlighted in a recent consensus document published by the American College of Cardiology.[6] Many of the technological improvements in image acquisition and post processing that are now widely used for the planning of TAVR and other structural heart diseases were initially developed for coronary computed tomography angiography.

The application of these new MDCT technologies and techniques in the context of TAVR have given a new appreciation of the complex and dynamic nature of the aortoannular complex, the vascular atherosclerotic burden and course of the thoracoabdominal aorta and its iliofemoral branches.[7] For instance, integration of MDCT has improved the accuracy of prosthesis sizing with concomitant decreases the presence of any paravalvular aortic regurgitation from 75.3% to 55% and a decrease in mild or greater paravalvular regurgitation from 20.5% to 7.5%.[8–11] The accumulating body of evidence for the use of MDCT in the planning of TAVR is compelling; and in most large volume centers, MDCT has become the foundation of the standard imaging pathway for TAVR preprocedural planning.[12,13]

## Technical considerations

In the context of TAVR, MDCT systems with at least 64-detectors and a spatial resolution of 0.5 to 0.6 mm are recommended. Processing should be performed on a dedicated workstation that at minimum has the ability to manipulate double oblique planes of a 3D dataset. Ideally a modern workstation with a semi-automated workflow with dedicated TAVR analysis packages should be utilized. Semi-automated software packages for TAVR analysis have been shown to be reproducible and are essential to an efficient clinical workflow.[14–18] Premedication with beta-blocker or nitrates should be avoided in patients with severe aortic stenosis at the time of scanning, in order to avoid hemodynamic complications. Although scanning protocols vary by vendor, typical protocols involve two main components. The first is an ECG gated acquisition of the aortic annulus and aortic root. ECG-synchronized imaging reduces motion artifact and allows reconstruction at any acquired phase of the cardiac cycle. These images serve a primary goal of valve sizing, but also provide the detailed information on the relationship of the coronary arteries, leaflet morphology, calcification and identification of other challenging anatomical features. The second step is a full chest, abdomen, and pelvic acquisition of the arterial vasculature, which does not typically require ECG gating.

Although quick and robust, MDCT does expose patients to potentially nephrotoxic iodinated contrast agents. Because a standard bolus of 80–120 ml of low osmolar iodinated contrast is necessary, the benefits versus risk of iodinated contrast need to be carefully weighed, especially in elderly patients.[19] Advances in CT technology such as iterative reconstruction allow for low tube voltage (kVp) scanning to reduce radiation dose while maintaining image quality. An additional beneficial impact of lower kVp setting is to improve the enhancement of contrast with CT, thus allowing reductions in contrast volume. Some centers have taken advantage of this to use diluted mixtures of contrast to obtain excellent image quality for TAVR scans with only 20 mL of contrast.[20–23] If absolutely no iodinated contrast administration is tenable, a non-contrast MDCT scan allows for the assessment of overall vessel size, calcification, and tortuosity. Often times due to the presence of surrounding fat, the size of the outer lumen of the vessel can be estimated as well. While knowledge of stenosis in the area would not be available on a non-contrast MDCT scan, potentially problematic aneurysmal segments may be identified. Thus, this approach requires an alternative method to evaluate for actual luminal stenosis, occlusion, dissection, or other aortic pathology.

In patients with poor renal function, there is intense interest and a rapid growth in the use of fusion imaging. In many cases, a magnetic resonance angiogram is combined with a non-contrast CT scan.[24] Others have employed an approach where a femoral sheath is left in place after cardiac catheterization and used to perform a pelvic CT angiogram with the injection of contrast directly through the sheath into the pelvic arterial vasculature. Such an approach has been successful in evaluating the infrarenal abdominal aorta with very low doses (~15 ml) of contrast.[25]

Additional tools available with MDCT include unique post processing or rendering techniques that improve understanding of valve pathology. These types of visualizations are not only valuable for making an accurate diagnosis, but assist in quickly and effectively communicating unusual aspects of cardiac and valve pathology that may be relevant to the success of the case.

A description of the role of MDCT in TAVR, along with suggested measurements is shown in Table 1. A detailed description is outlined below.

## Annular and aortic root assessment

Accurate assessment of the aortic annulus in the context of TAVR is crucial but often challenging, as it is an elliptical shaped, virtual ring formed by the joining of basal attachments of the aortic valvular leaflets (Figure 1). Additionally, it is also a dynamic structure that undergoes conformational pulsatile changes throughout the cardiac cycle with an average relative difference between the maximum and minimum cross sectional areas of 18.2 ± 6.1%.[26–28] Thus the annulus is typically measured at peak systole to avoid undersizing of the TAVR prosthesis[26,29] as valve undersizing may lead to paravalvular leak, valve migration or valve embolization.[26,30–35] The nuances of recommended valve sizing varies by vendor and has historically been performed using multiple different measurement techniques including (1) minimum and maximum cross sectional dimensions; (2) circumference; and (3) direct planimetry of the annular area.[13] While a nominal amount of oversizing of the valve (which is variable and depends upon operator preference and the type of valve) has been recommended to account for distortion and compliance of the annular tissue caused by valve deployment,[13] severe oversizing

Table 1. Typical computed tomography specific measurements for transcatheter aortic valve replacement (adapted from Ref. 6).

| Region of interest | Specific measurements | Measurement technique |
|---|---|---|
| Aortic valve morphology and function | Aortic valve | • If cine images obtained, evaluation of valve opening<br>• Planimetry of aortic valve area in rare cases<br>• Calcium score with Agatston technique or a volumetric technique to quantify calcification of aortic valve |
| LV geometry and other cardiac findings | Left ventricular outflow tract | • Perimeter<br>• Area<br>• Qualitative assessment of calcification |
| Annular sizing | Aortic annulus | • Defined as double oblique plane at insertion point of all three coronary cusps<br>• Major/minor diameter<br>• Perimeter<br>• Area |
| Aortic root measurements | Sinus of Valsalva | • Height from annulus to superior aspect of each coronary cusp<br>• Diameter of each coronary cusp to the opposite commissure<br>• Circumference around largest dimension<br>• Area of the largest dimension |
| | Coronary arteries | • Height from annulus to inferior margin of left main coronary artery and the inferior margin of the right coronary artery |
| | Aortic root angulation | • Angle of root to left ventricle<br>• Three-cusp angulation to predict best fluoroscopy angle |
| *Vascular assessment* | | |
| Vascular access | | |
| | Aorta | Major/minor diameters of the following:<br>• Aorta at sinotubular junction<br>• Ascending aorta in widest dimension<br>• Ascending aorta prior to brachiocephalic artery<br>• Midaortic arch<br>• Descending aorta at isthmus<br>• Descending aorta at level of pulmonary artery<br>• Descending aorta at level of diaphragm<br>• Abdominal aorta at level of renal arteries<br>• Abdominal aorta at the iliac bifurcation |
| | Primary peripheral vasculature | Major/minor dimensions, tortuosity, calcification of the following:<br>• Carotid arteries<br>• Subclavian arteries<br>• Bracheocephalic artery<br>• Vertebral arteries<br>• Bilateral subclavian arteries<br>• Great vessels<br>• Iliac arteries<br>• Femoral arteries |
| | Ancillary vasculature | Stenosis of the following:<br>• Celiac artery<br>• Superior mesenteric artery<br>• Both renal arteries |
| | Relationship of femoral bifurcation and femoral head | • Distance from inferior margin of femoral head to femoral bifurcation |

should also be avoided as it increases the risk of complications such as heart block[34,35] and annular rupture.[13,36,37]

Because 3D MDCT datasets are easily manipulated using dedicated workstations to visualize cardiac structures in any plane, it becomes an ideal tool for imaging of the aortic annulus as seen in Figure 1. As the aortic annulus is not a physical structure, but rather the virtual plane as prescribed by the insertion points of each of the three coronary cusps, measurement reproducibility can be a challenge for an inexperienced operator. When performed by experienced operators, aortic annulus measurements have an excellent correlation ($r$ values between 0.94 and 0.96).[38] Using any single methodology for annulus measurement for valve sizing (dimensions, perimeter, area) will yield a difference in prosthesis sizing between 6–11% between observers.[38] If multiple parameters are used for internal validation of prosthesis selection, differences in TAVR valve size selection occur in only 3–4% of patients.[38] This small but clinically significant variability highlights the critical importance of experience, training and continual quality assessment to achieve accurate and reproducible valve sizing.

Beyond simply sizing of the prosthesis, MDCT evaluation of the aortic annulus can also assist in patient selection in patients with low flow, low gradient severe aortic stenosis. Particularly if there are challenging echocardiographic windows, MDCT cine imaging of the stenotic valve with direct planimetry of the anatomic aortic valve area can be helpful in establishing the diagnosis and whether the patient may benefit from treatment with TAVR. Other uses of CT in this patient population include using the improved visualization of the aortic annulus as part of the continuity equation for calculation of the calculated aortic valve area.[39] Due to the possibility of systematically large aortic annulus seen on CT compared to echocardiography, it has been suggested that a calculated aortic valve area by MDCT of $<1.2$ cm$^2$ is comparable to the calculated aortic valve area by echocardiography of $<1.0$ cm$^2$.[40]

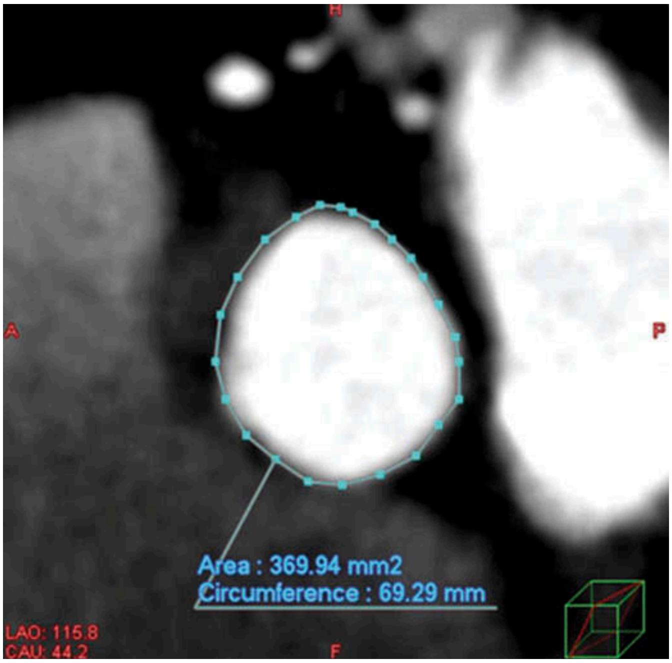


**Figure 1.** Reconstructed multiplanar reformatted contrast-enhanced computed tomographic image of the aortic annulus demonstrating diameter, area and circumference measurements.

Occasionally, there are reasons why MDCT must be avoided in a patient with TAVR. This is most commonly seen in patients with acute kidney injury or significant chronic kidney disease not yet requiring dialysis where iodinated contrast should be avoided if possible. However, there are controversies with regards to rates and extent of contrast-induced nephropathy, and more prospective data is needed before drawing definitive conclusions. Occasionally a patient will have such severe anaphylaxis to iodinated contrast that even with pre-treatment its use is best avoided. Finally, as the experience with transcatheter therapies increases, lower risk[5] and younger patients previously excluded from clinical trials such as those with bicuspid valves[41] and complex congenital heart disease are now undergoing TAVR. This means that younger patients will begin undergoing serial evaluations with MDCT and exposure to fluoroscopy at younger ages. While the effects of radiation are negligible for high-risk elderly patients with severe aortic stenosis, cumulative radiation exposure will be an important consideration going forward.[42] These patients will create an expanding role for alternative imaging techniques such as CMR,[43] leveraging recent advances in 3D transesophageal echocardiography (TEE), and driving fusion imaging. As this happens, care must be taken to ensure that a full understanding of the implications of using alternative imaging modalities for TAVR planning. A primary example of this is that direct planimetry of the aortic annulus on 3D TEE compared to MDCT shows a systemic underestimation of the echocardiographic-derived annular sizes.[44] This has important clinical implications with a retrospective evaluation suggesting that when compared to MDCT measurements, echocardiographic-sized TAVR valves may be discrepant in up to 50% of patients.[41] Given the nuances of understanding differences between modalities, the importance of meticulous attention to detail in valve sizing, and knowing the other aspects of periprocedural planning, alternative imaging should only be performed at an imaging center of excellence with structural heart imagers that are facile in multiple imaging modalities and have specific expertise in the planning of structural heart disease interventions.

## Peripheral and central vascular access

Because of the relatively large diameter of the delivery sheaths appropriate sizing and planning of vascular access is critical for TAVR. It is important to evaluate the entire thoracoabdominal aorta, the major thoracic arterial vasculature, carotids, as well as the iliofemoral vasculature. Imaging of the proximal ascending aorta focuses on valve morphology, leaflet length and the height of the coronary ostia (Figure 2). These measurements are helpful for predicting rare complications such as long aortic valve leaflets that may predispose a patient to coronary artery occlusion during valve deployment. More distally, the extent of atherosclerotic plaque in the ascending aorta and aortic arch have been associated with worse outcomes following cardiac surgery and increased complications following TAVR.[45,46]

The full assessment of the central aortic vasculature includes evaluating for the presence of aneurysm, ectasia, calcification, mobile plaque, mural thrombus, dissection, intramural hematoma and penetrating ulcers (Figure 3). In the pelvis, the main vessels evaluated include the iliofemoral vasculature (common iliac arteries, external iliac arteries, and common femoral arteries). Each of these vessels is carefully evaluated for minimal luminal diameter, tortuosity, degree of calcification, and morphology of calcification.[47]

Evaluation of the remainder of the central and peripheral aortic vasculature plays a primary role in selecting the route of access. The standard method is femoral artery access, but other common routes include the subclavian and apical approaches. In challenging cases where all of the standard routes of access are not ideal, numerous exotic routes have been attempted including a transcarotid approach[48,49] and a direct aortic approach.[50] For very high-risk patients without other options, even a transcaval to aortic approach has been performed with increasing frequency.[51,52]

MDCT allows for the careful measurement beyond just the aortic annulus, including the Sinuses of Valsalva, the coronary ostia distance from the annulus, the size of the aorta at the sinotubular junction, 40 mm above the annulus and extent and position of aortic calcifications.[53] MDCT is also excellent for evaluating the remainder of the thoracoabdominal vasculature for stenosis, tortuosity, and calcifications. Other risks that can be assessed with MDCT include aortic or vascular dissections, intramural hematomas, aortic ulcerations, as well as extensive atheroma.

## Direct interventional planning

In the preprocedure planning of TAVR, using MDCT helps to predict what the optimal delivery angle will be on fluoroscopy, understand potential complications, allows decision making

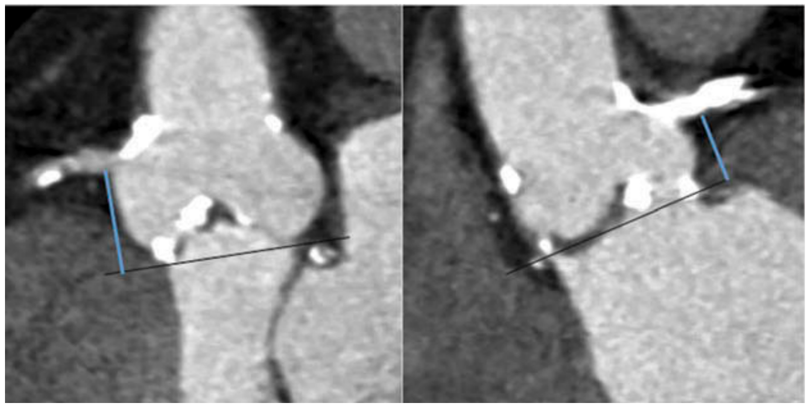

**Figure 2.** MDCT images of the aortic root demonstrating distance from the annulus to the coronary arteries.

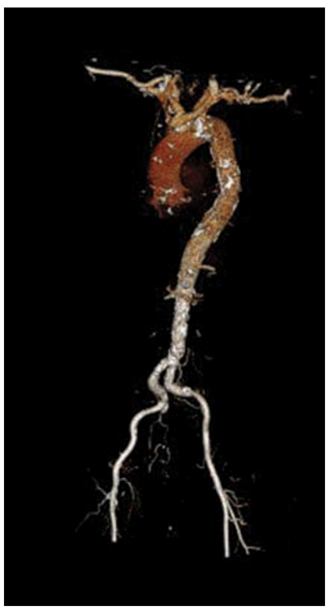

**Figure 3.** Reconstructed volume rendered contrast-enhanced computed tomographic image of the entire aortic tree demonstrating diffuse atherosclerosis.

on concomitant procedures such as PCI, as well as arriving at a consensus prior to the procedure on what bail-out surgical procedures if any will be offered or needed.

### *Prediction of delivery angles*

Knowledge of the correct delivery angle is of critical importance for TAVR deployment. Precise coaxial alignment of the stent-valve along the centerline of the aortic valve and aortic root is important during positioning to avoid procedural complications.[54] With the advent of routine MDCT use the delivery angles of fluoroscopy can be routinely predicted ahead of time.[55,56] Double-oblique multiplanar MDCT reconstruction allows preprocedural prediction of the aortic root angle, reducing the number of root shots required at the time of the procedure, thus saving time and contrast by potentially decreasing the number of aortograms required during the procedure. Newer scanning systems that allow for C-arm CT at the time of the procedure can also be used with excellent correlation to MDCT.[57]

### *Coronary artery analysis*

Coronary CTA (CCTA) is a rapid and accurate technique for the evaluation of coronary artery stenosis. Due to the similarities in image acquisition, most of the gated MDCT images used for pre-TAVR planning have contrast that is timed in a fashion that could allow for coronary artery analysis. However, a few issues challenge evaluation of coronary arteries in patients who are undergoing a standard pre-TAVR MDCT. First is that the current temporal resolution of most MDCT scanners requires beta blockade to a heart rate slow enough that coronary motion can be minimized on the images (typically <60 bpm). Many of the patients undergoing TAVR are acutely ill and will not tolerate this aggressive beta blockade regiment. And certainly the sublingual nitrates typically used to improve coronary artery visualization are ill advised in most patients with severe aortic stenosis. Thus, even using most modern MDCT scanners the coronary artery analysis in a pre-TAVR MDCT scan will show significant motion artifact and not be as dilated as expected. Second, CCTA is highly susceptible to the partial volume calcium blooming artifacts. Many of the patients undergoing evaluation for TAVR are elderly with pre-existing complex and highly calcified coronary artery disease; and while structures such as bypass grafts are typically well seen on CCTA, the graft lumen may be obscured if excessive staples are used and the distal diseased vessels can be more challenging to evaluate. Finally, coronary artery stents are often present and suffer from similar partial volume effects to calcified vessels making them also difficult to evaluate. Typically only stents that are larger than 3 mm have the potential for assessment.[58] Thus, complete coronary assessment with CCTA is typically limited in the current elderly population undergoing evaluation for potential TAVR. However, when the coronary arteries can be evaluated, CCTA evaluation (especially of the proximal coronary segments) can provide important adjunctive information for planning and may allow for avoidance of routine coronary angiography prior to TAVR. Additionally, detection of proximal coronary stenosis may provide incremental prognostic information.

### *Preoperative planning for cardiac reoperation*

MDCT is also of use in planning for possible surgical approaches should complications occur during device delivery.[59,60] The primary use in this regard is the evaluation of the relationship of cardiovascular structures to the sternum. Structures of particular importance include the RV free wall, ascending aorta, brachiocephalic vessels, and the pericardium. The sternum itself should be evaluated for deformities and adhesions from prior surgeries. It is of particular importance to make note of the relationship of coronary bypass grafts to the sternum, particularly any internal mammary bypass grafts.[61] Assessment of burden of atherosclerotic calcification of the ascending aorta is important as a high degree of calcification may increase the risk of stroke in the cannulation of the aorta for cardiopulmonary bypass. In cases with a "porcelain" aorta, alternative vascular access sites should be considered for cannulation.[46]

## Non-cardiac imaging prior to TAVR

Because of advanced age and/or other comorbidities, there is a higher than usual prevalence of noncardiac pathology like cancers, abdominal/pulmonary pathology, which should be carefully evaluated using MDCT[62–64] (Figure 4).

Figure 4. MDCT of the chest demonstrating a large noncalcified mass likely representing a malignant lung neoplasm (arrow).

## Periprocedural and postprocedural evaluation

Utilizing the standard imaging pathway with MDCT, imaging during the procedure should be confirmatory to the preprocedure planning. C-arm CT is becoming more widely available and may find a future role in particularly urgent periprocedure structural heart disease procedures.

MDCT has continued to play a role in the postprocedural evaluation of TAVR where it is used to evaluate prosthesis implantation height, valve geometry, and to better visualize complications such as chamber rupture.[65] There has long been an interest in the effect of TAVR on the geometry of the aortoannular complex. As the round valve is placed into the oval annulus, typically the annulus becomes more round. Non-circular valve deployment can be quantified by eccentricity >10%.[66] Highly eccentric valves are theorized to distort the prosthetic valve geometry after expansion and has been hypothesized to be a risk factor for valve degeneration.[67] In balloon expandable valves up to 2.5 years, the incidence of highly eccentric valves is rare and suggestive that valve geometry is reasonably stable after implantation.[68] The quantification of paravalvular leak by echocardiography is not fully standardized, and postprocedural assessment of residual aortic insufficiency by quantitative MRI might have a potential role in TAVR patients.[69]

The issue of valve durability is coming under increasing scrutiny as TAVR becomes more widespread, particularly as it expands to younger and lower risk cohorts.[5] Case reports of early valve failure show that the primary reported causes are endocarditis, structural valve failure and valve thrombosis.[70] This is discordant from the 5-year outcomes from the PARTNER I trial where no structural valve degeneration was seen in either the TAVR or SAVR groups.[71] Despite this, individual sites have shown signs of moderate prosthetic valve failure in 3.4% of patients who received a balloon expandable TAVR valve.[72] Similar results were seen with the 5-year experience with a self-expanding prosthesis with late prosthesis failure occurring in 1.4% of cases and 2.8% showing late mild stenosis. There is evidence that worsening dyspnea and an increasing TAVR valve gradient has been associated with valve thrombosis in 0.61% of patients, occurring mostly within 2 years of implantation. Treatment with anticoagulation is an effective treatment, even when the thrombosis is not clearly seen on echocardiography.[73] Using MDCT cine images, valve motion can be visualized more readily. The use of this technique was reported in a study by Makkar and colleagues which demonstrated hypoattenuated leaflet thickening (HALT), suggesting an increased concern for possible subclinical leaflet thrombosis (Figure 5) in a variety of transcatheter and surgically placed bioprosthetic aortic valves.[74] These reports of early valve degeneration are concerning and remains an area of active research.

## Conclusions and future directions

The growth of TAVR has pushed current imaging technology forward. The integration of MDCT into the standard

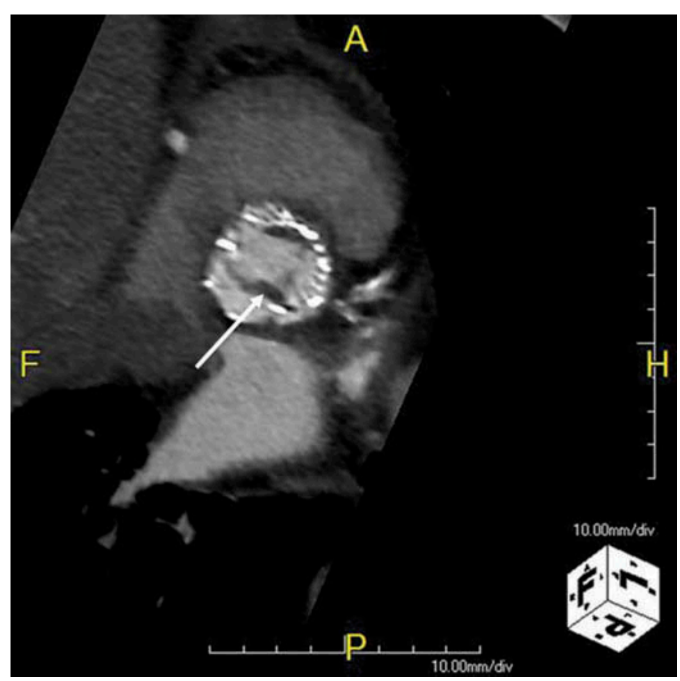


Figure 5. MDCT in a patient who is status post TAVR demonstrating hypoattenuated leaflet thickening (HALT) concerning for thrombus formation (arrow).

evaluation and preprocedure planning of TAVR has given numerous insights into the nuances of the aortoannular complex and it has become clear that accurate annular sizing is critical for prothetic valve selection and minimizing complications during procedures. These insights have solidified the role of MDCT for TAVR. The integration of imaging technologies with TAVR has also set the stage for integrative imaging for the rapidly growing world of structural heart disease interventions. MDCT continues to play a greater role in more complex interventions such as transcatheter mitral valve replacement.[75] As the type of interventions expand in indication and complexity, the experience with TAVR has shown us the importance of meticulous planning and periprocedural guidance of transcatheter therapies. However, given the complexity of structural imaging, it is recommended that the most complex of procedure be performed in structural imaging centers of excellence where dedicated experts are able to use an integrative imaging approach for improved outcomes.

## Disclosure statement

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