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CME

iREVIEWS

STATE-OF-THE-ART PAPER

A Practical Guide to Multimodality Imaging of Transcatheter Aortic Valve Replacement

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CME Objective for This Article: At the end of this activity the reader should be able to: 1) discuss the strengths and weakness of imaging modalities for pre-procedural assessment including a) determining patient suitability for the proposed access site, b) ensuring that the proposed device can be safely and successfully implanted based on device characteristics and the anatomic relationships between the aortic valve and root, left ventricle (LV) and coronary ostia, c) selection of device size, and d) for the development of a procedural plan; 2) select imaging modalities during transcatheter heart valve implantation to a) ensure the best prosthesis-patient match, b) assess THV position and function after deployment, and c) identify immediate complications; 3) identify imaging modalities for long term follow up including the a) assessment of valve hemodynamics including gradients and effective valve area, b) quantification of valvular and paravalvular regurgitation, c) determining the effect of implantation on the disease processes related to outflow obstruction (such as left ventricular hypertrophy, chamber remodeling, diastolic and systolic function), d) ongoing assessment of concomitant pathology, and e) detection of long term complications such as device migration, thrombus formation, ventricular perforation, mitral valve impingement and endocarditis.

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A Practical Guide to Multimodality Imaging of Transcatheter Aortic Valve Replacement

The advent of transcatheter aortic valve replacement (TAVR) is one of the most widely anticipated advances in the care of patients with severe aortic stenosis. This procedure is unique in many ways, one of which is the need for a multimodality imaging team-based approach throughout the continuum of the care of TAVR patients. Pre-procedural planning, intra-procedural implantation optimization, and long-term follow-up of patients undergoing TAVR require the expert use of various imaging modalities, each of which has its own strengths and limitations. Divided into 3 sections (pre-procedural, intraprocedural, and long-term follow-up), this review offers a single source for expert opinion and evidence-based guidance on how to incorporate the various modalities at each step in the care of a TAVR patient. Although much has been learned in the short span of time since TAVR was introduced, recommendations are offered for clinically relevant research that will lead to refinement of best practice strategies for incorporating multimodality imaging into TAVR patient care. (J Am Coll Cardiol Img 2012;5: 441–55)

Percutaneous placement of aortic valve prostheses is among the most widely anticipated innovations of the past decade (1,2). Such success is critically dependent on careful patient selection, optimal performance of a complex and technically demanding implantation procedure, and careful postoperative care. Multimodality imaging has emerged as an important ingredient of each of these steps such that the care team for patients undergoing percutaneous transcatheter aortic valve replacement (TAVR) must include skilled and knowledgeable cardiologists and radiologists able to perform and interpret a variety of imaging techniques, often in real time during the implantation procedure and who have specific expertise in TAVR imaging. The goal of this review is to comprehensively demonstrate how physicians currently derive multimodality imaging information and integrate it into the decision-making process for patient care for both self-expanding and balloon expandable TAVR. This review offers guidance for future imagers involved in this novel procedure and provides the basis for standardization of the imaging approach to TAVR, which has been lacking. In 3 sections (pre-procedural, intraprocedural, and long-term follow-up assessments), we highlight the importance of multimodality imaging and, when appropriate, compare the utility of various modalities. In some instances, local expertise will dictate which modalities are employed at each stage. It is hoped that this practical review addresses the requirements for and utility of multimodality imaging in the continuum of TAVR patient care.

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Pre-procedural Assessment

Multimodality imaging goals. The overall goals of the pre-procedural assessment are to: 1) ensure patient suitability for the proposed access site; 2) ensure that the proposed device can be safely and successfully implanted on the basis of device characteristics and the anatomic relationships between the aortic valve and root, left ventricle (LV), and coronary ostia; 3) select the device size; and 4) contribute to the development of a procedural plan.

Determining eligibility for iliofemoral vascular access. CONVENTIONAL ANGIOGRAPHY. Vascular access complications are common in TAVR implantation, with recently published rates ranging from 6.3% to 30.7% (1,3–5). These rates are influenced by various clinical factors, screening protocols, and the diameter of the arterial sheaths used. Given this high burden of vascular injury, increasing the effectiveness of pre-procedural screening of patients for TAVR is key. This often begins with conventional angiography, because virtually all patients undergo assessment of the descending aorta, abdominal aorta, and iliofemoral system to detect stenosis, occlusion, and aneurysmal disease of the proposed access site. Angiography provides a basic assessment of luminal size but a very limited evaluation of the presence of atherosclerosis and plaque burden as well as the degree of vessel tortuosity.

MULTIDETECTOR COMPUTED TOMOGRAPHY. Because of the limitations of angiography, multidetector computed tomography (MDCT) has become the single most important imaging modality for examination of the abdominal and iliofemoral arteries. A standardized approach reduces morbidity and mortality rates from vascular injury (6) and includes a number of reconstructions, including 3-dimensional (3D) volume rendered imaging, curved multiplanar reformats, and maximum intensity projection images (Fig. 1). Employing a centerline approach to elongate the vessel image, multiple luminal measurements should be made in a plane orthogonal to the vessel rather than in the transverse axial plane. With this approach, MDCT can evaluate vessel size, degree of calcification, minimal luminal diameter, plaque burden, and vessel tortuosity and also identify high-risk features including dissections and complex atheroma. Angulations in the iliofemoral system >90° might preclude insertion of large-bore catheters or cause significant vessel trauma. In the absence of severe calcification, bulky atheromatous burden, or severe tortuosity, short segments of relatively compliant artery can be up to 1- to 2-mm smaller in diameter than the intended sheath, allowing it to be safely cannulated (7). Less than 180° of calcification and eccentric calcification are less likely to create procedural difficulty than almost circumferential and luminal calcification. A sheath/femoral artery ratio of 1.05 or higher has also been shown to predict both vascular complications and 30-day mortality (8). Although minimal vessel diameters have been suggested (7), as smaller sheaths become available the optimal vessel diameter is likely to be a moving target. In general, when imaging characteristics are unfavorable, alternative approaches such as transapical, transaxillary, or direct aortic should be considered (7,9). It should be emphasized that, as devices and technology change, the imaging parameters used to assess patient suitability and access planning might be modified (6). To help reduce the risk of contrast-induced nephropathy, protocols have been published that employ direct power injection of diluted contrast in the infra-renal aorta and provide excellent image quality (6,10).

ULTRASOUND. Surface ultrasound of the access site is not frequently used but can be helpful to assess vessel size, tortuosity, and calcification and identify the optimal site for puncture (11). Intravascular ultrasound is helpful to see the lumen in patients when there is blooming artifact from calcifications. Coronary intravascular ultrasound catheters can be used in the periphery at time of diagnostic coronary angiography for this purpose.

ABBREVIATIONS AND ACRONYMS

AR = aortic regurgitation
CMR = cardiac magnetic resonance
CT = computed tomography
DVI = Doppler velocity index
EF = ejection fraction
EOA = effective orifice area
LV = left ventricle/ventricular
LVOT = left ventricular outflow tract
MDCT = multi-detector computed tomography
P-PM = prosthesis-patient mismatch
SAVR = surgical aortic valve replacement
STJ = sinotubular junction
TAVR = transcatheter aortic valve replacement
TEE = transesophageal echocardiography
THV = transcatheter heart valve
TTE = transthoracic echocardiography

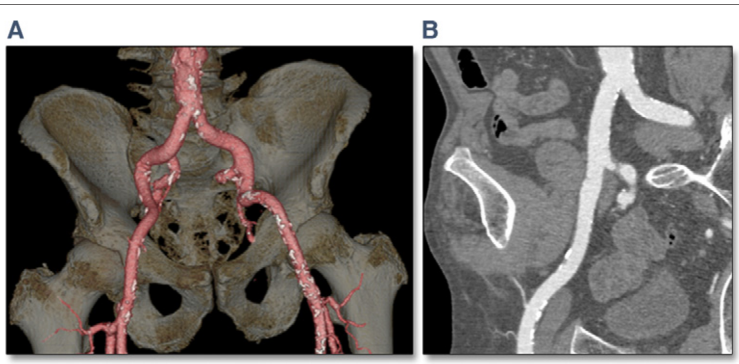

Figure 1. Multi-Detector Computed Tomography Visualization of Iliofemoral Vasculature

(A) Three-dimensional volume rendered image of the iliofemoral vessels and boney pelvis. This reconstruction provides landmarks to display the site of minimal luminal diameter. **(B)** Curved multiplanar reformat of the right iliofemoral system in an 84-year-old male with severe aortic stenosis. The curved multiplanar reformat demonstrates elongation of the arterial system and allows for assessment of luminal diameter and degree of encroachment by calcified plaque in multiple projections.

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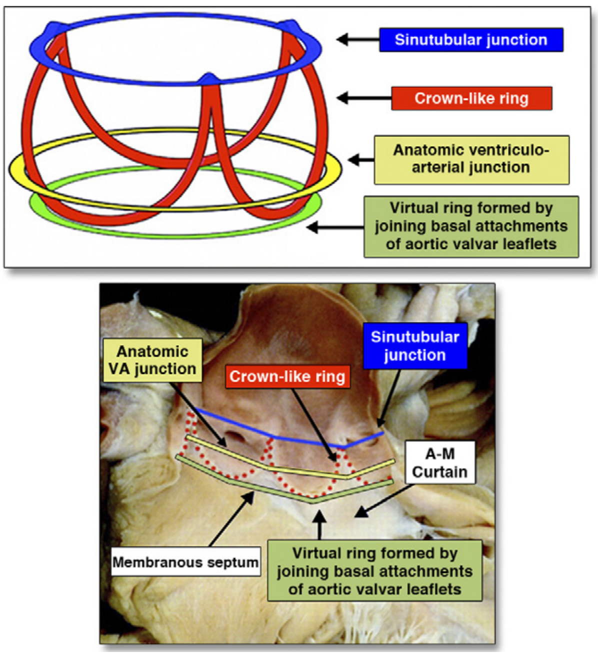

Figure 2. **Aortic Root Anatomy**

(A) Diagram of aortic root anatomy showing coronet shape and location of various annular planes and coronary ostia relative to leaflet attachments. **(B)** Imaging planes and leaflet attachments from **(A)** shown superimposed on postmortem specimen. Reprinted, with permission, from Piazza et al. (12). A-M = aorto-mitral; VA = ventriculo-arterial.

Aortic root assessment for TAVR: device sizing and selection. Imaging of the aortic root and heart for pre-procedural device sizing and selection and procedural planning and execution is performed with the goals of: 1) measuring aortic annulus size; 2) measuring leaflet length and calcification; 3) locating the coronary ostia; 4) identifying other features that might interfere with successful implantation; and 5) contributing to pre-procedural planning. In particular, a careful multimodality imaging evaluation with MDCT, echocardiography, and root angiography will identify high-risk predictors of complications in advance and might result in patient exclusion or other anticipatory action.

Aortic valve and root anatomy and transcatheter heart valve characteristics. To fully understand the use and value of imaging it is essential to appreciate the complex anatomy of the aortic valve and root and the specifications of transcatheter heart valves (THVs) currently available. The aortic annulus, the commissures, the sinuses of Valsalva, the coronary ostia, and the sinotubular junction (STJ) are the framework in which the valve leaflets are suspended (12) (Fig. 2). It is well-established that the annulus is an oval-shaped, 3-pronged coronet with 3 anchor points at the nadir of each aortic cusp rather than a cylindrical structure. The attachment of the aortic cusps is semilunar, extending throughout the aortic root from the LV distally to the STJ. Two virtual rings are usually defined: an inferior basal ring formed by joining the basal attachment of the leaflets (aortic annulus), and a superior ring at the top of the crown that is a true ring, corresponding to the STJ (12) (Fig. 2). The aortic annulus measurement by all modalities is assessed at the lowest hinge point of the aortic valve leaflets at the virtual basal plane in systole.

The THV characteristics are also important and must be integrated with imaging findings (Table 1). The height of the valve prosthesis and the parts of the prosthesis that are covered by fabric (the "skirt") are important to understand with regard to pre-procedural planning and implantation. In the SAPIEN (Edwards Lifesciences, Irvine, California) valve, the skirt covers the proximal 2 links, whereas in the CoreValve (Medtronic, Minneapolis, Minnesota) the proximal 12 mm are covered, and the valve leaflets are mounted supra-annularly. This is an important distinction, because high placement might interfere with coronary flow and future access as well as increase the likelihood of significant paravalvular regurgitation.

Aortic annulus measurement. Accurate aortic annulus measurement is critical for the success of the TAVR, because the size of the annulus will determine the size of the prosthesis that should be used

Table 1. **Device Dimensions and Recommended Echocardiographic Aortic Root Measurements**

	THV Height	THV Skirt Coverage	Recommended Aortic Annulus Size	Recommended Annulus to Ostia Height
SAPIEN 23 mm	14.5 mm	7.74–10.1 mm	18–21 mm	>10 mm
SAPIEN 26 mm	16 mm	8.67–11.4 mm	22–24.5 mm	>11 mm
CoreValve 26 mm	53 mm	12 mm	20–23 mm	n/a
CoreValve 29 mm	59 mm	12 mm	23–27 mm	n/a

Device dimensions and recommended echocardiographic aortic root measurements for the use of the SAPIEN (Edwards Lifesciences, Irvine, California) and CoreValve (Medtronic, Minneapolis, Minnesota) transcatheter heart valves (THVs) (from Piazza et al. [12] and Jayasuriya et al. [13]).

(12,13) (Table 1). Mismeasurement of the annulus is the most common reason for complications such as aortic regurgitation (AR) (14). Systolic annulus measurement can be obtained by virtually any technique, although results differ across modalities in magnitude and reproducibility, including the ability to accurately capture the true elliptical anatomy of the annulus (Online Figs. 1 and 2).

ECHOCARDIOGRAPHY. Echocardiographic measurements of the aortic annulus for selecting THV size (Table 1) have traditionally used the sagittal plane acquired from a 2-dimensional (2D) parasternal long-axis image on transthoracic echocardiography (TTE) or a mid-esophageal long-axis transesophageal echocardiography (TEE) image between 120° and 140° (Fig. 3). The annular dimension most commonly used in decision-making for TAVR bisects the annulus at its maximum diameter during early-systole, from the hinge point of the right coronary cusp to the left-noncoronary commissure. When the cusps are open in systole, the commissure measurement is particularly difficult, and care must be taken not to measure too far into the aortic root. Transesophageal echocardiography measurements underestimate cylindrical sizers during surgery (15), because of the oval shape of the annulus. Biplane imaging or 3D reconstruction can be used to obtain measurements in the sagittal and coronal planes. Finally, TEE imaging of balloon aortic valvuloplasty might help define the annular dimension in difficult cases.

MDCT. Recent improvements in MDCT spatial and temporal resolution and higher detector number systems allow imaging of the aortic root with a minimal slice thickness of 0.5 to 0.75 mm, resulting in almost isotropic datasets allowing oblique reconstruction without degradation of spatial resolution. The aortic annulus plane is obtained by a double oblique multiplanar reconstruction with 2 orthogonal planes representing the short and long axis of the virtual basal ring (Fig. 4). Measurements are taken from systolic phase reconstructions ranging from 20% to 45% of the R-R interval, during

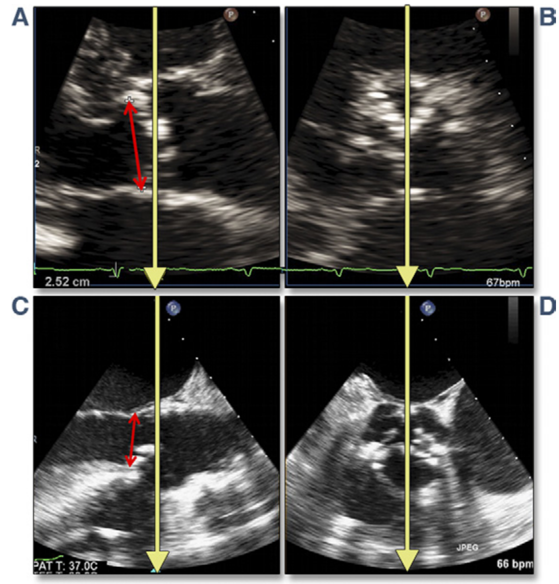

Figure 3. Biplane Echocardiographic Imaging Identifies the Sagittal Imaging Plane That Bisects the Largest Dimension of the Aortic Annulus

(A and B) Biplane transthoracic imaging shows the sagittal **(A)** and corresponding transverse **(B)** plane. The **yellow arrows** define the imaging plane for the orthogonal view. The **red arrow** shows the appropriate annular measurement in the on-axis sagittal plane. **(C and D)** Biplane transesophageal imaging shows the sagittal **(C)** and corresponding transverse **(D)** plane. **Red arrow** in panel **C** shows the appropriate annular measurement in the on-axis sagittal plane.

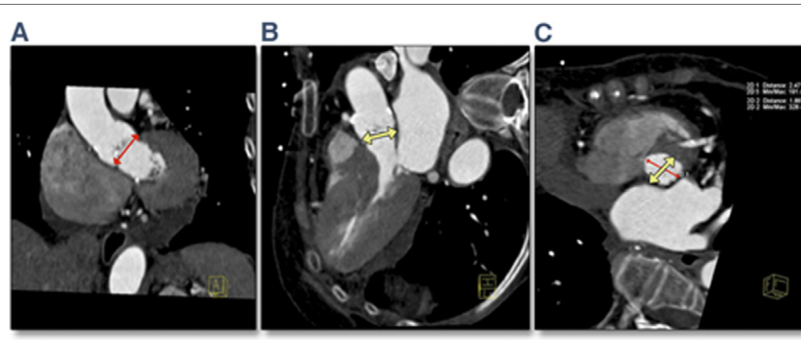

Figure 4. Measurement of the Aortic Annulus With Multi-Detector Computed Tomography

(A) Coronal plane view through the long axis of the left ventricular outflow tract. The longer dimension of the aortic annulus is depicted by the **red arrow**. **(B)** Sagittal plane view through the long axis of the left ventricular outflow tract. The shorter dimension of the annulus is depicted by the **yellow arrow**. Transverse plane reconstructed with the double oblique technique of multiplanar reconstruction **(C)**.

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Table 2. Relative Usefulness of TEE, CT, and CMR for Aortic Valve and Root Characteristics

	Aortic Root Imaging Modality				
	TEE			CMR	
	2D	3D	CT	2D	3D
AS severity	++	+	±	±	±
Aortic valve morphology	++	++	+	±	±
Calcium distribution	+	+	++	—	—
Aortic root orientation	—	—	++	+	++
Aortic annulus diameter	++	++	++	+	++
Aortic root morphology (size and shape)	++	++	++	+	++
Coronary ostia to aortic annulus distance	±	+	++	+	++

— = not useful; ± = limited usefulness; + = useful; ++ = very useful; 2D = 2-dimensional; 3D = 3-dimensional; AS = aortic stenosis; CMR = cardiac magnetic resonance; CT = computed tomography; TEE = transesophageal echocardiography.

retrospective electrocardiographic gating imaging, using the phase with the maximum valve opening as is performed in echocardiography. Computed tomography (CT)-based sizing guidelines under development integrate 3D data afforded by CT into the prosthesis selection process, with recommendations as follows for MDCT mean basal ring measurements: 23-mm valve for annulus ≥19.5 to ≤22.5 mm, 26-mm valve for >22.5 to ≤26.5 mm, and 29-mm valve for >26.5 to ≤29.5 mm (16).

CARDIAC MAGNETIC RESONANCE. Cardiac magnetic resonance (CMR) allows for an anatomic and functional assessment of the aortic valve and aortic root. However, similar to standard echocardiography, most CMR sequences are 2D with the plane of imaging chosen at the time of the examination (17). Whole heart, echo-gated 3D CMR with contrast and a slice thickness of 1.5 mm, a spatial resolution of 1 mm in-plane and 1 mm through plane (compared with 0.5 × 0.5 × 0.5 mm by MDCT) provides isotropic images for multiplanar reconstruction and shows the oval shape of the annulus with maximal and minimal diameters (Online Fig. 2).

COMPARISON OF AORTIC ANNULUS MEASUREMENTS BY TTE, TEE, CMR, AND MDCT. Every technique has its advantages and disadvantages (Tables 2 and 3), and it often falls to the operator and to local expertise to make the safest and most cost-effective choice. The sagittal plane measurement of the aortic annulus by TTE and TEE usually approximates the minor axis of the elliptically shaped annulus as measured by MDCT. The coronal plane is typically the major (larger) dimension and corresponds to the maximum dimension measured from the anteroposterior view on cine-angiography. In general, the annulus size as measured by TTE is 1-mm smaller than measurements by TEE, and the TEE measurement is 1.0-mm to 1.5-mm smaller than MDCT measurement (18,19). There are no studies to date comparing CMR measurements of the annulus with those by echocardiography or MDCT. Despite these differences, TAVR outcomes with the conventional anteroposterior (sagittal plane) diameter by TEE are excellent (19), and TTE or TEE aortic annulus measurement continues to be the gold standard.

Imaging of the aortic leaflets and coronary ostia. Echocardiography, CMR, or MDCT can be used to measure the distance from the annulus/leaflet hinge point to the left main ostium and the length of the corresponding coronary cusp, important parameters in planning strategies to reduce the risk of coronary obstruction (9). Multiplanar 3D techniques (i.e., TEE, MDCT, or CMR) allow for reconstruction of the plane of the coronary ostia with corresponding better visualization and assessment of these complex structures and their interrelationships (Fig. 5). Bicuspid aortic valves are considered contraindications to TAVR, although it can be difficult to assess whether a valve is bicuspid or not when it is heavily calcified.

Both echocardiography and MDCT can evaluate the extent, location, and distribution of aortic annulus and leaflet calcifications, thereby providing important information for successful implantation, although severe calcification might cause acoustic shadowing with echocardiography. For this reason and due to the high spatial resolution of MDCT, this method is currently the test of choice in quantifying severity and identifying the location of aortic cusp calcification. Because of the signal void caused by calcium, CMR is not a suitable choice. Multimodality imaging also provides valuable information about the distribution and extent

Table 3. Comparative Test Characteristics of TEE, CT, and CMR for Aortic Root Imaging

	Aortic Root Imaging			
			CMR	
	TEE	CT	2D	3D
Radiation	No	Yes	No	No
Contrast	No	Yes	No	Yes
Cost	Lower	Higher	Higher	Higher
Length of test	Longer	Very short	Longer	Longer
Need for sedation	Yes	No	No	No

Abbreviations as in Table 2.

of calcification in other areas, such as the mitral annulus. For example, dense calcification in the intertrigonal area (the aortomitral curtain) increases the risk of paravalvular AR due to asymmetric expansion of the stented valve (20).

Concomitant cardiac pathology. The degree of LV hypertrophy, particularly upper septal hypertrophy and the angle between the aorta and the LV are important in planning the TAVR procedure. A septal bulge protruding into the left ventricular outflow tract (LVOT) provides a challenge to the operator in the accurate placement of the valve and presents a significant risk of THV repositioning with cessation of the pacing run. Left ventricular dysfunction also influences the strategy of the procedure. For instance, in patients with severely depressed LV function, the number of pacing runs should be minimized to avoid hemodynamic compromise. The degree of baseline AR should be evaluated, because balloon dilation might worsen the regurgitant lesion and cause hemodynamic compromise (21). In these cases, the team should be prepared to implant the valve expeditiously. Because catheters and wires are placed in the ventricle, mitral valve compromise might occur at any point in the procedure and therefore the severity of mitral regurgitation should be routinely assessed at baseline and throughout the procedure.

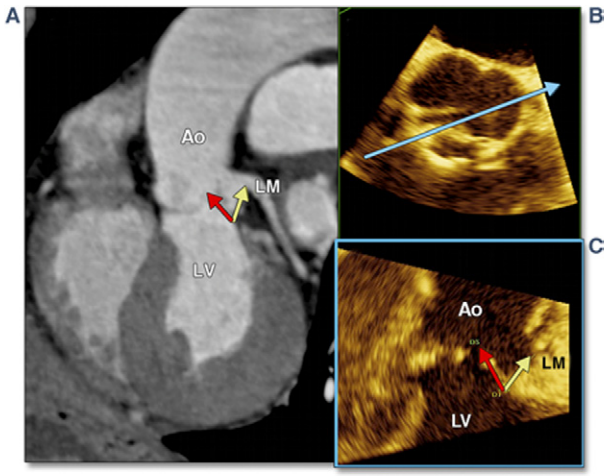

Figure 5. Localization of the LM Coronary Artery by Multi-Detector Computed Tomography and 3D TEE

(A) Multi-detector computed tomography imaging used to acquire the plane of the left main (LM) coronary artery, with **yellow arrow** indicating the distance from the hinge point of the left coronary cusp to the LM, and **red arrow** indicating the length of the left coronary cusp. **(B)** Multiplanar reconstruction of a 3-dimensional (3D) transesophageal echocardiography (TEE) volume set in the transverse plane. The **blue arrow** shows the plane of the LM coronary artery. **(C)** Multiplanar reconstruction of a 3D TEE volume set showing the plane of the LM ostium and coronary artery. This plane is used to measure the length of the left coronary cusp **(red arrow)** and the distance from the hinge point of that cusp to the LM coronary ostium **(yellow arrow)** in systole. Ao = aorta; LV = left ventricle.

Routine and "Interventional" Imaging During THV Implantation

Multimodality imaging goals. The goals of multimodality imaging in the implantation phase include: 1) ensuring the best prosthesis-patient match; 2) assessing THV position and function after deployment; and 3) identifying immediate complications.

Ensuring proper placement. ANGIOGRAPHY. Proper valve placement depends on knowledge of the exact location and orientation of the annular plane, which should be precisely defined either by angiography or CT scan before the procedure (22,23) and overlaid on the screen with fluoroscopy (24) (Fig. 6). Rotational angiography with pacing might also help to define this plane (25) (Online Fig. 3 and Video 1).

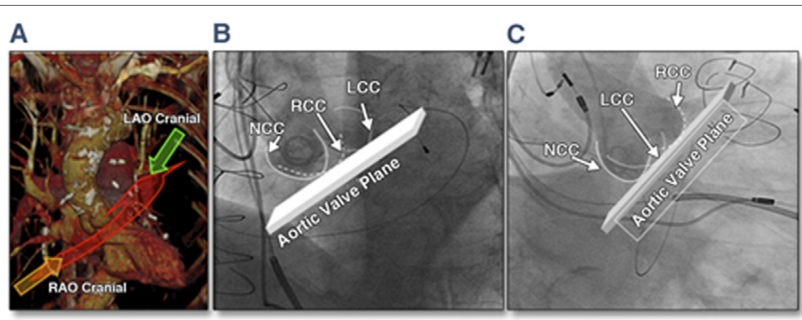

Figure 6. Determination of the Aortic Plane With Pre-Procedural Computed Tomography Scan and Angiography

(A) Three-dimensional computed tomography reconstruction demonstrating the aortic plane running from right anterior oblique (RAO) caudal to left anterior oblique (LAO) cranial angles. **(B and C)** Aortic root injection in LAO **(B)** and RAO **(C)** views demonstrates the aortic valve plane with location of each leaflet, respectively. LCC = left coronary cusp; NCC = noncoronary cusp; RCC= right coronary cusp. See Online Video 1.

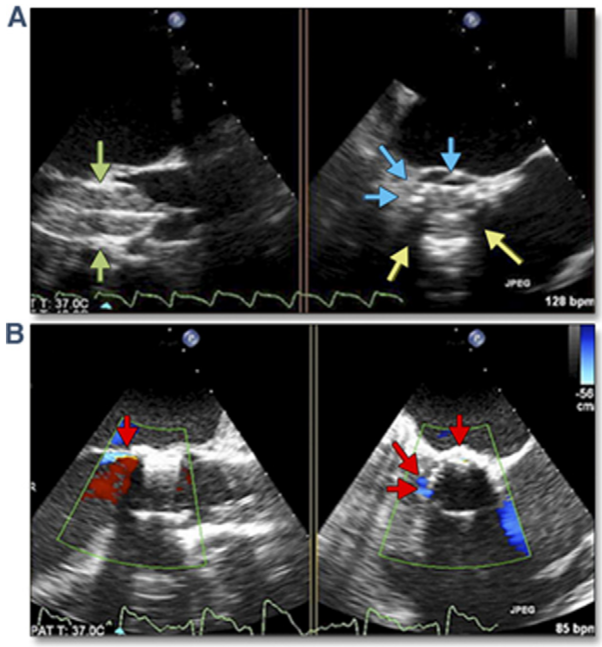

Figure 7. Transesophageal Echocardiography Biplane Imaging to Assess Annular Dimensions and Predict Aortic Regurgitation

(A) Biplane imaging during balloon inflation. The **green arrows** identify the waist of the balloon at the level of the annulus. The **blue arrow** shows asymmetric balloon dilation at the commissure between the left and non-coronary cusps. The **yellow arrows** depict acoustic shadowing, which prevents adequate visualization of the peri-balloon region (see Online Video 2 for a moving image of using balloon aortic valvuloplasty for sizing). Biplane imaging immediately after transcatheter aortic valve replacement of the case from **(A)** shows aortic regurgitation at the sites predicted during balloon aortic valvuloplasty **(red arrows)** **(B)**. See Online Video 2.

In addition to fluoroscopic visualization of balloon inflation (Online Fig. 4), injection of contrast at the time of placement is helpful to make final adjustments as necessary with slow balloon inflation and for the final confirmation of the valve position. The CoreValve (Medtronic) can be pulled up while being deployed, if it is thought to be too deep in the ventricle.

ECHOCARDIOGRAPHY. Transesophageal echocardiography provides continuous real time visualization of the annulus, valve, and balloon, thereby aiding device placement and prediction and immediate detection of AR. The desired "50-50" positioning of the SAPIEN (Edwards Lifesciences) valve within the LVOT and aortic root depends on proper identification of the hinge points of the native aortic valve leaflets and its relation to the extent of the prosthesis above or below that point. This landmark is not optimal, because the hinge points are not all at the same level within the oval-shaped annulus and at times can be difficult to visualize. Side-to-side exploration or biplane imaging might minimize some of these limitations. Experience with intracardiac echocardiography is limited.

Differentiating the valve and balloon just proximal to the valve with imaging can be difficult. To overcome this, the operator can compare the length of the stent segment by echocardiography with known stent length to confirm that the stent is identified accurately. Transesophageal echocardiography can also be used to assess whether the delivery system, including the valve, is coaxial to the LVOT. The tips of the leaflets provide another echocardiography landmark necessary to make sure that the distal end of the SAPIEN (Edwards Lifesciences) stent covers the tip of native aortic valve, although the trajectory of the delivery system in relation to the LVOT can also affect this interpretation.

Preventing, detecting, and managing AR. Transesophageal echocardiography is particularly useful in predicting and managing acute AR (1,26,27). When it is suspected that asymmetric calcification might affect final THV shape, imaging during balloon aortic valvuloplasty can be used to localize regions of asymmetric dilation and thus predict the localization of post-TAVR AR (Fig. 7) (Online Video 2).

Although minor AR is common after TAVR, moderate or severe AR is not common, occurring in 5% to 22% of cases (28,29). For both types of THVs, the most important determinants of post-TAVR AR are: undersizing of the prosthesis, the extent of calcification of the valve, and the prosthesis position in relation to the annulus (30). Studies of the SAPIEN valve (Edwards Lifesciences) (14) showed that the cover index (calculated as the difference between the prosthesis diameter and TEE annulus diameter, divided by the prosthesis diameter) is also an important predictor of post-TAVR AR. Moderate or greater AR was never observed in patients with a cover index >8% (i.e., valve diameter >8% larger than the measured annulus) (14). Valve anatomy, severity of calcification, symmetry of valve opening, as well as the angle of the LVOT/aorta have also been described by others as potential determinants of post-TAVR AR for the self-expanding valve (31).

To prevent paravalvular leak, the covered part of the prosthesis must be well-apposed to the native leaflets and interleaflet triangles. The ventricular edge of the device must be just below the hinge points of the aortic valve. If the balloon-expandable valve is placed too deep within the LV, it can potentially embolize into the ventricle but more commonly might leave native leaflets uncovered, creating leaflet overhang—which alters the hemodynamic status of THV valve closure and causes significant central AR. If the valve is placed too high within the aorta, it can potentially embolize into the aorta, resulting in coronary artery obstruction or significant paravalvular regurgitation by leaving significant portions of the valve apparatus uncovered by the stent.

Placement of a self-expanding valve too deeply into the ventricle can also cause considerable AR through the uncovered part of the prosthesis (32). Impingement and injury of the anterior leaflet of the mitral valve is also a concern for "deeply" placed valves. There is potential for paravalvular AR if 1 of the commissures is not covered by the stent due to high positioning. Alternatively, central AR can result if the stent is "flared" too much on the aortic side due to high positioning.

Immediately after valve deployment, TAVR stent positioning, shape, leaflet motion, and AR can rapidly be assessed with TEE imaging in biplane mode (Fig. 7) or a single plane short-axis view (33). For paravalvular regurgitation, the short-axis plane of imaging should be just below the TAVR stent and skirt and just within the LVOT; if the imaging plane is above the stent, regurgitation might not be visualized or color flow just above the annulus but contained within the sinuses of Valsalva might be mistaken for regurgitant jets into the LV. Confirmation of the severity of AR should always be performed from multiple echocardiographic views. The deep gastric view allows imaging of the LVOT without acoustic shadowing (Fig. 8). Imaging the entire annulus is mandatory and requires rotating 180° while centered on the valve. The severity of AR typically lessens over the next 30 min after implantation. Thus, small central or paravalvular regurgitant jets are commonly seen and do not require intervention. Patients with more than mild paravalvular regurgitation, however, could be considered for a second balloon dilation (Online Fig. 5 and Online Videos 3 and 4). In many instances, post-deployment balloon dilation results in an immediate reduction in paravalvular regurgitation.

Other TAVR implantation complications. The diagnostic considerations in a severely hypotensive patient with post-deployment cardiovascular collapse are not limited to AR, and real time multimodality imaging can detect and guide the management of many of them. The differential diagnosis includes coronary artery obstruction, pericardial tamponade, severe mitral regurgitation, aortic dissection, LV damage or perforation or rupture, and embolization of the THV (34). As such, TEE or fluoroscopy can yield the diagnosis within seconds by demonstrating a wall motion abnormality, large pericardial effusion, color flow signal of severe regurgitation, dissection of the ascending aorta or rupture of the annulus, and the location of the THV, respectively (Online Videos 5, 6, 7, and 8 for selected examples). Because of the implantation positioning of the ventricular portion of the self-expanding valve, there has been a higher reported incidence of heart block (32).

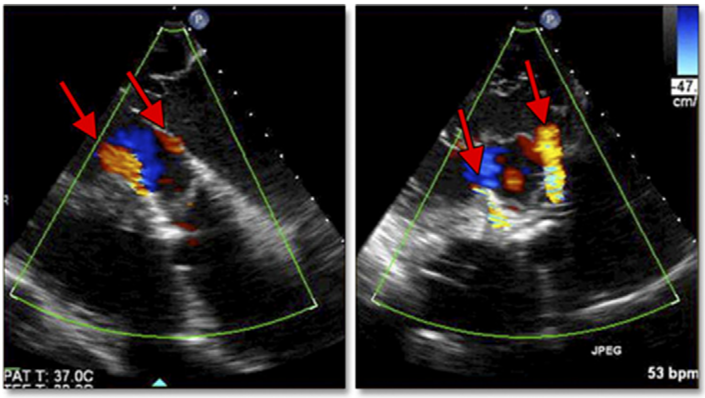

Figure 8. Deep Gastric Transesophageal Echocardiography Views to Visualize Paravalvular Aortic Regurgitation

Deep gastric transesophageal echocardiography views of post-transcatheter heart valve paravalvular aortic regurgitation **(red arrows)**. Biplane imaging or a full rotation to image 360° of the annulus are required to fully assess the type and severity of aortic regurgitation. See Online Videos 3 and 4 to see how TEE demonstrates reduction of paravalvular aortic regurgitation after a second balloon inflation.

Long-Term Follow-Up

Multimodality imaging goals. The goals of post-implantation imaging include: 1) assessment of valve hemodynamic status, including gradients and effective valve area; 2) quantification of valvular and paravalvular regurgitation; 3) determination of the effect of implantation on the disease processes related to outflow obstruction (such as LV hypertrophy, chamber remodeling, diastolic and systolic function); 4) ongoing assessment of concomitant pathology; and 5) detection of long-term complications such as device migration, thrombus formation, ventricular perforation, mitral valve impingement, and endocarditis.

Evaluation of post-implantation THV function. Echocardiography is the imaging modality of choice for long-term surveillance, because it provides substantial benefits over other techniques, including widespread availability, lack of need for ionizing radiation, and ability to image structures as well as accurately measure hemodynamic status. Furthermore, both the SAPIEN (Edwards Lifesciences) and CoreValve (Medtronic) systems have good ultrasound imaging characteristics such that a detailed assessment of position, hemodynamic status, and of the types and degrees of AR with TTE is possible without significant acoustic shadowing (35,36) (Online Videos 9 and 10).

However, MDCT and CMR are playing larger roles in the post-procedural evaluation of TAVR patients, allowing the evaluation of structural integrity, sphericity, position, aortic regurgitant volume, and post-procedural complications (5) (Online Fig. 6). These modalities also afford excellent anatomic detail, allowing for simultaneous assessment of the prosthesis and its relationship to the native valve, root, and ventricle as well as detecting pseudoaneurysms of the root or apex and other rare complications (Fig. 9 and Online Fig. 7).

EVALUATION OF MYOCARDIAL FUNCTION AND HEMODYNAMIC STATUS. Left ventricular mass regression and improvement in ejection fraction (EF) have been well-documented in patients after surgical aortic valve replacement (SAVR) for aortic stenosis (37). Similarly, in patients undergoing TAVR there are reductions in LV mass, modest improvement in EF (38), and improved diastolic function (39), and mitral regurgitation might improve (40). A recent comparison of SAVR with TAVR in patients with low EF showed a greater increase in EF in the TAVR group (41). The LV mass, size, and diastolic and systolic function should thus be followed routinely after TAVR to quantify the late effects of the hemodynamic improvement. Echocardiography is the imaging modality of choice in evaluating LV mass (42); however, LV mass by CMR also offers a highly accurate estimate (43).

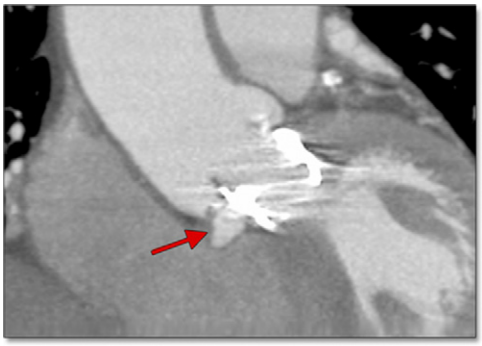

Figure 9. Pseudoaneurysm of the Aortic Root Visualized by Multi-Detector Computed Tomography

Coronal multiplanar reconstruction of the aortic root in an 89-year-old female patient 3 days after transcatheter aortic valve replacement. Difficulties with the rapid ventricular pacing were encountered, resulting in a low deployment, root injury, and a resultant pseudoaneurysm **(arrow)**. See Online Videos 5, 6, 7, and 8.

GRADIENTS, VALVE AREA, AND DIMENSIONLESS INDEX. Key metrics of prosthetic valve function include mean and peak transvalvular pressure gradients and the derived indexes of effective orifice area (EOA) and Doppler velocity index (DVI) (36). Determination of valve gradients with continuous wave Doppler is relatively straightforward, noting that suprasternal notch and right parasternal windows and imaging and nonimaging Pedoff probes should be routinely used to ensure that maximal gradients are captured. Both the SAPIEN (Edwards Lifesciences) and CoreValve (Medtronic) have excellent flow characteristics with mean gradients of 10 to 15 mm Hg (Table 4) (44,45). The 3-year results from a balloon-expandable valve (5) suggest that a small increase in mean transvalvular gradient (3.8%/year) and a small reduction in valve area (0.06 cm^2 /year) might occur over time.

Although calculations of EOA and DVI provide flow-independent indexes of valve function, they are more challenging to perform in THV than for conventional surgical prostheses because the supporting stent creates acceleration at both the level of the stent and within the stent at the level of the cusps (46) (Fig. 10). This unique flow characteristic and the potential for variability in cross-sectional area calculations make it imperative that the subvalvular velocities used in either the DVI or EOA be routinely sampled proximal to the stent. Sampling within the stent will result in an overestimation of valve area or DVI. Additionally, inconsistent sampling sites (within the stent at 1 time, below the stent at another) will result in variable valve areas that might be misinterpreted as changing valve hemodynamic status.

The projection of the stent into the LVOT can also lead to confusion as to the optimal site for measuring LVOT diameter. Because there is reduced variability and better correlation with transvalvular gradients when EOA is calculated with diameters measured immediately proximal to the stent (47), optimal assessment of EOA and DVI for the SAPIEN valve (Edwards Lifesciences) should employ velocities and diameters obtained proximal to the valve stent. The flow characteristics of the CoreValve (Medtronic) and

Table 4. Selected Published Gradients for the Edwards SAPIEN and Medtronic CoreValve Transcatheter Heart Valves

Valve and Reference #	Sample Size	Mean Gradient (mm Hg)	EOA (cm^2)	Follow-Up Period
SAPIEN Leon (1)	144	11.4 ± 7.0	1.5 ± 0.4	30 days*
	88	13.2 ± 11.2	1.6 ± 0.5	1 yr*
SAPIEN Smith (2)	287	9.9 ± 4.8	1.7 ± 0.5; (n = 279)	30 days*
	246	10.2 ± 4.3	1.6 ± 0.5; (n = 219)	1 yr*
SAPIEN Gurvitch (5)	70	10.0 (8–12)	1.7 ± 0.4	Hospital discharge
	37	12.1 (8.6–16.0)	1.4 ± 0.3	3 yrs
CoreValve Buellesfeld (44)	126	8.5 ± 4.0	NR	30 days
	126	9 ± 3.4	NR	2 yrs
CoreValve Gotzmann (45)	51	16 ± 0.5	1.96 ± 0.3	1 yr

Mean gradient is mean ± SD or interquartile range. *Core laboratory-adjudicated measurement.
EOA = effective orifice area; NR = not reported.

the optimal site for measuring LVOT diameter for this THV have not been reported.

Prosthesis-patient mismatch (P-PM) occurs when the EOA of the implanted prosthesis is too small in relation to body size, and severe P-PM is defined by an EOA $\leq$0.65 cm^2/m^2. The P-PM determines morbidity (48), LV mass regression (49), and mortality (50) after SAVR. A considerable proportion (20% to 70%) of patients have P-PM after open aortic valve replacement (30), but this seems to be less of a problem after TAVR with CoreValve (Medtronic) or SAPIEN (Edwards Lifesciences) THVs (P-PM incidences 16% to 32% and 6%, respectively) (30,51,52). Given that the experience with TAVR is still growing, the long-term imaging assessments after TAVR should include a thorough examination to document the presence or absence of P-PM to understand the potential clinical significance of P-PM in this population.

PARAVALVULAR, TRANSVALVULAR, AND TOTAL AR. Both transvalvular and paravalvular AR might be seen after TAVR, with mild or less being the most common severity found for either THV (26,28). Differences between the balloon-expandable (SAPIEN [Edwards Lifesciences]) and self-expanding valves (CoreValve [Medtronic]) have not been fully characterized; however, in 1 registry (53) there was an insignificant but higher odds ratio for significant AR with the self-expanding valve. Follow-up echocardiograms should identify the presence, location, and severity of both types of regurgitation. The optimal views for detection of regurgitant jets include the parasternal long-axis, short-axis, apical long-axis, and 5-chamber views, although—due to

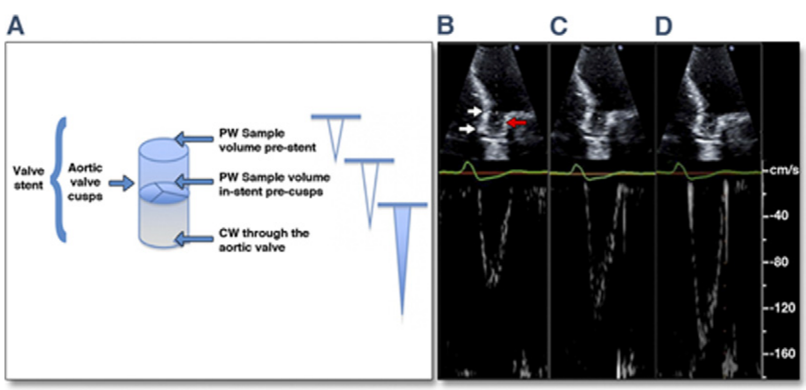

Figure 10. Schematic and Examples of Spectral Doppler Flow Acceleration in a SAPIEN Transcatheter Heart Valve

(A) Schematic presentation of echocardiographic pulse-wave (PW) Doppler patterns when the sample volume is placed pre-stent, in-stent but pre-cusps, and continuous wave (CW) through the aortic valve. Due to flow acceleration, it is imperative that the subvalvular velocities used in either Doppler velocity index or effective orifice area be sampled proximal to the stent. **(B)** The PW Doppler pattern of a sample volume placed before stent. **White arrows** show the extent of the transcatheter heart valve in the aortic root. **Red arrow** shows the level of the prosthetic aortic cusps. **(C)** The PW Doppler pattern of sample volume placed within the stent but before cusps. **(D)** The PW Doppler pattern of a sample volume placed at the level of the cusps. See Online Videos 9 and 10.

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eccentric jets—off-axis views should also be used to ensure accurate determination of the location and severity of regurgitation. Color and spectral Doppler techniques are applied in a manner similar to that of other prosthetic aortic valves (36), with determination of flow convergence, measurement of the vena contracta, and extent of regurgitation into the LV and spectral Doppler parameters such as the pressure half-time and holodiastolic flow reversal into the descending aorta. Because both types of regurgitation affect LV hemodynamic status, a summary measurement of regurgitation, or "total AR," should routinely be calculated and measured as outlined in the following text.

Significant transvalvular AR after TAVR is usually due to valvular damage during the implantation procedure, too large a prosthesis for a small annulus resulting in valve deformation, or severe calcification of the native valve leading to deformation of the frame of the THV (54). Short-axis and off-axis views can be especially helpful to characterize the origin of the jet passing through the prosthetic leaflets. With eccentric transvalvular AR jets, care should be taken to measure the vena contracta in the correct plane, because measurements of regurgitant jet width parallel to the LVOT measurement risk overestimating the degree of regurgitation. With the recent prosthetic valve guidelines, transvalvular AR should be reported as: 1) mild; 2) moderate; or 3) severe (55). Trivial or trace regurgitation might also be noted.

Paravalvular AR (or paravalvular leak, perivalvular leak, or paraprosthetic regurgitation), in contrast to transvalvular AR, is usually caused by incomplete prosthesis apposition to the native annulus due to remaining material of the native valve or ridges of calcium, too small a prosthesis for a large annulus, or too-low implantation of the valve leading to paravalvular leakage through uncovered portions of the prosthesis (54,56). Because paravalvular AR jets travel along the natural curvature of the prosthesis-annular interface, imaging in multiple planes is necessary (Fig. 11) and might be difficult to differentiate from transvalvular AR. The transthoracic short-axis view is usually the best to view the true orifice of paravalvular AR and helps to prevent the overestimation of AR severity that can occur when relying solely on apical views. With recently proposed criteria for standard endpoint definitions for TAVR clinical trials, the circumferential extent of paravalvular AR can be graded with <10% being associated with mild paravalvular AR, 10% to 20% being associated with moderate, and >20% being associated with severe AR (55) (Fig. 12). As with all AR parameters, the approximation of circumferential extent should be weighed with all other available criteria for assessing the degree of regurgitation.

The total amount of regurgitation is the most important factor with regard to the hemodynamic response to the increased volume load, which in turn might affect chamber dilation, LV function, and development of pulmonary hypertension (57). Combining information from color and spectral Doppler for both transvalvular and paravalvular AR with established grading criteria, the total AR should be part of the routine assessment after TAVR as an assessment of the total volume load. In most cases, this will be equal to the most severe degree of AR of either transvalvular or paravalvular

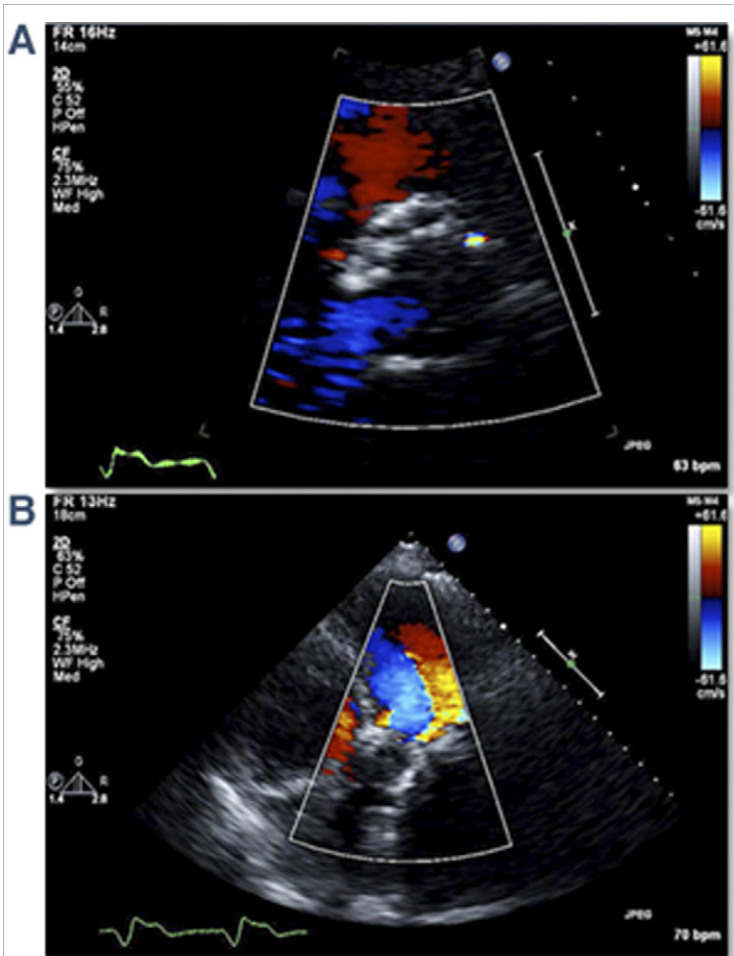

Figure 11. Severity of Aortic Regurgitation Varies in Different Echocardiographic Windows

(A) Paravalvular aortic regurgitation seems trivial in the short-axis view at the level of the aortic annulus. **(B)** Paravalvular aortic regurgitation grade is moderate in this off-axis apical 5-chamber view of the same patient.

AR. However, in some instances, the addition of the 2 flows will push the grading to the next level of severity (e.g., mild transvalvular AR plus mild-moderate paravalvular AR are graded as moderate total AR).

Quantitative assessments of regurgitant fraction and regurgitant volume can also be helpful in determining the severity of total AR (55). CMR might be a useful supplement to echocardiography and might be the modality of choice when the degree is severe or when there is discordance in grading from different echocardiographic windows (58).

Multimodality imaging research opportunities in TAVR. There is rich opportunity for research in multimodality imaging related to TAVR, especially because most work to date has been observational and limited to a single THV device. As experience develops, it follows that prospective studies should be performed to compare different imaging strategies and different THV devices. Along with this work, the trial endpoints and methodologies proposed by the Valve Academic Research Consortium (55) and/or used by TAVR core laboratories need to be validated to guide future clinical trials, observational studies, and state-of-the-art clinical practice. Finally—although substantial redundancy in imaging with multiple techniques to assess the same structures or frequently repeated tests is warranted initially—as experience grows, developing a rational algorithm for imaging use both before and after implant will become a priority.

There are also specific research opportunities at each phase of TAVR patient care. Techniques for pre-procedural assessment can be refined and employed in systematic comparisons of the accuracy of different techniques in determining parameters, such as annular dimensions and annulus to left main coronary distance (e.g., a multi-center study that randomizes patients to receive either annular sizing with MDCT or echocardiography). Assessment of the relative value of multimodality imaging findings to select the optimal THV device as well as predictors of subsequent implantation success and complications are other important areas of investigation.

Much of the utility of imaging during implantation comes from offering real time guidance of the procedure, including rapid detection of malpositioning and complications. Because of the novelty of TAVR, case reports and case series with imaging are helpful to document the range of complications and to educate less experienced implanting teams.

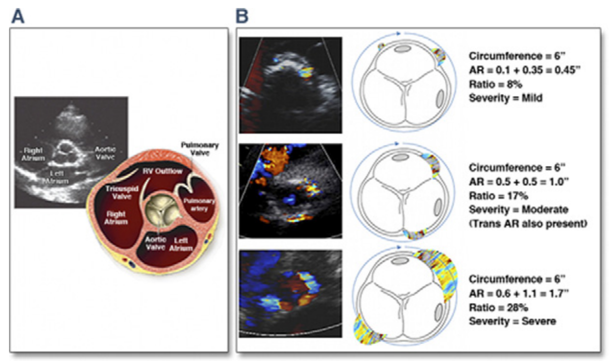

Figure 12. Grading Criteria for Paravalvular AR

(A) Schematic and illustrated representation of the short-axis view at the level of the aortic valve by echocardiography. **(B)** Echocardiographic and schematic illustrations of the short-axis view of the aortic valve. Paravalvular aortic regurgitation (AR) can be graded according to the circumferential extent of the regurgitant jet. Paravalvular AR can be graded as mild, moderate, or severe on the basis of a circumferential extent of <10%, 10% to 20%, or >20%, respectively. See Leon et al. (55). RV, right ventricle. Image credit: CC Patrick J. Lynch and C. Carl Jaffe, Yale University, 2006.

The post-implantation THV assessments detailed here reflect expert consensus, and their utility should be validated by comparison with other techniques and long-term outcomes. This is particularly true for quantitative assessments of paravalvular, transvalvular, and total AR—which might differ slightly between devices—and the impact of total AR on long-term cardiac structure, function, and clinical outcomes. With regard to AR, more specific, reproducible, and quantitative criteria need to be developed. Comparison of regurgitant volumes obtained by 2D and 3D TTE and TEE, quantitative Doppler, and CMR as well as consideration of invasive and hemodynamic correlates will be informative and might refine the perceived significance of this complication. The long-term clinical impact of relief of pressure overload on regression of LV hypertrophy, chamber remodeling, diastolic and systolic function, mitral regurgitation, and other compensatory or concomitant cardiac abnormalities needs to be more fully characterized, compared across THVs and with SAVR, and related to functional status and outcome. In a similar way, detection and quantification of P-PM and its frequency and implications is an important and rich area for future investigation.

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Key Words: imaging ■ multimodality ■ transcatheter aortic valve replacement.

APPENDIX

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