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# MULTIMODALITY NONINVASIVE IMAGING FOR TRANSCATHETER AORTIC VALVE IMPLANTATION: A PRIMER

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**Abstract**

Transcatheter aortic valve implantation (TAVI) has recently emerged as a treatment option for patients with severe aortic valve stenosis (AS). For patients who are deemed inoperable for surgical aortic valve replacement (SAVR), TAVI has a significant mortality benefit compared to medical therapy. This review discusses established and emerging roles for multimodality imaging and focuses on the application of these technologies for patient selection, intraprocedural guidance, and the detection and quantification of acute and chronic complications of this novel procedure.

## Background

Currently there are two different valve systems that have been approved for TAVI (Table 1). The Edwards SAPIEN Transcatheter Heart Valve System™ was approved in Europe in 2007, and its use has been reported widely in multiple registries including the Source registry.[1] It was also studied in two recent landmark randomized controlled trials. Both trials reported a significant mortality benefit in patients with extreme risk for SAVR[2] and noninferiority to SAVR in patients who had a high preoperative risk assessment.[3] The Edwards SAPIEN valve is a balloon-expandable valve that is cylindrical in shape and is constructed from leaflets made of bovine pericardium sewn within a stainless steel stent. The valve was designed to be implanted with the prosthesis positioned 2 to 4 mm below the annulus in the left ventricular outflow tract (LVOT). The current version comes in two sizes: the 23-mm valve, which is designed for patients with an aortic annulus of 18 to 21 mm in diameter, and a 26-mm valve designed for patients with an annulus from 22 to 25 mm diameter. The Edwards SAPIEN valve was recently approved by the US Food and Drug Administration for use within the United States.

The other major percutanous aortic valve system is the Medtronic CoreValve ReValving System®. This system has also been in clinical use in Europe and Canada for several years, but its current use within the United States is limited to an ongoing clinical trial. This valve is an hourglass-shaped device that is considerably longer than the Edwards SAPIEN counterpart. The Medtronic CoreValve is designed of porcine pericardial tissue mounted within an asymmetric self-expanding nitinol stent frame (Figure 1). The lower edge of the device is designed to be implanted proximal to the aortic annulus, within the LVOT. The leaflet coaptation is considerably supra-annular, which is evident on the post-implant echocardiogram (Figure 2). The current commercially available CoreValve also comes in two sizes: a 26-mm valve designed for patients with an aortic annulus of 20 to 23 mm diameter, and the larger 29-mm valve designed for patients with annular diameters of 24 to 27 mm. A larger valve (31 mm) is under evaluation in a US registry and is approved for clinical use in Europe.

| Table | Aortic Annulus Diameter | Appropriate Valve Size* |
|---|---|---|
| Edwards SAPIEN Valve | 18-21 mm | 23 mm |
| | 22-25 mm | 26 mm |
| | | |
| Medtronic CoreValve | 20-23 mm | 26 mm |
| | 24-27 mm | 29 mm |
| | 26-29 mm | 31 mm |

**Table 1.** Comparison of commercially available transcatheter heart valves. **Valve sizing is determined by the diameter of the most proximal portion of the valve stent. The larger CoreValve sizing reflects the more flared design of the proximal portion of the valve.*

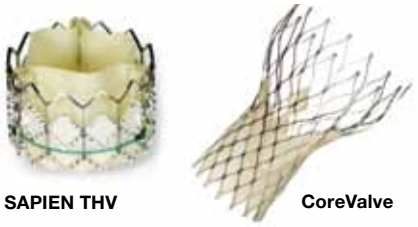



**Figure 1.** The two most commonly implanted transcatheter valves are the Edward SAPIEN valve and the CoreValve.

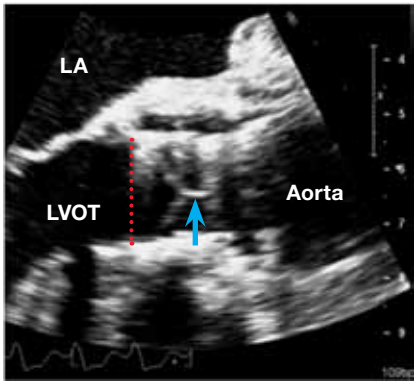



**Figure 2.** TEE depicting a deployed CoreValve. Note that the prosthetic leaflet coaptation point (blue arrrow) is considerably distal to the aortic annulus (red line).

Selection of candidates for TAVI is complex and involves a multidisciplinary team approach; the process often employs a multimodality imaging strategy to fully delineate the complex anatomy of the aortic valve, aortic root, the entire thoracic aorta, and the peripheral arterial vasculature. In general, the severity of AS has been defined using echocardiography (echo) criteria. Most studies to date have defined severe AS as a mean transaortic valve gradient of at least 40 mmHg or a peak velocity of at least 4 m/second *and* a calculated valve area of less than or equal to 0.8 $cm^2$ (less than or equal to 0.5 $cm^2/m^2$). As such, a transthoracic echo with Doppler evaluation is the primary screening method to identify patients with severe AS. Echo is also used to assess aortic annulus size and to screen for the common anatomic or physiologic exclusions for TAVI.

## Patient Selection

The appropriate patient for a TAVI procedure has senile degenerative AS of a trileaflet valve. Currently, TAVI is not indicated to treat aortic regurgitation or bicuspid valve stenosis. Although current AHA and ACC Guidelines define severe aortic stenosis as a valve area of less than 1.0 $cm^2$, the inclusion criterion for both the recent Edwards SAPIEN valve as well as the ongoing Medtronic CoreValve US Pivotal Trial both require a valve area of 0.8 $cm^2$ or less.

### *Echocardiography*

In addition to establishing the severity of AS, a screening transthoracic echocardiogram is important to exclude common contraindications to TAVI, which include severe aortic regurgitation, severe mitral valve regurgitation, and significant hypertrophy of the proximal septum. Significant septal hypertrophy is a concern with the Edwards SAPIEN valve in particular as it has been associated with post-implant device migration. Another important role for the initial transthoracic echocardiogram is to determine the diameter of the aortic annulus to facilitate appropriate prosthetic valve sizing.

In general, the annulus is measured at the point of leaflet insertion into the LVOT tissue. It is widely acknowledged that this is not a true annulus, like the mitral valve annulus, but rather a reasonable anatomic reference. The method of measurement is made using a parasternal long-axis zoomed view of the LVOT (Figure 3). While the LVOT diameter can be used for determining LVOT stroke volume (via application of a continuity equation to determine aortic valve area), the annular diameter must also be reported to facilitate appropriate device sizing. In a patient with mild to moderate calcification, this measure is fairly reproducible and should be taken from the point of aortic cusp implantation into the tissues contiguous with the LVOT. On two-dimensional (2D) echocardiogram, the standard is to follow trailing edge to leading edge, meaning that the measurement starts at the anterior tissue-blood interface and continues down to the posterior blood-tissue interface. However, when there is severe valve calcification with ballooning artifact, one approach is to start at the anterior and posterior measurements adjusted roughly 1 mm into the calcification. This measurement methodology can be difficult when there is significant calcification and likely leads to some of the variability in measurements between transthoracic echo and CT or MRI discussed below. The other significant discrepancy between these multimodality measures is the fact that 2D echocardiogram is measured on a single plane that may not bisect the aortic annulus at its largest point, particularly if the aortic annulus is elliptical (Figure 4). For this reason, CT angiography is often a preferred method to more fully define the long-axis and short-axis diameter (and circumferential area) of the aortic annulus.

### *CT Angiography*

Contrast computed tomography (CT) is a noninvasive technique that allows an accurate three-dimensional (3D) assessment of cardiac and vascular structures (Figure 5). In this regard it is well suited for evaluating potential candidates for TAVI, where adequate vascular access (Figure 6) and proper sizing of the valve prosthesis to the aortic annulus are critical issues.

Due to the relatively large diameter of the delivery sheaths (>18-20 French, 6-7 mm), the vascular diameters of the femoral and iliac arteries must be measured to determine whether the sheath and catheters can be safely advanced to the aortic root (Figure 7). CT allows assessment of not only the lumen diameter but also the arterial wall with regard to plaque composition and severity of calcification. Small luminal diameter and/or stenosis in addition to extensive and circumferential calcification increase the risk of complications such as arterial dissection or perforation. The 3D-rendered images display vessel tortuosity, information that assists the operator in safely advancing the device. In patients with either extensive lower-extremity peripheral vascular or aortic atherosclerotic disease (Figure 8), CT can measure the diameter of both subclavian arteries to determine whether they are suitable for deploying the device.

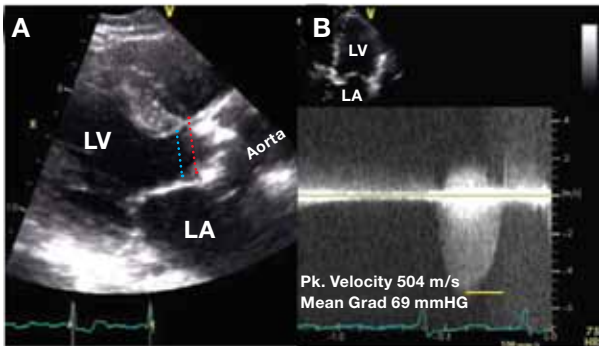
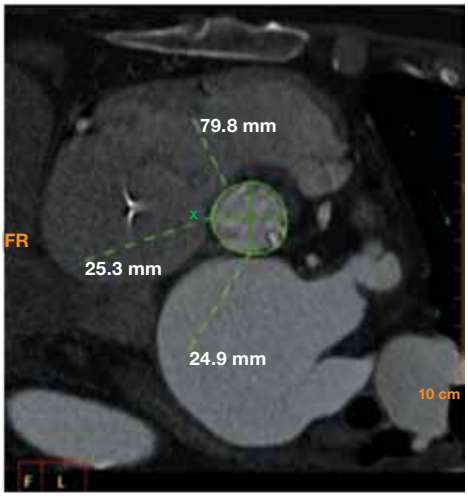



**Figure 3.** Transthoracic echo is used to assess AS severity and aortic annular diameter. (A) LVOT diameter (blue line) is usually used to derive LV stroke volume whereas aortic annular diameter (red line) is used for to determine appropriate prosthetic valve size. (B) Continuous wave Doppler recording is used to measure peak velocity and mean transvalvular gradient across the aortic valve.




Annulus

**Figure 4.** Aortic annulus measurement by CTA. The annulus is defined at the tranverse plane immediately below the lowest insertion point of the aortic leaflets as assessed by double oblique transverse images of the aortic root at the level of the basal ring. Measurements are taken from the systolic phase of the cardiac cycle when the valve is maximally opened. The perimeter of the basal annulus is traced manually. The measurements are performed in two planes because the annulus is usually elliptical in shape. First the major diameter through the center of the annulus is measured. The minor diameter is measured by tracing perpendicularly to the major diameter and through the center of the annulus. Note in this case, that the basal ring is fairly circular.

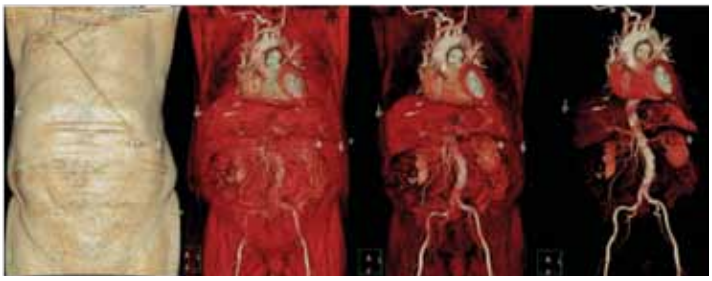



**Figure 5.** Three-dimensional (3D) volume-rendered image of aortic-iliofemoral vasculature by adjusting the CT attenuation threshold of the entire dataset (left to right) and using the bone-removal tool. The far right is a 3D volume-rendered image of the aortic-iliofemoral vasculature with bone removed. These images display the presence of significant arterial stenosis, areas of minimal luminal diameter, the presence and extent of arterial calcification and degree of vessel tortuosity. Presence of extensive calcified plaque, small arterial size, and significant tortuosity represent contraindication for transfemoral approach for TAVR.

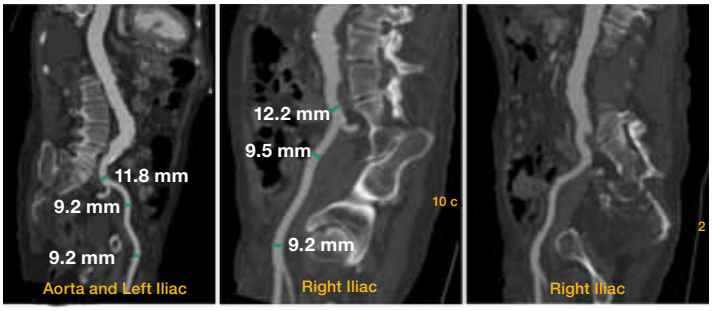



**Figure 7.** Curved multiplanar CT reformation and reconstruction using a centerline approach of the peripheral iliofemoral arteries and the entire aorta. Centerline image processing of the distal aorta and iliofemoral arteries allows measurement of the maximum and minimum arterial diameters at variouis levels as well as assessment of vascular dimensions, arterial calcification, and tortuosity of the vessels from the site of femoral puncture up to the aortic annulus. This figure shows an example of a 93-year-old male patient who was accepted for a transfemoral TAVI approach since he had adequate arterial sizes, paucity of calcification, and minimal vessel tortuosity.

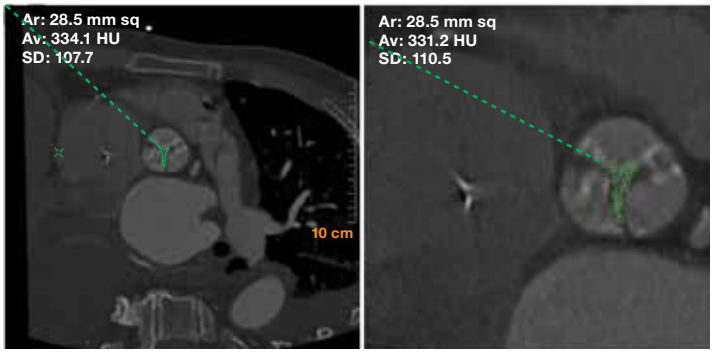



**Figure 9.** Aortic valve area (AVA) by CTA. Computed tomography angiographic double-oblique transverse images of the aortic valve at the level of the cusp tips during systole when the valve is maximally opened (typically 30%-40% of RR-interval). The smallest aortic valve area is identified by scrolling up and down through the dataset. The AVA is then measured by planimetry. In this patient, planimetry reveals critical aortic stenosis with only a slit-like opening. The extent of leaflet calcification can also be quantified on either the contrast (above) or non-contrast CT study.

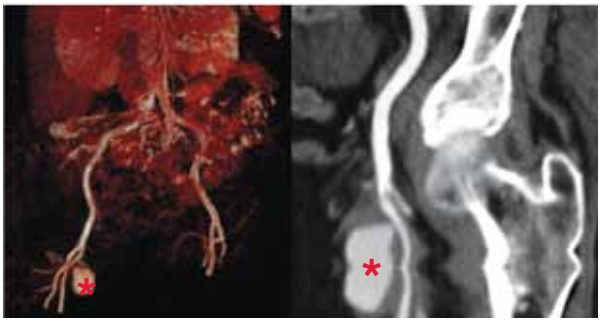


**Figure 6.** Three-dimensional (3D) volume-rendered CTA image (left) and curved multiplanar reformation/reconstruction (right) displaying the right iliofemoral arteries of an 88-year-old female patient transferred from an outside institution for TAVR after an invasive coronary angiogram. This figure shows an example of an large pseudoaneurysm (*) of the right femoral artery. The patient underwent an ultrasound-guided direct thrombin injection into the pseudoaneurysm with a good result and she subsequently had a successful TAVI through the left femoral artery.

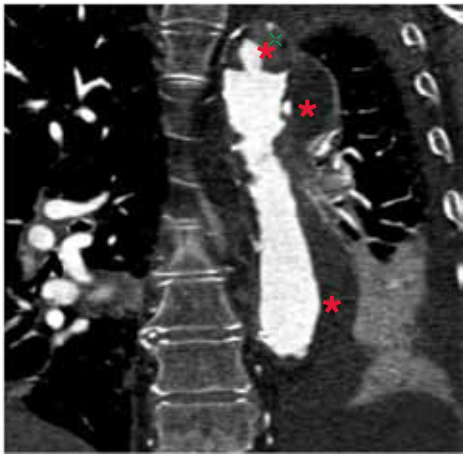


**Figure 8.** Coronal oblique CT projection of distal aortic arch and aneurysmal descending thoracic aorta in an 86-year-old female. The presence of extensive and severe atherothrombotic plaque burden along the aorta (*) is a contraindication for the transfemoral approach.

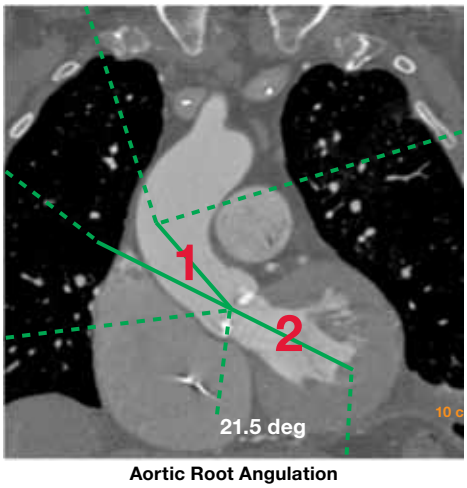



**Figure 10.** CTA of left ventricular outflow track (LVOT) aortic root angulation (ARA). Measurement of LVOT-ARA is performed using a coronal oblique projection and is defined as the angle between the axis of the first portion of the ascending aorta[1] corresponding to the upper part of the bioprosthesis, and the LVOT axis[2] corresponding the distal portion or landing zone of the prosthesis. This measurement is critical for determining whether the prosthesis will properly sit within the aorta. Patients with an LVOT-ARA >90 degrees are not candidates for TAVI.

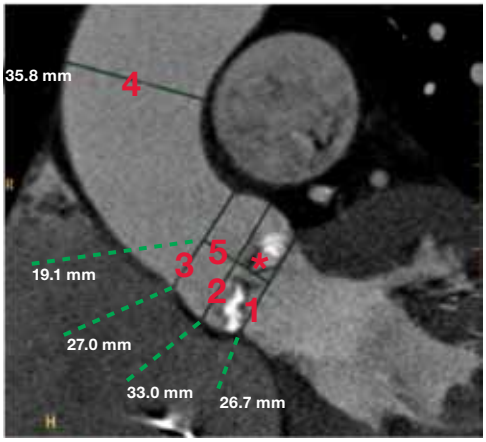
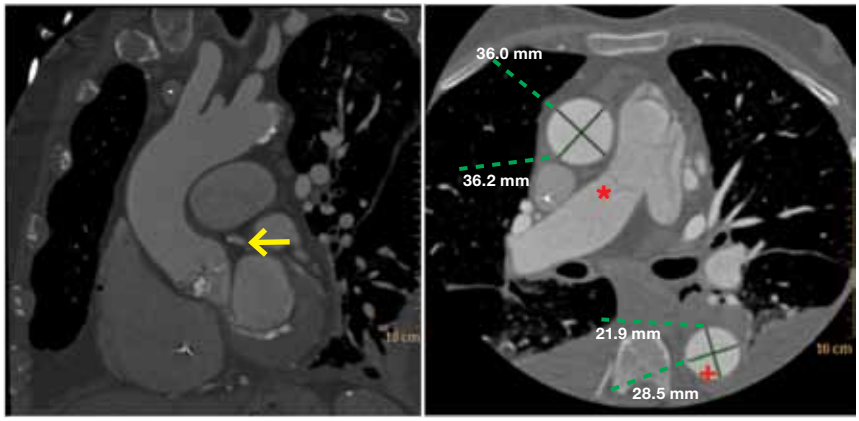



**Figure 11.** Coronal oblique views of aortic root and thoracic aorta show a severely calcified aortic valve*. Standard diameter measurements in the aortic root are made in systole at the level of the annulus[1], sinus of Valsalva[2], and sinotubular junction (STJ)[3]. Additional aortic root measurements include the maximum ascending thoracic aorta diameter[4] and the sinus Valsalva height defined as the distance between the annulus plane and the STJ[5].




Ascending aorta and proximal aortic arch | Aortic measurements

**Figure 12.** Assessment of the aortic arch and great vessels by CTA.
(A) Assessment of ascending thoracic aorta, proximal aortic arch, and great vessel origins using a coronal oblique projection. Note the marked thickening and calcification of the aortic valves and relative absence of significant aortic atherosclerotic plaque. The distance between the aortic annulus and the left main coronary artery (arrow) can be accurately measured by CT so as to ensure that the prosthesis does not impede coronary blood flow once inserted. The great vessels arise normally off the aortic arch. (B) Transverse images of the aorta at the level of the ascending* and descending+ thoracic aorta with measurement of their respective major and minor diameters. Note the absence of significant aortic atherosclerotic plaque.

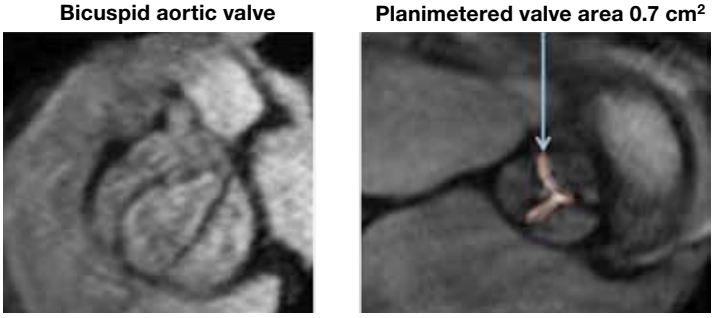



**Figure 13.** CMR for the identification of aortic valve morphology and valve area.

CT provides a detailed evaluation of the aortic valve, the annulus, and its relationship to the coronary arteries. In this regard, AS severity can be evaluated by planimetry of the aortic valve orifice during systole (Figure 9). Previous studies have shown a good correlation between anatomic assessments of AS by CT as compared to functional assessments by echocardiography.[4] The extent and severity of aortic valve leaflet calcification can be quantified from both contrast and noncontrast images. This is important since recent studies suggest a higher rate of post-procedure balloon dilatation is required in patients with heavily calcified valves.[5] Since the aortic annulus is generally oval in shape rather than circular, CT can also provide accurate measurement of the major and minor axes of the annulus, and its perimeter can be measured by planimetry (Figure 4). These measurements are critical for choosing the proper size prosthesis.[6] An oversized prosthesis can result in damage to the annulus with subsequent heart block or potentially coronary artery occlusion. An undersized prosthesis can lead to significant aortic insufficiency as well as device migration.

The ascending thoracic aorta and its relation to the LVOT (i.e., root angulation) can be assessed by contrast CT (Figure 10). Root orientation is critical for precise positioning of the device along the centerline of the aorta and perpendicular to the valve plane. In addition, measurement of the aortic root, sinotubular junction, and sinus of Valsalva height are critical for proper positioning of the device and ensuring there is no infringement on the coronary ostia (Figure 11). As is routine for CT, the thoracic aorta can be assessed for aneurysmal dilatation, and the aortic arch and the great vessels can be visualized (Figure 12). In this regard, CT is a critical imaging tool when choosing the proper patient for a TAVI procedure, selecting the safest device delivery route, and properly sizing the device to the individual patient.

### *Cardiac Magnetic Resonance*

While the full potential of cardiac magnetic resonance (CMR) in the preoperative and postoperative evaluation of TAVI is still being realized, there are a number of areas where it is showing great promise and in some cases is considered a mandatory imaging modality necessary for a structural heart program.[7] In preoperative patient selection, CMR may be especially useful in quantifying the severity of AS if there is a discrepancy between clinical and echocardiographic examinations. Specifically, in individuals with technically limited echocardiographic images, CMR offers the ability to obtain an independent measure of peak aortic valve velocity using a phase contrast technique.[8] High-resolution cine CMR imaging can provide a detailed anatomic assessment of the aortic valve that can be used to (1) identify the presence of congenital valvular abnormalities that may preclude TAVI (i.e., bicuspid aortic valve), and (2) obtain a directly planimetered aortic valve area (Figure 13).[9] This has been shown to correlate well with transesophageal echocardiography (TEE) but does not require a semi-invasive procedure.[8]

In those with AS and associated aortic valvular regurgitation, CMR is unique in that it is used to directly quantify valvular regurgitation in ml/minute rather than provide an estimate using another surrogate measure.[10] It is also important to exclude the presence of significant associated mitral insufficiency as this can pose a relative contraindication for TAVI. CMR is a superb

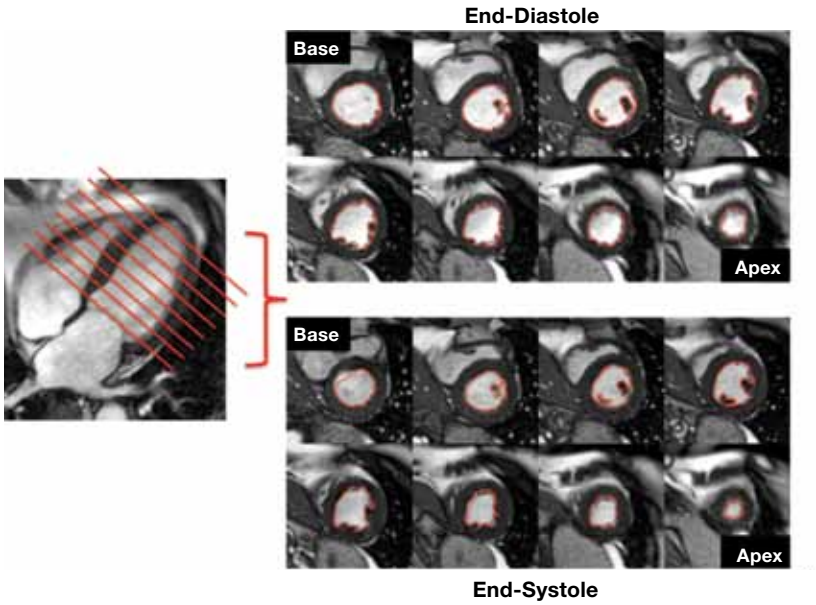



**Figure 14.** CMR can be used to obtain highly reproducible measures of LV size, volumes, and function.

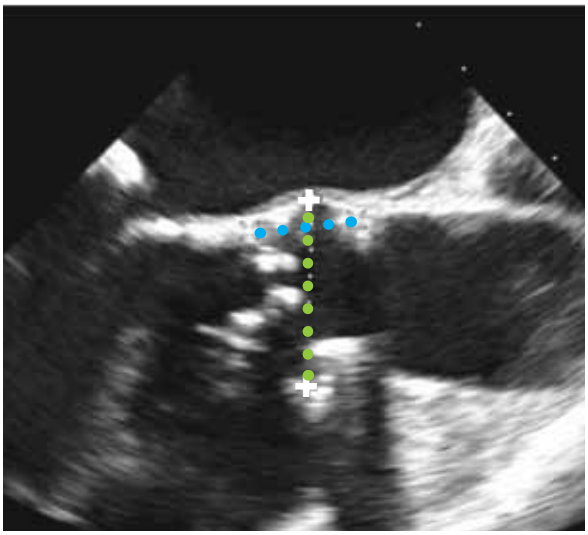


**Figure 15.** The standard "three-chamber" transesophageal echocardiogram (TEE) view is used to assess aortic valve calcification, leaflet mobility, and root dimensions. Much like CTA (Figure 11), TEE is used to measure sinotubular junction height (blue line) and aortic root diameter at the sinus of Valsalva (green line).

technique that can directly quantify mitral insufficiency severity without concern of acoustic window limitations from body habitus or coexisting lung disease.[8, 11]

In addition to identifying the severity of valvular disease, CMR is the optimal modality to identify how the valve lesion(s) affects LV performance. Cine CMR techniques can be used to obtained highly reliable measures of LV regional function, dimensions, volumes, mass, and ejection fraction (Figure 14).[9, 11] Accurate assessment of these parameters is important not only in determining optimal time for intervention but also for identifying patients in whom TAVI is contraindicated (i.e., left ventricular ejection fraction <20%).

Lastly, in patients with reduced LV systolic function, CMR can provide information about myocardial viability and scarring using delayed-enhancement CMR (DE-CMR).[3, 4] In patients with associated coronary artery disease, DE-CMR can help identify the extent of myocardial infarction, and in our experience it has helped to identify the occasional LV systolic dysfunction due to an associated infiltrative cardiomyopathy such as cardiac amyloidosis.

## Procedural Guidance

### *Echocardiography*

Cine angiography remains the primary imaging modality during a TAVI procedure. However, TEE plays a very important role. It can provide the baseline evaluation of aortic valve function and aortic annular and annular root anatomy, and it can evaluate for significant concomitant valve dysfunction (MR or AR). TEE also provides a baseline assessment of LV segmental wall motion and pericardial fluid collections that may be important should complications arise.[12] The standard intra-procedural TEE typically includes a complete baseline study of all chambers and valves followed by a more detailed analysis of the LVOT and aortic root geometry. Deep transgastric views are often employed to optimize the Doppler assessment of LVOT stroke volume and aortic valve gradient. A midesophageal probe position, typically at 110 to 130 multi-plane degrees, permits a long-axis view of the left ventricle, left atrium, and LVOT (i.e., the "three-chamber view") (Figure 15). At this view, the aortic annulus can be accurately measured as described above for transthoracic imaging. In addition, the proximal ascending aorta can usually be well delineated and the coronary sinuses easily identified. Often, a TEE within the operating room or hybrid OR-cath lab can be used to provide the required measurements of sinotubular junction diameter, sinotubular height from aortic annulus, and sinus of Valsalva diameter. The distance from the aortic annulus to the sinotubular junction is an important measure, particularly with the Edwards SAPIEN valve, to ensure that the length of the longest aortic cusp is less than the distance from the aortic annulus to the sinotubular junction of the ascending aorta.[13] Failure to assess this may result in coronary osteal occlusion after device deployment. This initial view is also very helpful to assess the degree of aortic cusp and annular calcification as well as to delineate whether the calcification is symmetrically distributed throughout the valve circumference.

Following this study of baseline morphology and function, the emphasis then turns to an evaluation of catheter and device positioning. As the interventional team places a pig-tail catheter into the noncoronary cusp (anatomically, the lowest cusp), they may ask the echocardiographer to confirm this catheter positioning. This can be accomplished by a 2D multi-planer assessment of the aortic valve in short-axis and long-axis, but it can be more quickly assessed using the x-plane (bi-plane) imaging feature now available when using a Matrix 3D TEE probe. When the aortic valve cusps and at least a portion of the fluid-filled catheter can be identified in simultaneous short- and long-axis views, then catheter position can be determined with confidence (Figure 16).

Currently, all patients undergo balloon dilatation of the native aortic valve immediately prior to TAVI. This critical step is not dependent on TEE guidance; however, an assessment of aortic valve regurgitation severity is often required immediately following balloon dilatation (Figure 17). The critical step of

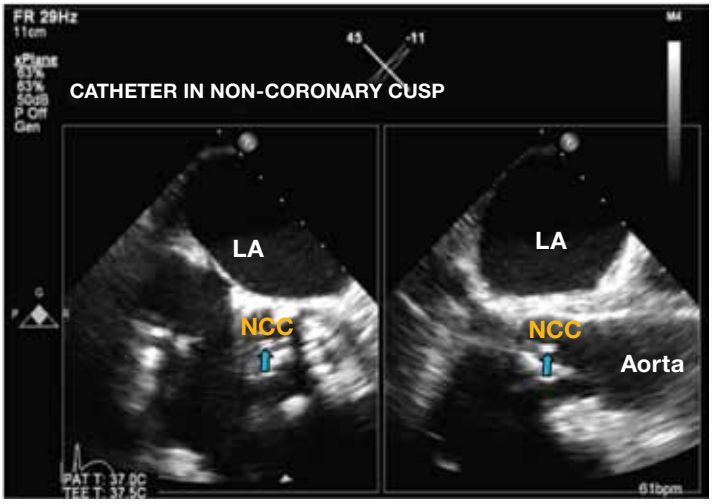



**Figure 16.** Transesophageal echocardiogram (TEE) can be used to assist with localization of catheters and devices. In this example, a pigtail catheter is clearly depicted (blue arrow) within the noncoronary cusp (NCC) of the aortic root. This form of biplane imaging can easily be created using the 3D matrix TEE probe.

deploying the stent-valve is often performed without real-time TEE imaging. In fact, in a minority of cases the TEE probe must be partially withdrawn because it may obstruct the cine angiographic views of the aortic valve. This imaging "conflict" is largely secondary to the chosen implant angle but may also be affected by other patient-specific features including the anatomic relation of the esophagus to the aortic valve.

## Detection of Early or Late Complications

### *Echocardiography*

The potential complications that can be encountered during a TAVI procedure have been well described.[2] In general, they fall into three categories:

*(1) Disruption or perforation leading to acute hemopericardium and tamponade.* This can occur with catheter perforation of the LV, pacemaker perforation of the RV, or balloon disruption of the aortic root (Figure 18). Intraprocedural tamponade requires emergent recognition by the echocardiographer and urgent action by the interventionalist-surgical team. It is important to evaluate for any pericardial effusion at baseline so that even a small change in pericardial fluid volume during the procedure will be quickly recognized.

*(2) New LV segmental wall motion abnormalities.* An obvious concern after TAVI deployment is that of complete or partial occlusion of the left or right coronary ostea. While this is a rare complication, it must be recognized quickly to allow appropriate intervention. However, other events may cause transient changes in regional LV systolic function. Activation of the temporary pacemaker within the right ventricle may alter LV apical contraction. Likewise, a new left bundle branch block may occur immediately following TAVI (especially with the CoreValve) and must be considered when new wall motion abnormalities are encountered. In addition, global LV function may be adversely affected (often transiently) following rapid pacing and balloon aortic valvuloplasty.

*(3) Residual paravalvular aortic regurgitation (PVAR).* Although trace or mild paravalvular AR is common, moderate or greater PVAR may have important acute and chronic hemodynamic consequences and must be further evaluated. Assessment of both the mechanism and quantification of PVAR often requires focused efforts immediately following the stent-valve deployment. The mechanism is often attributed to less than ideal device location either too low or too high relative to the aortic annulus. It is also recognized that other risk factors for significant PVAR include large annulus size and asymmetric annular and leaflet calcification.[14]

The color Doppler jet of a paravalvular leak is often best appreciated from the deep transgastric TEE view (Figure 19). This view usually permits the best axial alignment for the quantitative Doppler measure of regurgitant pressure half-time. The midesophageal views provide the cross-sectional and long-axis views to facilitate identification of the site and extent of paravalvular leak. The vena contracta diameter and area can be assessed using 2D and 3D color Doppler application, respectively (Figure 20).

### *CT Angiography*

Although rarely required, CT can be used to gauge the correct anatomic position of a catheter-deployed valve. Because of its excellent special resolution, CT can accurately indicate the depth of implant within the LVOT and can be used to assess stent shape. The latter may be particularly useful when there is concern about complete or partial stent deployment (Figure 21).

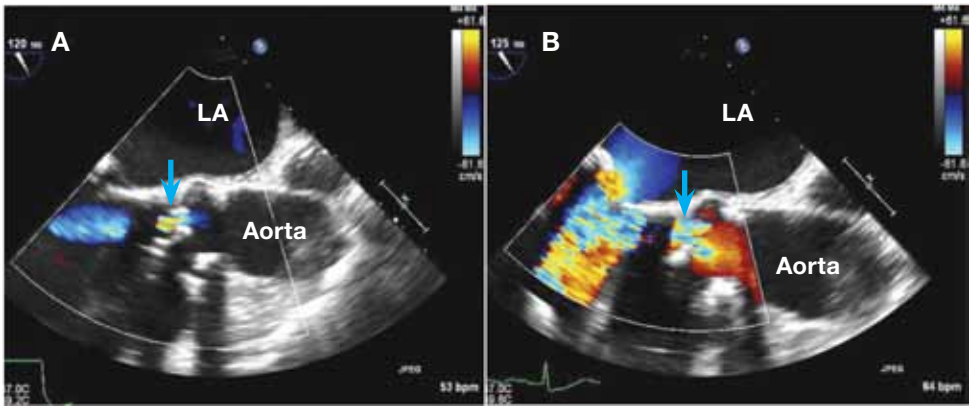



**Figure 17.** Transesophageal echocardiogram with color Doppler is used to compare severity of aortic regurgitation before (A) and after (B) balloon valvuloplasty of the aortic valve.

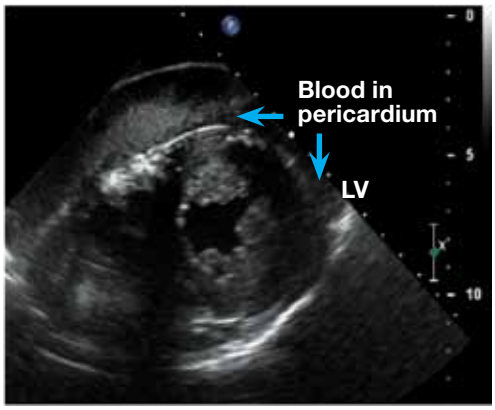



**Figure 18.** Transgastric TEE view clearly depicts a large collection of blood within the pericardial space. In this case, intraprocedural pericardial tamponade was quickly recognized allowing prompt surgical intervention.

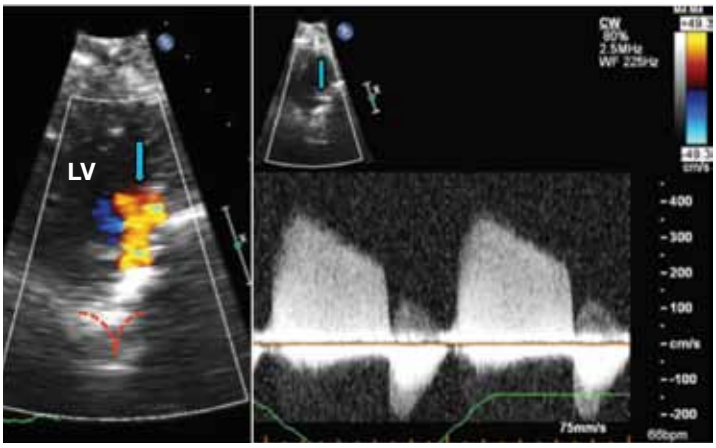



**Figure 19.** Doppler echocardiography is used to quantify paravalvular regurgitation severity. A deep transgastric TEE view with color Doppler is used to identify the site of regurgitation relative to the prosthetic aortic leaflets (identified in red). Spectral Doppler exam permits quantitative and quantitative assessment of the regurgitant jet (shown with perimeter traced for pressure half-time determination).

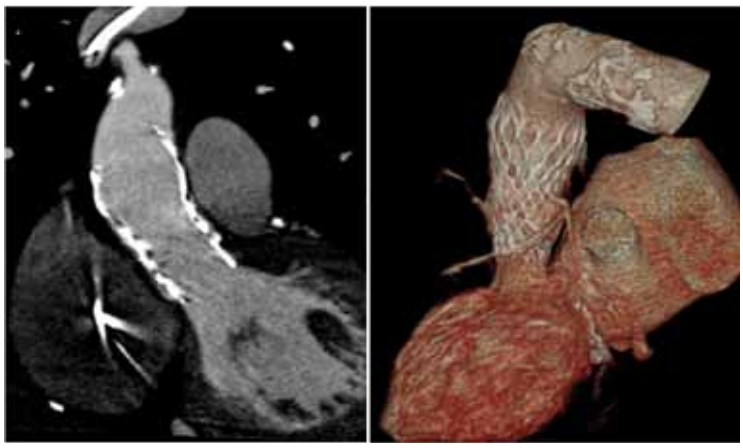


**Figure 21.** Coronal oblique CT views of aortic root (left) and three-dimensional (3D) volume-rendered image (right) of the ascending aorta in an male patient 2 weeks after transcatheter aortic valve replacement (TAVR) with a Medtronic CoreValve. The CT was performed due to the suggestion of suspected paravalvular aortic regurgitation seen on a surveillance echo. Note the adequate deployment and positioning of the prosthesis, the absence of in-stent stenosis, and the integrity of the valve stent struts.

### *Cardiac Magnetic Resonance*

CMR is also showing promise in evaluating postprocedural complications after TAVI. Care must be taken to utilize optimized imaging sequences to minimize metallic artifact from the implanted Core valve. In general, standard steady-state free precession (SSFP) cine sequences will yield greater artifact, but use of gradient recalled echo (GRE) based sequences with short echo times can help to reduce image artifact (Figure 22). Additionally, GRE-based phase contrast CMR techniques allow quantification of postprocedural aortic insufficiency volume by measuring aortic forward and reverse flow in the aortic root. While this requires further study, CMR may become the optimal method for assessing postprocedural aortic insufficiency as it is independent of jet morphology, unlike most echocardiographic techniques.

An important consideration is the performance of CMR in patients with implanted cardiac devices. Since a significant proportion of patients post-TAVI will require permanent pacemaker placement, the use of CMR would seem to be limited in this population.[15] However, several recent studies have demonstrated that MRI may be safely performed in patients with implanted cardiac devices but requires device reprogramming and careful monitoring.[6] While the worldwide experience with CMR in patients with devices is limited, the procedure is no longer considered an absolute contraindication at some centers with selected expertise. However, it is important to note that patients with recent devices (≤6 weeks) cannot undergo MRI scanning, therefore the role of CMR in the immediate postoperative period may be limited. Nonetheless, for the more than 70% of TAVI patients who do not require permanent pacemaker placement, CMR may be a viable option if performed at centers with expertise.

## Summary

As TAVI technology continues to evolve, so do the imaging modalities that support its use. Today the use of echocardiography (TTE and TEE) is firmly established for both patient selection and live intraprocedural imaging guidance (Figure 23). CT has also become a critical imaging component for patient selection. Not only is CT required to assess the peripheral arterial vasculature for catheter access and navigation, but CT has become increasingly important to assess the aortic root geometry and orientation to the LVOT — relationships that often cannot be assessed by echocardiography. Although CMR has a more limited role today,

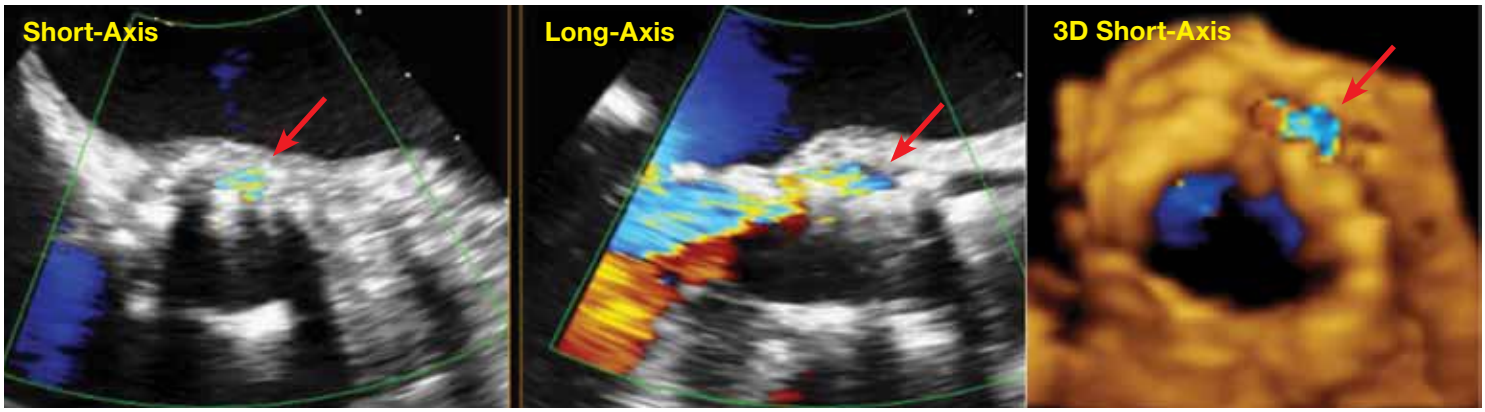
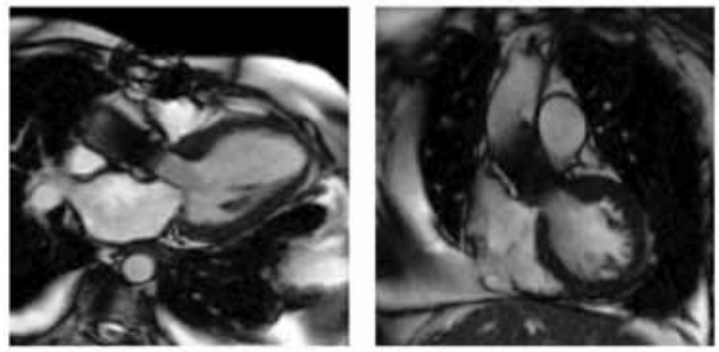
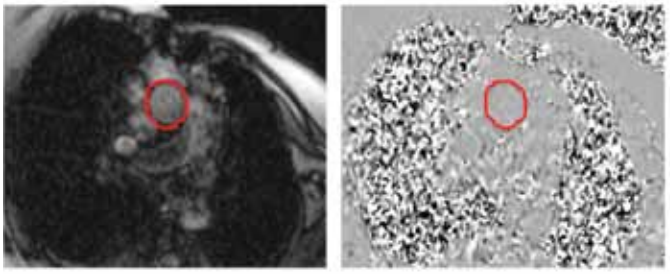


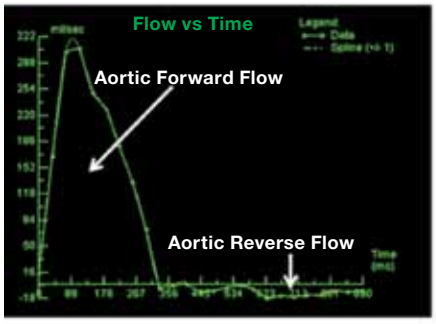

**Figure 20.** Three-dimensional (3D) TEE imaging for the characterization of paravalular flow. The vena contracta (narrowest portion the regurgitant jet) is shown in simultaneous short (left) and long axis (center) views. The extent of paravalular flow is appreciated using volume-rendered 3D imaging (right).



PHASE CONTRAST CMR



Rephased Image Phase Image




Ao Forward Flow = 63 ml
Ao Reverse Flow (AI) = 12 ml
AI Regurgitant Fraction = 19 ml

**Figure 22.** Cardiac magnetic resonance uses phase contrast techniques to derive regurgitant flow by comparing total forward flow and reverse flow within the ascending aorta.

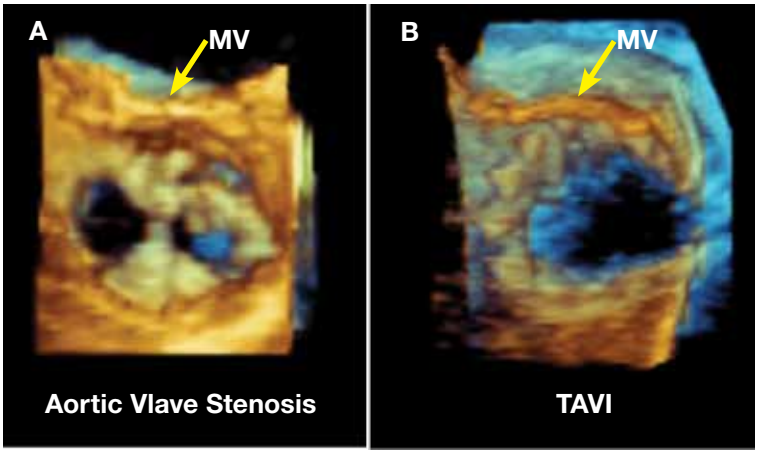



**Figure 23.** Three-dimensional TEE depicts comparative views of the aortic valve before and after TAVI. In this case, the lower portions of an appropriately deployed CoreValve are clearly visible within the LV outflow tract. The base of the anterior mitral valve (MV) is identified to orient the reader to this enface view of the aortic valve from the perspective of the LVOT.

it has already been shown to accurately assess AS severity, aortic root geometry, and peripheral vascular anatomy and function. It is likely that CMR will emerge as an increasingly important modality for the functional assessment of catheter-deployed valves over the next few years.

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## References

1. Thomas M, Schymik G, Walther T, Himbert D, Lefèvre T, Treede H, et al. One-year outcomes of cohort 1 in the Edwards SAPIEN Aortic Bioprosthesis European Outcome (SOURCE) registry: the European registry of transcatheter aortic valve implantation using the Edwards SAPIEN valve. Circulation. 2011 Jul 26;124(4):425-33. Epub 2011 Jul 11.
2. Leon MB, Smith CR, Mack M, Miller DC, Moses JW, Svensson LG, et al.; PARTNER Trial Investigators. Transcatheter aortic-valve implantation for aortic stenosis in patients who cannot undergo surgery. N Engl J Med. 2010 Oct 21;363(17):1597-607. Epub 2010 Sep 22.
3. Smith CR, Leon MB, Mack MJ, Miller DC, Moses JW, Svensson LG, et al; PARTNER Trial Investigators. Transcatheter versus surgical aortic-valve replacement in high-risk patients. N Engl J Med. 2011 Jun 9;364(23):2187-98. Epub 2011 Jun 5.
4. Tzikas A, Schultz CJ, Piazza N, Moelker A, Van Mieghem NM, Nuis RJ, et al. Assessment of the aortic annulus by multislice computed tomography, contrast aortography, and trans-thoracic echocardiography in patients referred for transcatheter aortic valve implantation. Catheter Cardiovasc Interv. 2011 May 1;77(6):868-75. Epub 2011 Apr 14.
5. Jabbour A, Ismail TF, Moat N, Gulati A, Roussin I, Alpendurada F, et al. 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 Nov 15;58(21):2165-73.
6. Tops LF, Wood DA, Delgado V, Schuijf JD, Mayo JR, Pasupati S, et al. Noninvasive evaluation of the aortic root with multislice computed tomography implications for transcatheter aortic valve replacement. JACC Cardiovasc Imaging. 2008 May;1(3):321-30.
7. Holmes DR Jr, Mack MJ; Writing Committee. Transcatheter valve therapy: a professional society overview from the American College of Cardiology Foundation and the Society of Thoracic Surgeons. Ann Thorac Surg. 2011 Jul;92(1):380-9.
8. Cawley PJ, Maki JH, Otto CM. Cardiovascular magnetic resonance imaging for valvular heart disease: technique and validation. Circulation. 2009 Jan 27;119(3):468-78.

9. Hendel RC, Patel MR, Kramer CM, Poon M, Hendel RC, Carr JC, et al. ACCF/ACR/SCCT/SCMR/ASNC/NASCI/SCAI/SIR 2006 appropriateness criteria for cardiac computed tomography and cardiac magnetic resonance imaging: a report of the American College of Cardiology Foundation Quality Strategic Directions Committee Appropriateness Criteria Working Group, American College of Radiology, Society of Cardiovascular Computed Tomography, Society for Cardiovascular Magnetic Resonance, American Society of Nuclear Cardiology, North American Society for Cardiac Imaging, Society for Cardiovascular Angiography and Interventions, and Society of Interventional Radiology. J Am Coll Cardiol. 2006 Oct 3;48(7):1475-97.
10. American College of Cardiology Foundation Task Force on Expert Consensus Documents, Hundley WG, Bluemke DA, Finn JP, Flamm SD, Fogel MA, Friedrich MG, et al. ACCF/ACR/AHA/NASCI/SCMR 2010 expert consensus document on cardiovascular magnetic resonance: a report of the American College of Cardiology Foundation Task Force on Expert Consensus Documents. J Am Coll Cardiol. 2010 Jun 8;55(23):2614-62.
11. Shah DJ. Functional valve assessment: the emerging role of cardiovascular magnetic resonance. Methodist Debakey Cardiovasc J. 2010 Jan-Mar;6(1):15-9.
12. Zamorano JL, Badano LP, Bruce C, Chan KL, Gonçalves A, Hahn RT, et al. EAE/ASE recommendations for the use of echocardiography in new transcatheter interventions for valvular heart disease. J Am Soc Echocardiogr. 2011 Sep;24(9):937-65.
13. Moss RR, Ivens E, Pasupati S, Humphries K, Thompson CR, Munt B, et al. Role of echocardiography in percutaneous aortic valve implantation. JACC Cardiovasc Imaging. 2008 Jan;1(1):15-24.
14. Detaint D, Lepage L, Himbert D, Brochet E, Messika-Zeitoun D, Iung B, et al. Determinants of significant paravalvular regurgitation after transcatheter aortic valve: implantation impact of device and annulus discongruence. JACC Cardiovasc Interv. 2009 Sep;2(9):821-7.
15. Calvi V, Conti S, Pruiti GP, Capodanno D, Puzzangara E, Tempio D, et al. Incidence rate and predictors of permanent pacemaker implantation after transcatheter aortic valve implantation with self-expanding CoreValve prosthesis. J Interv Card Electrophysiol. 2011 Nov 26. [Epub ahead of print].