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The Role of Multimodality Imaging in Transcatheter Aortic Valve Replacement

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Abstract

Purpose of Review Multimodality imaging is integral for diagnosis, procedural guidance, and follow-up of patients undergoing transcatheter aortic valve replacement (TAVR). In this review, we provide an overview of the role of each imaging modality and highlight technical considerations and pitfalls. We also address current controversies and new developments in the field.

Recent Findings Echocardiography remains the primary imaging modality for diagnosis of aortic stenosis and intraprocedural guidance for TAVR, but computed tomography (CT) imaging has supplanted echocardiography for annular sizing and access site evaluation. Magnetic resonance imaging (MRI) shows promise in targeted patient populations. Refined parameters and guidelines for valve sizing and paravalvular regurgitation have sought to standardize these complex assessments.

Summary Multimodality imaging remains critical to the success of TAVR, but its role has evolved over time. Understanding the applications, strengths, and limitations of each imaging modality is a crucial skill for the modern structural imager.

Keywords TAVR · Transcatheter aortic valve replacement · Multimodality imaging · Echocardiography · Computed tomography

Abbreviations

3D	Three-dimensional
AS	Aortic stenosis
AVA	Aortic valve area
AVR	Aortic valve replacement
CT	Computed tomography
CW	Continuous wave
DVI	Doppler velocity index
LFLG	Low-flow low-gradient
LVEF	Left ventricular ejection fraction
LVOT	Left ventricular outflow tract
MPR	Multiplanar reconstruction
MRI	Magnetic resonance imaging
MSCT	Multislice computed tomography
PARTNER	Placement of AoRTic TraNscathetER Valve
PET	Positron emission tomography
PVL	Paravalvular leak
PW	Pulse wave
TAVR	Transcatheter aortic valve replacement
TTE	Transthoracic echocardiography
TTR	Transthyretin
TEE	Transesophageal echocardiography
VTI	Velocity time integral

This article is part of the Topical Collection on *Echocardiography*

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Introduction

Transcatheter aortic valve replacement (TAVR) has been one of the most revolutionary cardiovascular procedures in the past decade, effectively changing the landscape of treatment for patients with aortic stenosis (AS). Since the initial Placement of AoRTic TraNscathetER Valve (PARTNER) trials in inoperable and high-risk patients [1, 2], subsequent studies have continued to expand indications for TAVR to lower risk populations. With the recent publication of the PARTNER 3 and Evolut Low Risk trials [3••, 4••], TAVR now appears to be a viable alternative to surgery in the vast majority of patients with symptomatic severe aortic stenosis. As the target patient population expands, multimodality imaging continues to play a pivotal role in selecting and stratifying appropriate patients,

monitoring procedural success, and following patients after the procedure. In this paper, we review the current data and practice patterns for use of multimodality imaging in the comprehensive evaluation of patients with aortic stenosis (AS), focusing primarily on transthoracic echocardiography (TTE), transesophageal echocardiography (TEE), and multislice computed tomography (MSCT). In addition, we will address some of the current imaging controversies surrounding TAVR and future directions in the field.

Preprocedural Imaging

Diagnosing Aortic Stenosis

The 2014 ACC/AHA valvular heart disease guidelines [5] divide specific valvular diseases into stages with stage D including symptomatic patients with severe disease. Class I indications for TAVR include patients with severe symptomatic high-gradient AS (stage D1) with prohibitive or high surgical risk and asymptomatic patients with high gradients and left ventricular ejection fraction (LVEF) < 50% (stage C2). In addition, there are class IIa indications for aortic valve replacement in patients with severe low-flow low-gradient (stage D2) and paradoxical low-flow low-gradient aortic stenosis (stage D3), and the 2017 focused update [6] included a class IIa indication for high-gradient symptomatic patients with intermediate surgical risk. Clinical assessment and imaging should therefore classify whether a patient falls into one of these established benefit groups.

Transthoracic Echocardiography

TTE is the most important modality for establishing the diagnosis of severe AS [5]. However, accurate diagnosis is dependent on careful image acquisition and methodical measurement of anatomic dimensions and Doppler signals [7]. Echocardiographic criteria for severe high-gradient AS include the following parameters: peak velocity > 4 m/s, mean gradient > 40 mmHg, and aortic valve area (AVA) by continuity equation < 1.0 cm^2. Each of these components has a potential for error, commonly leading to underestimation of AS severity.

The largest source of error in assessment of AS severity is usually in the measurement of the left ventricular outflow tract (LVOT) diameter, as any error in measurement is squared in the continuity equation. Despite some disagreement as to the exact location of the measurement [8], multiple studies have related echocardiographic AVA obtained using a linear LVOT measurement to clinical outcomes [9–11]. With more widespread use of three-dimensional (3D) echocardiography and MSCT, the shape of the LVOT has been characterized as more elliptical, with the smaller dimension in the sagittal plane, leading many authors to attempt more "accurate" measurements of the LVOT using direct planimetry [12–15]. While these methods have been shown to be reproducible, use of these measures has not been shown to improve correlation with transvalvular gradient or concordance between gradients and AVA. Clavel et al. showed that because AVA using MSCT is larger than AVA by echo, a higher cut-point should be used for severe AS using the CT method (< 1.2 cm^2) compared with the echo method (< 1.0 cm^2) to predict similar long-term survival [10].

In order to improve reproducibility and accuracy of LVOT diameter measurements (Fig. 1), the following techniques should be used [8]:

- LVOT diameter should be measured in early to midsystole from the image that produces the largest diameter. This image typically slices through the commissure between the left and noncoronary cusps.
- LVOT diameter should be measured from inner edge to inner edge, excluding any ectopic calcium from the LVOT border. Ectopic calcium is often seen anterior to the A2 scallop of the mitral valve and can lead to significant underestimation of LVOT diameter if included.
- Guidelines recommend measuring the LVOT diameter 0.5–1.0 cm below the level of the aortic annulus. However, especially in the cases of significant septal hypertrophy, the LVOT diameter should be measured at the level of the aortic annulus to avoid underestimation.

Measurement of Doppler velocities plays another important role in grading severity of AS, and standardized acquisition of Doppler signals is important to help minimize error (Fig. 2).

- Continuous wave (CW) Doppler velocities should be measured in multiple views, including the right parasternal view, and nonimaging transducers should be used to obtain the highest possible gradient. Failure to use nonapical windows led to misclassification of AS severity in 23% of patients [16]. One study noted that patients with a more acute left ventricular-aortic root angle measured in the parasternal long-axis view were more likely to have the highest gradient recorded from a nonapical window [17].
- Flow through the vena contracta should be as parallel as possible to the ultrasound beam.
- The LVOT pulse wave (PW) Doppler region should be placed just proximal to flow acceleration so that no opening or closure clicks are seen. Gain should be reduced to show the modal velocity.

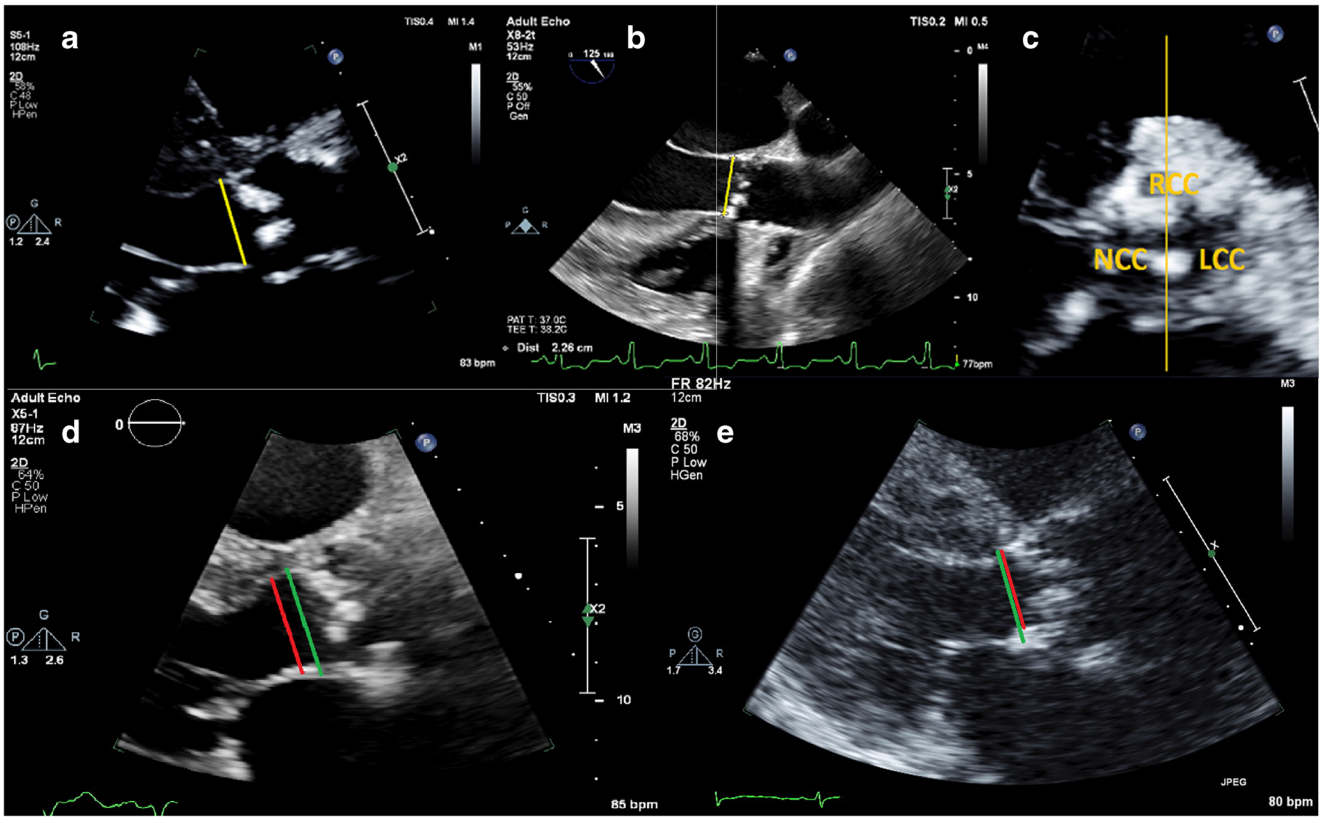

Fig. 1 Optimal measurement of LVOT diameter is shown on TTE (**a**) and TEE (**b**). On biplane imaging (**c**), the image frame can be confirmed to cut through the right coronary cusp and commissure between the left and noncoronary cusps. The maximal LVOT diameter can then be measured from inner edge to inner edge at or just below the level of the aortic annulus. In the setting of septal hypertrophy, the LVOT significantly narrows within the left ventricular cavity, and the optimal measurement should therefore be taken at the level of the aortic annulus (**d**). Ectopic calcification is also commonly seen at the base of the anterior mitral leaflet extending into the LVOT. The correct LVOT measurement should exclude this calcification (**e**)

Finally, both two-dimensional and three-dimensional planimetry have been validated as adjunctive measures of aortic stenosis severity, although severe aortic valve calcification has been correlated with worse performance of planimetry [18], likely due to incomplete visualization of the orifice due to shadowing. 2D planimetry may be useful if biplane imaging confirms that the measurement is taken at the leaflet tips, while multiplanar reconstruction (MPR) can be used to align the measurement at the leaflet tips for 3D planimetry.

TTE is also useful for identifying specific subgroups that may derive less benefit from TAVR, such as patients with cardiac amyloidosis. Several studies have cited a prevalence of transthyretin (TTR) amyloidosis ranging from 6 to 16% in the calcific AS population [19, 20]. Retrospective analyses suggest that the prognosis of these patients is driven more by their underlying TTR amyloidosis than by severe aortic stenosis [21], although further prospective investigation is needed. The average of the septal and lateral mitral annular tissue Doppler S' has been suggested as a sensitive and specific measure for the presence of TTR amyloidosis [19], but other more established echocardiographic measures such as strain may also be useful to further define this patient population [22].

Stress Echocardiography

The role of stress echocardiography in evaluation of patients with aortic stenosis falls into two categories: exercise testing for assessment of symptoms in patients who have "asymptomatic" severe AS (stage C) and dobutamine echocardiography for determination of AS severity and contractile reserve in patients with severe low-flow low-gradient AS (stage D2) [23].

While exercise stress testing is contraindicated in patients with severe AS and definite or probable symptoms, a significant proportion of patients deny clinical symptoms at the time of initial diagnosis. Patients who are asymptomatic generally have a better prognosis, although up to 75% still die or undergo aortic valve replacement (AVR) at 5 years [24]. Symptom-limited exercise testing can be utilized to help risk stratify these patients. Exercise testing can also identify a limited

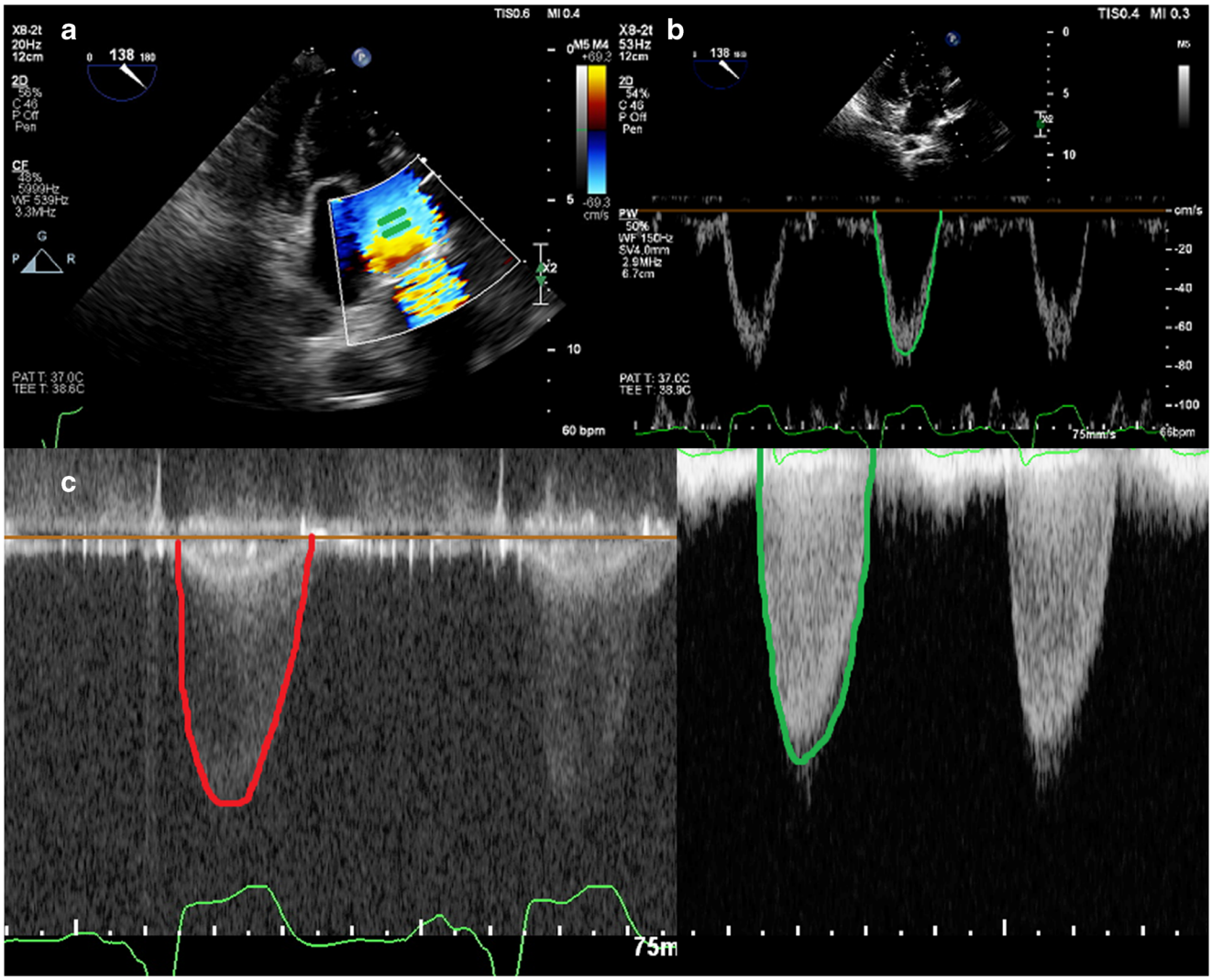

Fig. 2 Optimal acquisition of Doppler signals is shown. The pulse wave Doppler sample volume should be placed just outside the region of flow acceleration, which can be well delineated by color Doppler (**a**). Placing the sample volume within this region leads to significant overestimation of the LVOT VTI. Gains should be optimized to clearly visualize the modal velocity and reduce spectral broadening (**b**). For continuous wave Doppler, an on-axis signal that cuts through the vena contracta should yield a dense, relatively uniform spectral profile (**c**)

exercise capacity, arrhythmia, or an abnormal hemodynamic response (e.g., hypotension or failure to increase blood pressure with exercise). Multiple studies have suggested that patients with AS who manifest symptoms, have an abnormal BP response (< 20 mmHg increase), or develop ST segment abnormalities with exercise have poor outcomes [24]. Other markers of poor outcome on stress echocardiography include increase in mean aortic pressure gradient by ≥ 18–20 mmHg [25, 26], a decrease or no change in LVEF suggesting subclinical LV dysfunction) [27, 28], and induced pulmonary hypertension (systolic pulmonary artery pressure > 60 mmHg) [29].

Dobutamine stress echocardiography is used to evaluate the severity of AS and contractile reserve in low-flow low-gradient (LFLG) AS. The protocol for dobutamine stress echocardiography for evaluation of AS severity in the setting of LV dysfunction uses a low-dose protocol, starting at 2.5 or 5 mcg/kg/min with an incremental increase in the infusion every 3–5 min to a maximum dose of 10–20 mcg/kg/min [23]. Medical supervision is advised, given the risk of hemodynamically significant arrhythmia and high doses of dobutamine should be avoided. The infusion should be stopped as soon as a positive result is obtained (adequate contractile reserve defined as a > 20% increase in SV from baseline, an increase in AS jet velocity ≥ 4.0 m/s, or a mean gradient ≥ 30–40 mmHg) or when the heart rate begins to rise more than 10–20 bpm over baseline or exceeds 100 bpm, on the assumption that the maximum inotropic effect has been attained. Criteria for true-severe AS during dobutamine stress echocardiography include a mean pressure gradient ≥ 40 mmHg or peak aortic jet velocity ≥ 4 m/s with an AVA < 1.0 cm^2. Pseudo-severe AS is typically defined as a peak stress mean pressure gradient < 40 mmHg and a peak stress AVA >

1.0 cm^2. In the setting of persistent mean gradient and calculated AVA discordance, failure to achieve a normal flow rate (Q) (i.e., 250 ml/s) may be the reason. In these cases, a projected AVA can be calculated by measuring the slope of the regression line between AVA and flow rate and extrapolating to a standardized flow rate [30, 31]. Prior studies have shown that patients without contractile reserve have a higher operative mortality [32]. However, more recent data in the TAVR era have shown robust increases in LV function and similar clinical outcomes regardless of contractile reserve [33, 34], so this parameter should not be used in isolation to determine candidacy for TAVR.

Transesophageal Echocardiography

While transesophageal echocardiography is not part of the routine evaluation for patients with severe AS, it does have utility in specific cases. In patients with limited windows on TTE or when there is uncertainty regarding the diagnosis of severe AS, TEE can be used to obtain an accurate diagnosis. With adequate deep gastric views, gradients across the aortic valve and PW Doppler of the LVOT can be reliably obtained in the vast majority of patients. In addition, 2D and 3D planimetry can be effectively utilized to directly measure the AVA.

For aortic annular sizing, TEE measurements have been well validated and typically correspond well to CT measurements [35]. Therefore, patients with a contraindication to contrast CT, poor quality CT imaging, or borderline annular size should undergo preprocedural or intraprocedural TEE to verify annular sizing and select the correct valve size.

Computed Tomography

Computed tomography imaging has grown to become an integral component of preprocedural planning for TAVR, and CT angiography of the chest, abdomen, and pelvis is now part of the standard evaluation for most patients undergoing TAVR [36]. The most important use of preprocedural CT is measurement of the aortic annulus for accurate prosthesis sizing. Retrospective ECG-gated MDCT has become the gold standard for aortic annular measurement, and use of a CT-based annular sizing algorithm has been shown to significantly reduce the incidence of more than mild paravalvular regurgitation [37].

Technical aspects of aortic annular measurement are extensively described in a recent consensus statement from the Society of Cardiovascular CT [38••]. The annular plane is defined as the plane that slices through the basal hinge points of all three aortic valve cusps. Identification of the annular plane can be performed using manual multiplanar reformats or with semiautomated software. The aortic annulus has been shown to be dynamic throughout the cardiac cycle and is typically at its largest and most circular in systole. Once the systolic frame with the largest annular area and best image quality to identify the annular contour is selected, a manual or automated contour-based tracing of the aortic annulus can be obtained (Fig. 3). Measurements of the annular area, perimeter, and maximum and minimum dimensions are then reported.

CT has also been used to further delineate regional anatomy and determine risk of complications. Size of the sinuses of Valsalva and sinotubular junction, as well distance from the aortic annulus to the coronary ostia, can also be reliably measured [39], and these parameters have correlated with risk of aortic root injury and coronary artery occlusion. Device landing zone calcification has also been shown to correlate with risk of paravalvular regurgitation and potentially permanent pacemaker implantation [40–42]. Finally, especially for the balloon-expandable Edwards SAPIEN valve series, it is important to determine a fluoroscopic angulation that visualizes all three cusps of the aortic valve in an orthogonal plane, typically with the right coronary cusp in the center. In these cases, preprocedural CT has been effectively utilized to predict the correct fluoroscopic angulation [43].

A contrast CT also provides important information about the size and calcification of the peripheral vasculature. Transfemoral access remains the preferred method of transcatheter aortic valve deployment, and data from PARTNER have shown increased complications and increased mortality with transapical placement [44]. However, in patients with severely calcified or very small peripheral arteries, risk of vascular access complications increases dramatically. In one study, arterial lumen diameter that is smaller than the size of the access sheath was associated with increases in both vascular access complications and 30-day mortality [45]. In the cases of borderline transfemoral access, CT can also help evaluate the suitability of alternative access sites (subclavian, transaortic, transapical), so an informed decision can be made regarding the best choice of access.

Intraprocedural Guidance

While TEE was initially the default modality, recent studies have supported more routine use of TTE in selected patient populations [46–48]. There are potential advantages in decreased procedural time with TTE, and patients forego the risk of general anesthesia, which is especially important in patients with difficult airways or chronic lung disease [49]. However, real-time imaging with TEE provides improved visualization and has been associated with lower fluoroscopy times and reduced incidence of acute kidney injury [50]. Therefore, while recent practice has trended towards a minimalist approach in TAVR, selection of TTE or TEE for TAVR should be made on an individual basis after taking into account

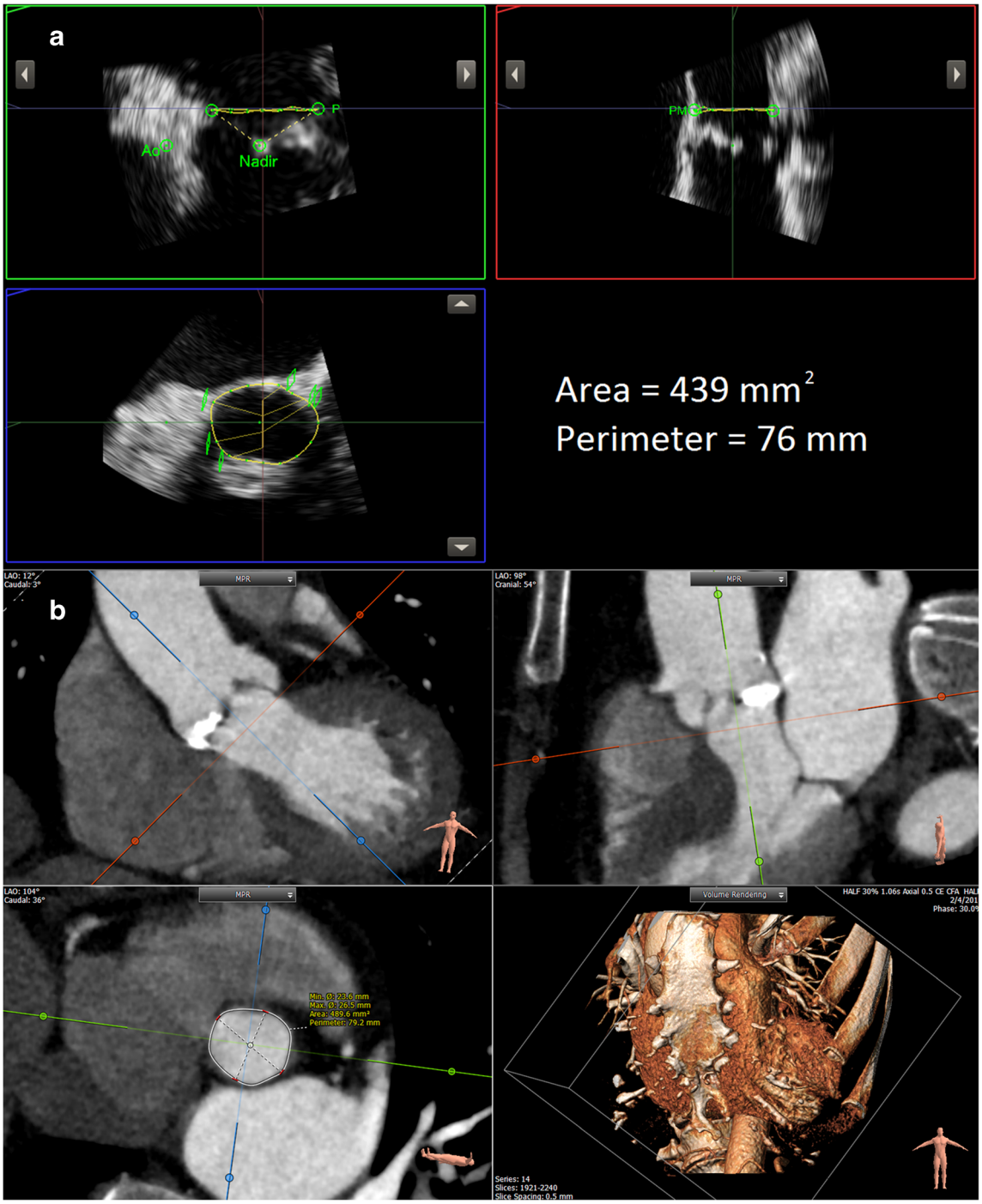

Fig. 3 Measurement of the aortic annulus by TEE can be performed using either direct planimetry or semiautomated indirect planimetry (**a**). Care should be taken to acquire an image without significant shadowing of the annulus and optimize gains to clearly visualize the blood-tissue interface. CT annular measurements are performed by aligning the MPR along oblique projections following the trajectory of the ascending aorta in the coronal and sagittal planes (**b**). The perpendicular plane is lowered to the level of the annulus for direct measurement

patient and procedural factors. In patients who are at high risk for complications such as annular rupture [51] or left main occlusion [52], TEE imaging may be beneficial [53••].

Fusion imaging has been a promising technology for guidance of complex structural interventions. Both CT and TEE fusion provide 3D anatomic data and allow the operator to accurately localize the position of the aortic annulus and sinuses [54, 55]. However, while this may improve guidance of valve positioning intraoperatively, increased operator experience and relatively forgiving positioning with newer valve designs has made fusion imaging unnecessary in the vast majority of TAVR cases.

Transthoracic and Transesophageal Echocardiography

The two most common valve types currently being utilized for TAVR are balloon-expandable (SAPIEN, SAPIEN XT, SAPIEN 3, S3 Ultra) and self-expanding (CoreValve, Evolut R, Evolut Pro) valves. Sizing and expected hemodynamics of each valve are summarized in Table 1. The ideal sizing range for each valve is determined by the percent oversizing, as calculated by (nominal THV area / native annular area − 1) × 100.

SAPIEN valves are bovine pericardial valves mounted on a cobalt chromium frame with a fabric skirt. The SAPIEN 3 valve includes an additional outer fabric sealing skirt to reduce paravalvular leak (PVL). For SAPIEN 3 valves, percent

Table 1 Valve sizing and expected hemodynamics for self-expanding and balloon-expandable valves

Valve Type	CoreValve				Evolut R / Pro			Evolut R
Size (mm)	23	26	29	31	23	26	29	34
CT Annular Diameter (mm)*	18-20	20-23	23-27	26-29	18-20	20-23	23-26	26-30
Perimeter (mm)*	56.5-62.8	62.8-72.3	72.3-81.7	81.7-91.1	56.5-62.8	62.8-72.3	72.3-81.7	81.7-94.2
Effective orifice area (cm^2)†	1.12 ± 0.36	1.74 ± 0.49	1.97 ± 0.53	2.15 ± 0.72	1.09 ± 0.26	1.69 ± 0.40	1.97 ± 0.54	2.60 ± 0.75
Mean gradient (mmHg) †	14.43 ± 5.72	8.27 ± 3.82	8.85 ± 4.17	9.55 ± 3.44	14.97 ± 7.15	7.53 ± 2.65	7.85 ± 3.08	6.30 ± 3.23
Doppler velocity index†	0.44 ± 0.09	0.59 ± 0.15	0.54 ± 0.12	0.49 ± 0.12	0.42 ± 0.04	0.61 ± 0.13	0.59 ± 0.14	0.59 ± 0.15
Valve Type	Sapien XT			Sapien 3				
Size (mm)	23	26	29	20	23	26	29	
TEE Annular diameter (mm) *	18-22	21-25	24-27	16-19	18-22	21-25	24-28	
CT Derived Area (mm^2) *	314-415	415-530	530-660	273-345	338-430	430-546	540-683	
Effective orifice area (cm^2)†	1.41 ± 0.30	1.74 ± 0.42	2.06 ± 0.52	1.22 ± 0.22	1.45 ± 0.26	1.74 ± 0.35	1.89 ± 0.37	
Mean gradient (mmHg)†	10.41 ± 3.74	9.24 ± 3.57	8.36 ± 3.14	16.23 ± 5.01	12.79 ± 4.65	10.59 ± 3.88	9.28 ± 3.16	
Doppler velocity index†	0.52 ± 0.10	0.54 ± 0.11	0.53 ± 0.11	0.42 ± 0.07	0.43 ± 0.08	0.43 ± 0.09	0.40 ± 0.09	

Modified from Hahn RT et al. JACC Cardiovasc Imaging. 2019;12(1):25–34, with permission from Elsevier [56••]

*Valve sizing is taken from FDA instructions for use

† Transthoracic echocardiographic Doppler-derived hemodynamic data

oversizing should be between − 5 and 20%, as > 20% oversizing has been associated with an increased risk of annular rupture [51]. During deployment, the ideal final position of the inflow edge of the valve should be approximately 2 mm below the level of the annulus.

CoreValves are porcine pericardial valves mounted on a self-expanding nitinol frame. The lower 12 mm of the valve is covered by a pericardial sealing skirt with an external pericardial wrap added in the Evolut Pro series to reduce PVL. The valve is partially recapturable and sits in a supraannular position. Optimal sizing is typically based on a perimeter oversizing of 10–15%. During deployment, the inflow edge of the valve should sit at most 4 mm below the level of the annulus to reduce the risk of pacemaker implantation.

During the procedure and immediately postimplantation, the primary role of echocardiography should be to assess for complications along each step. Adequate preprocedural planning can help to identify patients at high risk of complications, such as those with low takeoff of the left main coronary artery or bulky annular calcification. In these cases, communication between the echocardiographer and the interventionalist is important to anticipate critical portions of the procedure and utilize all available tools to minimize risk.

- Confirm placement of the pacing wire in the right ventricle and assess for pericardial effusion that may suggest perforation.
- Confirm placement and stability of stiff wire in the apex of the left ventricle. Evaluate for pericardial effusion (perforation) and worsening mitral regurgitation (entanglement in mitral apparatus).
- During and after balloon valvuloplasty, assess leaflet mobility and severity of aortic regurgitation. With real-time TEE imaging, appropriateness of sizing can also be evaluated.
- Ensure appropriate predeployment position of the transcatheter valve (Fig. 4).
- During deployment of the valve, real-time TEE imaging can be used to confirm valve position during rapid ventricular pacing and visualize motion of calcium to ensure adequate but safe balloon expansion and reduce the risk of coronary obstruction or annular rupture.

Immediately after deployment, a rapid assessment should be performed to assess for complications that may require urgent or emergent intervention.

- Assess for pericardial effusion and tamponade, especially in the setting of hypotension.
- Evaluate for global and regional left ventricular wall motion abnormalities. With TEE imaging, color Doppler can be used to assess flow in the coronary arteries, and the coronary ostia can be directly visualized.
- Examine the aortic root and ascending aorta for signs of hematoma, dissection, or rupture.
- Evaluate severity of mitral regurgitation to assess for valvular perforation or tethering of mitral valve leaflets by the TAVR valve.
- Assess position and adequate expansion of the valve.
- Evaluate for paravalvular regurgitation. Prior studies have shown that moderate or severe paravalvular regurgitation is a strong predictor of increased mortality [57]. Technical details are further discussed below.
- Determine valve hemodynamics using spectral Doppler. Technical details are further discussed below.

Postprocedure Follow-Up

Postprocedural follow-up imaging focuses on identifying structural valve deterioration and assessing severity of paravalvular regurgitation. Since TAVR is a relatively new technology, one big question that has yet to be definitively answered is the durability of TAVR valves. The 5-year echocardiographic follow-up to the PARTNER trial showed relative stability of mean gradient, effective orifice area, and Doppler velocity index [58]. However, surgical literature on bioprosthetic valve durability has shown an increase in prosthesis degeneration in the 10- to 15-year timeframe [59, 60], so long-term follow-up studies will be important.

Transthoracic Echocardiography

TTE is the primary imaging modality for postprocedural assessment of valve function and paravalvular regurgitation. The structure of the valve should be evaluated on standard 2D and 3D imaging. The valve should be well seated approximately 1–2 mm below the annulus for a balloon-expandable valve and within 4 mm below the annulus for a self-expanding valve. A well-expanded valve should be circular in cross section, and leaflets should be mobile without significant pinwheeling.

Doppler assessment should be used to calculate the aortic valve area and compare with reference ranges for the specific implanted valve type [56••]. By convention, the LVOT diameter should be measured from outer to outer stent frame, as this has been shown to correlate best with mean gradients [61]. However, one study notes that using preimplantation LVOT diameter yields comparable aortic valve area compared with planimetry [62]. The PW sample volume for measurement of the LVOT VTI should be placed just apical to the proximal edge of the stent to avoid flow acceleration within the stent. Finally, the CW across the valve should be angulated to be as

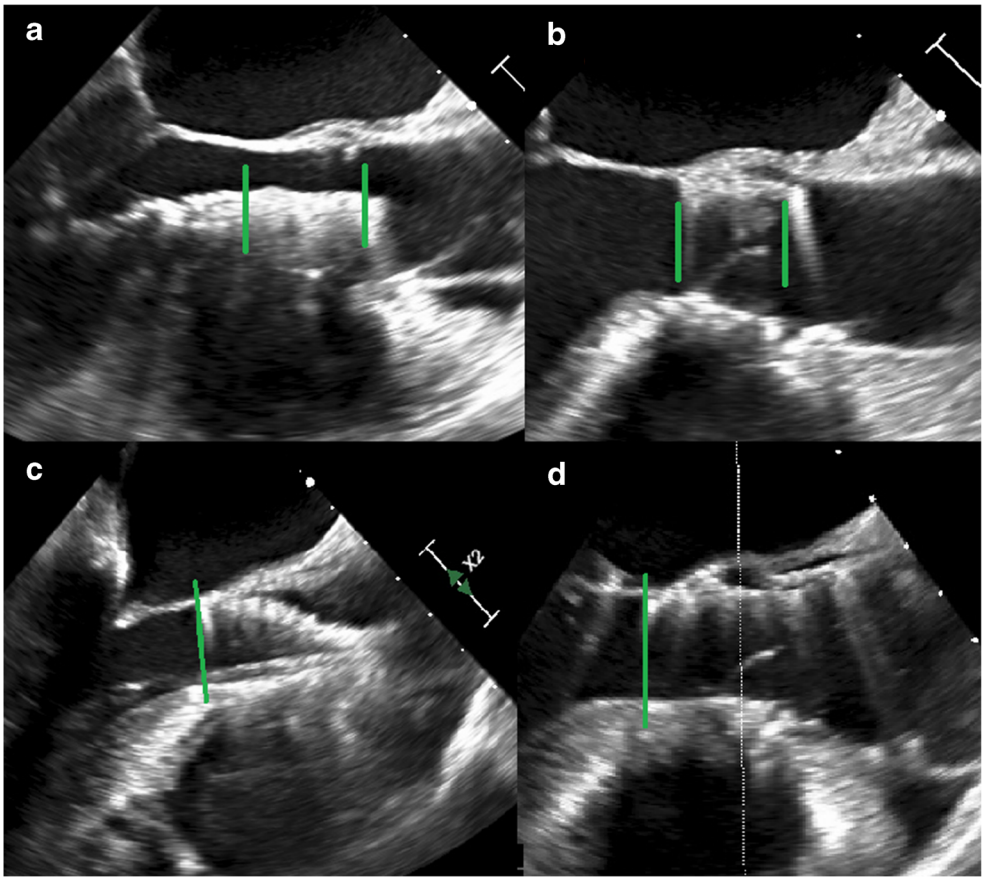

Fig. 4 Optimal positioning during real-time TEE-guided deployment is shown for balloon-expandable (**a**) and self-expanding (**c**) valves. The final position of the ventricular edge should be 1–2 mm below the annulus for balloon-expandable valves (**b**) and 3–5 mm below the annulus for self-expanding valves (**d**)

parallel as possible to flow across the valve. The Doppler velocity index (DVI) should typically be > 0.45 [63].

Assessment for paravalvular leak (PVL) should also be performed with TTE, with referral for TEE in cases where more detailed imaging is necessary. PVL after TAVR can be very complex, and comprehensive assessment requires integration of multiple echocardiographic parameters [64, 65••]. Depth of prosthesis implantation and stent and leaflet morphology should always be evaluated, as these are frequently abnormal in patients with severe PVL. Using color Doppler, regurgitant jets are often eccentric, and some color flow jets are localized entirely within the stent frame and do not represent true regurgitation. Multiple views must be utilized in combination with dynamic movement of the ultrasound probe to accurately localize the PVL jet **(**Fig. 5**)**. The general location of PVL is described on a short axis view of the aortic valve using a clock face, with the tricuspid valve at 9 o'clock. On this view, it is important to scan through the entire valve and into the LVOT in order to trace complex jets of PVL down to their site of exit. Longitudinal cuts of the prosthesis can be obtained at various trajectories around the clock face using the parasternal long-axis (5 to 7 o'clock, 11 to 1 o'clock), apical 5-chamber (3 to 5 o'clock, 8 to 10 o'clock), and apical 3-chamber (6 to 8 o'clock, 12 to 2 o'clock) views. Qualitative and quantitative methods can then be applied to further characterize the severity of PVL. Cutoffs for severe are shown below in parentheses.

- 3D vena contracta area of the regurgitant jet (≥ 0.30 cm^2) can be performed using direct 3D planimetry. Low frame rates and blooming artifact can make precise measurement difficult, and with very eccentric jets or shadowing from the prosthesis, the exact vena contracta can be difficult to localize.
- Regurgitant volume (> 60 ml) and regurgitant fraction (≥ 50%) can be assessed by quantitative Doppler. Determination of LV stroke volume is reliant on accurate measurement of the LVOT diameter from outer edge to outer edge of the stent and positioning of the pulse wave sample volume just apical to the stent. Systemic stroke volume can be assessed using either mitral inflow, RV outflow, or LV volumetric measurements.
- Circumferential extent of color Doppler jet (≥ 30% of the entire clock face) is measured on a short axis image of the aortic valve at the level of the vena contracta.
- Pressure halftime (typically < 200 ms) can be less reliable in this population, as it is affected by compliance of the

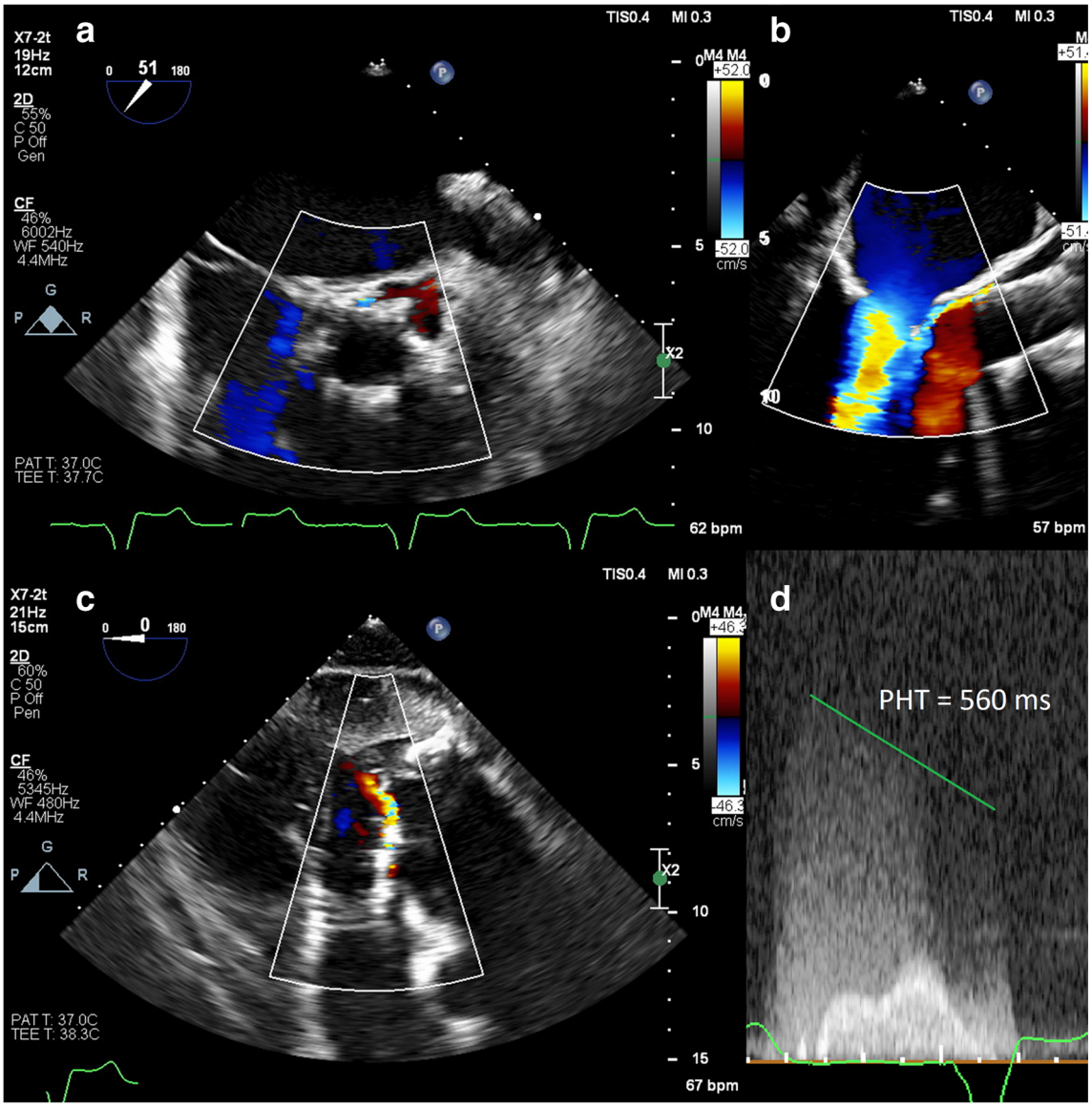

Fig. 5 Paravalvular regurgitation should be evaluated from multiple imaging planes. The short axis view (**a**) is often useful for assessing the extent and location of a paravalvular jet, although care should be taken to sweep from the level of the valve into the LVOT to ensure that visualized color jets exit the valve. Long-axis (**b**) and transgastric (**c**) views can track the course of complex jets and confirm the exact exit site. These views are often well aligned to obtain hemodynamic parameters such as pressure halftime (**d**)

aorta and left ventricle, both of which are often very abnormal in patients with severe aortic stenosis [66]. Routine use of pressure halftime is thus discouraged in this patient population.

- Vena contracta width on 2D (> 0.6 cm).
- Flow reversal in the descending aorta (typically holodiastolic with end-diastolic velocity ≥ 20 cm/s), also less reliable in this elderly population.

Transesophageal Echocardiography

Transesophageal echocardiography in the postprocedural follow-up period has been primarily utilized for assessment of dysfunctional valves on transthoracic imaging. Specifically, concern for significant paravalvular regurgitation or leaflet dysfunction that is incompletely visualized on TTE warrants further assessment by TEE. Accurate assessment of the location, extent, severity, and mechanism of PVL is critical for planning an optimal treatment strategy. PVL due to valve underexpansion or recoil can be treated with balloon valvuloplasty or valve-in-valve TAVR, while high or low valve placement necessitates deployment of a new valve. In contrast, focal areas of PVL are better addressed with vascular plugs, and sizing and localizing the defect will help guide the interventionalist to optimize procedural success.

Computed Tomography

CT can be useful for evaluation of structural deterioration of TAVR valves. One specific issue that has received significant attention in the TAVR literature is subclinical prosthetic leaflet thrombosis. The initial data came from a patient in the PORTICO IDE study and the RESOLVE and SAVORY registries, where CT was part of the standard postprocedural imaging protocol. In this cohort, upwards of 40% of patients were found to have reduced leaflet motion, and this finding was associated with subclinical thrombosis of the corresponding leaflet, often at the base [67]. Anticoagulants may have a protective effect, but a portion of these cases have regressed even without therapeutic anticoagulation [68]. When leaflet thrombosis is suspected, multimodality imaging is critical in the timely evaluation and accurate diagnosis of this phenomenon.

Cardiac Magnetic Resonance Imaging

Cardiac MRI has several advantages compared with echocardiography for assessment of paravalvular regurgitation. Measurements of left ventricular volumes and quantitation of function are more accurate and reproducible, allowing for more reliable volumetric analysis of PVL regardless of the number and complexity of individual PVL jets [69, 70]. Phase-contrast imaging can be used to visualize individual paravalvular jets, but this technique is often limited by susceptibility artifact from the stent frame and can miss very eccentric jets entirely. Currently, volumetric analysis with MRI can be utilized when there is discordance between clinical presentation and echocardiographic analysis to help answer the question of whether PVL is significant, as MRI-based assessment of PVL may have better prognostic value [71].

Future Directions

As indications for TAVR expand, the target population is set to drastically increase with the pending inclusion of low-risk patients with severe aortic stenosis. Trials such as TAVR UNLOAD are also exploring whether patients with heart failure and at least moderate aortic stenosis may benefit substantially from the procedure [72]. Imaging will continue to play an integral part in the evaluation, guidance, and follow-up of TAVR procedures, but as operators become increasingly proficient with the procedural intricacies of TAVR, the focus of imaging will likely shift more toward patient and procedure selection. Which patients will obtain the greatest benefit or warrant earlier intervention? Which patients may not benefit at all? What valve type is most suitable for the patient's anatomy and physiology?

One promising imaging modality that may help answer some of these questions is cardiac magnetic resonance imaging (MRI). MRI has several advantages over currently used modalities, combining excellent spatial resolution on cross-sectional imaging with assessment of flow and myocardial characteristics. In particular, MRI has recently been used to characterize the complex ventricular response to pressure overload in AS by measuring myocardial fibrosis and MRI-derived longitudinal strain [73, 74]. Myocardial fibrosis as measured by late gadolinium enhancement (LGE) was associated with poor prognosis and increased 10-year mortality in patients with aortic stenosis even after aortic valve replacement [75–77]. Significant decreases in longitudinal strain have also been reported in the AS population, although these changes show some reversibility after AVR [78]. MRI still has distinct disadvantages in terms of time investment and cost, but more detailed imaging will likely find an initial role in high-risk subsets where the benefit of intervention may be questionable.

Positron emission tomography (PET) imaging with ^{18}F fluoride has also been utilized to characterize inflammation in both native and TAVR valves. Numerous investigators have suggested that the development of aortic stenosis may begin with valve inflammation, and the degree of inflammation as characterized by ^{18}F uptake has been shown to be both a marker of disease severity and a predictor of disease progression [79–81]. PET has also been studied as a method for early diagnosis of bioprosthetic valve degeneration. In one study of 71 patients without known valve degeneration, ^{18}F uptake correlated with more rapid deterioration of prosthetic valve function over the 2-year follow-up period [82]. While further studies are needed, PET imaging may provide clinical utility for identification of patients at risk for rapid AS progression or prosthetic valve dysfunction.

Conclusions

Imaging in TAVR has evolved dramatically in the past decade. Just as advances in valve technology have decreased vascular access complications and paravalvular regurgitation, systematic use of multimodality imaging has helped to streamline patient selection, procedural planning, and intraprocedural guidance of TAVR. While echocardiography remains the mainstay of diagnosis and intraprocedural guidance, the role of other imaging modalities has expanded significantly. Optimized CT acquisition and processing protocols have turned CT into a vital modality for valve sizing and access site

assessment, and MRI shows considerable promise for detailed myocardial and volumetric assessment. As the field of structural heart disease evolves, it is important to understand the role of each imaging modality as well as their individual strengths and weaknesses. For the modern structural imager, there is now a wealth of new data to translate into practice and a broader technical skillset to master, but a thorough understanding of multimodality imaging will continue to be critical to the success of any TAVR program.

Compliance with Ethical Standards

Conflict of Interest Qi Liu reports no conflicts.

Rebecca T. Hahn reports speaker fees from Boston Scientific Corporation and Baylis Medical; consulting for Abbott Structural, Edwards Lifesciences, Medtronic, Navigate, Philips Healthcare, and Siemens Healthcare; nonfinancial support from 3mensio and GE Healthcare; and is Chief Scientific Officer for the Echocardiography Core Laboratory at the Cardiovascular Research Foundation for multiple industry-sponsored trials, for which she receives no direct industry compensation.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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