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JACC STATE-OF-THE-ART REVIEW

Best Practices for Imaging of Transcatheter Valve Failure

An Update From the Heart Valve Collaboratory

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ABSTRACT

This updated Heart Valve Collaboratory framework addresses the growing concern for transcatheter valve failure (TVF) following transcatheter aortic valve replacement (TAVR). With the increasing volume of redo-TAV and surgical TAV explantation, there is a critical need for standardized pathways and protocols for evaluating TVF using echocardiography and cardiac computed tomography (CT) angiography. This document clarifies prior definitions of bioprosthetic valve deterioration and bioprosthetic valve failure in a practical, imaging directed context for TAVR. It discusses various imaging modalities for diagnosing TVF, including echocardiography, cardiac CT angiography, cardiac magnetic resonance, and positron emission tomography/CT. Recommendations are provided on the systematic imaging for: 1) follow-up post-TAVR; 2) procedural planning for redo-TAV; and 3) post-redo-TAV, emphasizing the importance of regular monitoring and the need for comprehensive imaging data to optimize patient outcomes in the lifetime management of aortic valve disease. (JACC. 2025;85:1042–1055) © 2025 Published by Elsevier on behalf of the American College of Cardiology Foundation.

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As lower-risk patients are treated, the mean age of transcatheter aortic valve (TAV) replacement (TAVR) patients is decreasing,[1] resulting in a growing number of patients with transcatheter valve failure (TVF) and raising clinical questions about lifetime management.[2] Symptomatic, bioprosthetic valve dysfunction (BVD) may necessitate redo-TAV or surgical TAV explantation. Although mid- to long-term failure rates of TAVR have been relatively low at 1% to 5%,[3,4] the number of repeat interventions is likely to increase with time as the current volume of 1 million global TAVR procedures expands.

Importantly, several definitions of structural valve dysfunction/deterioration have emerged that not only mix definitions of structural and nonstructural BVD but also incorporate different degrees of hemodynamic valve dysfunction. Thus we favor the initial Valve Academic Research Consortium (VARC)-3/Heart Valve Collaboratory (HVC) framework for bioprosthetic valve failure (BVF) and its components,[5,6] now adjusted and clarified with international consensus in the present document (**Figure 1**). This will continue to evolve based on systematic prognostic validation and research. This document aims to serve as a practical guide for the application of this updated HVC-endorsed framework for BVD/BVF using multimodality imaging in the diagnosis and management of TVF; specifically to direct the broad medical community in the optimal imaging: 1) of TVF; 2) for procedural planning; and 3) for procedural guidance and follow-up.

DIAGNOSIS OF TVF

The following sections discuss various imaging modalities in the context of diagnosing TVF including the stepwise echocardiographic assessment of nonstructural BVD, structural BVD, and potentially reversible structural BVD (ie, thrombosis and endocarditis), as well as the evolving and potential roles of cardiac computed tomography angiography (CCTA), invasive assessment, cardiac magnetic resonance (CMR) imaging, and positron emission tomography (PET). The importance of pre-TAVR planning to optimize initial valve deployment, including the development of computed tomography (CT)-based simulation, as well as the use of the Redo TAV app (KRUTSCH), is discussed, incorporating specific new terminologies fundamental to redo-TAV risk, such as the neoskirt plane and coronary risk plane (**Figure 2**).

ECHOCARDIOGRAPHY. Complete transthoracic echocardiography (TTE) and transesophageal echocardiography acquisition protocols to evaluate prosthetic aortic valve disease have been described comprehensively in prior documents, including the previous HVC document on standardized definitions of BVD.[6-8] Leaflet thickening, important in the initial identification of BVD, should be assessed on echocardiography (TTE or transesophageal echocardiography). However, if leaflets are not well seen or in the presence of diagnostic doubt, CCTA may be used to evaluate leaflet thickening/hypoattenuated leaflet thickening (HALT)/calcification.

ASSESSMENT OF TAV DYSFUNCTION. BVD is suspected when structural or hemodynamic "red flags" are detected on multimodality imaging studies (**Figure 1**, **Table 1**). Etiologies of BVD can be divided into: 1) nonstructural; 2) structural; and 3) potentially reversible forms of structural BVD—thrombosis and endocarditis (**Figure 1**).

ABBREVIATIONS AND ACRONYMS

AR = aortic regurgitation
BVD = bioprosthetic valve dysfunction
BVF = bioprosthetic valve failure
CCTA = cardiac computed tomography angiography
CMR = cardiac magnetic resonance
CT = computed tomography
EOA = effective orifice area
HALT = hypoattenuated leaflet thickening
PET = positron emission tomography
PPM = prosthesis-patient mismatch
PVL = paravalvular leak
TAV = transcatheter aortic valve
TAVR = transcatheter aortic valve replacement
TTE = transthoracic echocardiography
TVF = transcatheter valve failure

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The authors attest they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the Author Center.

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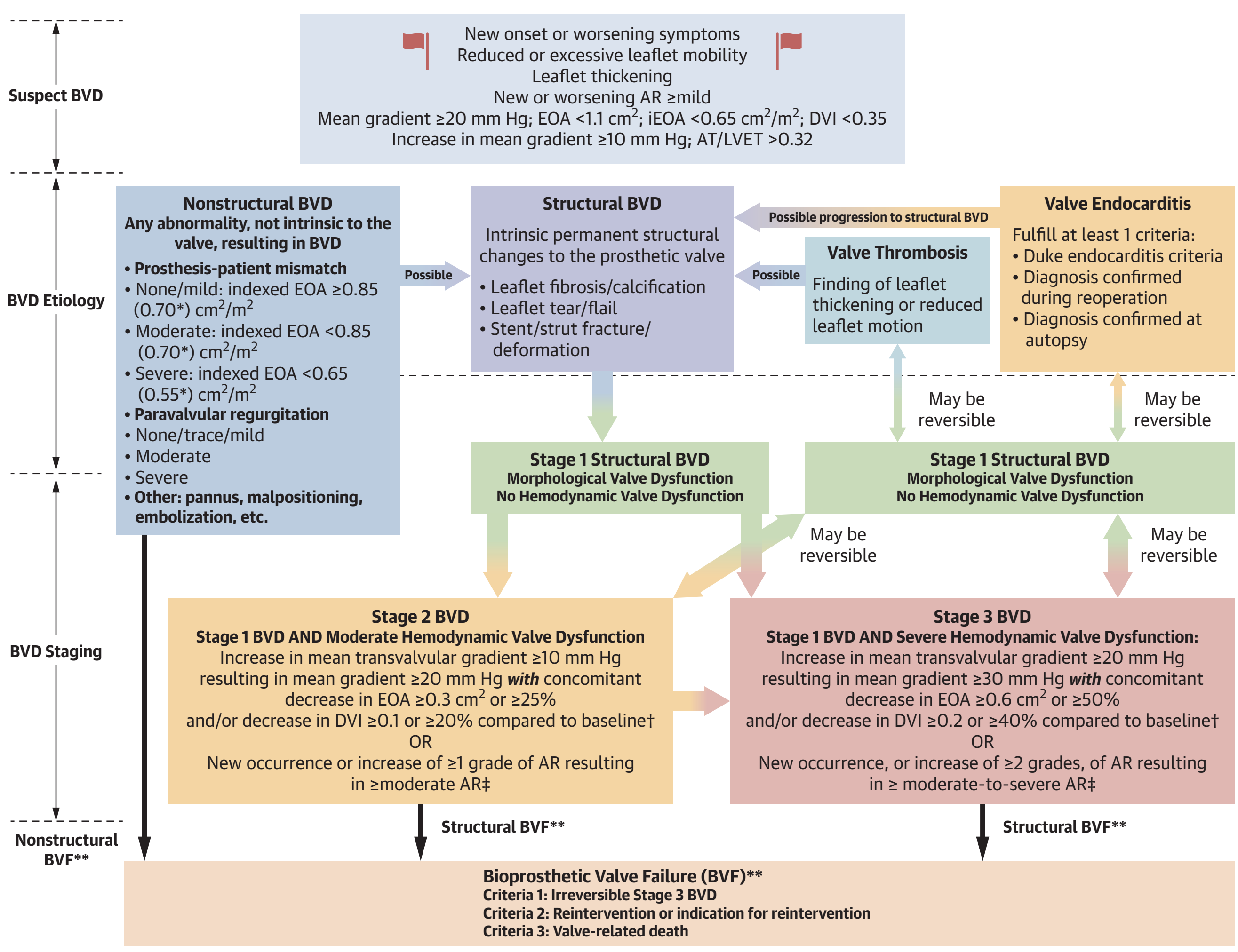
FIGURE 1 **BVD: Parameters to Suspect BVD (Red Flags), BVD Etiology, and BVD Staging**

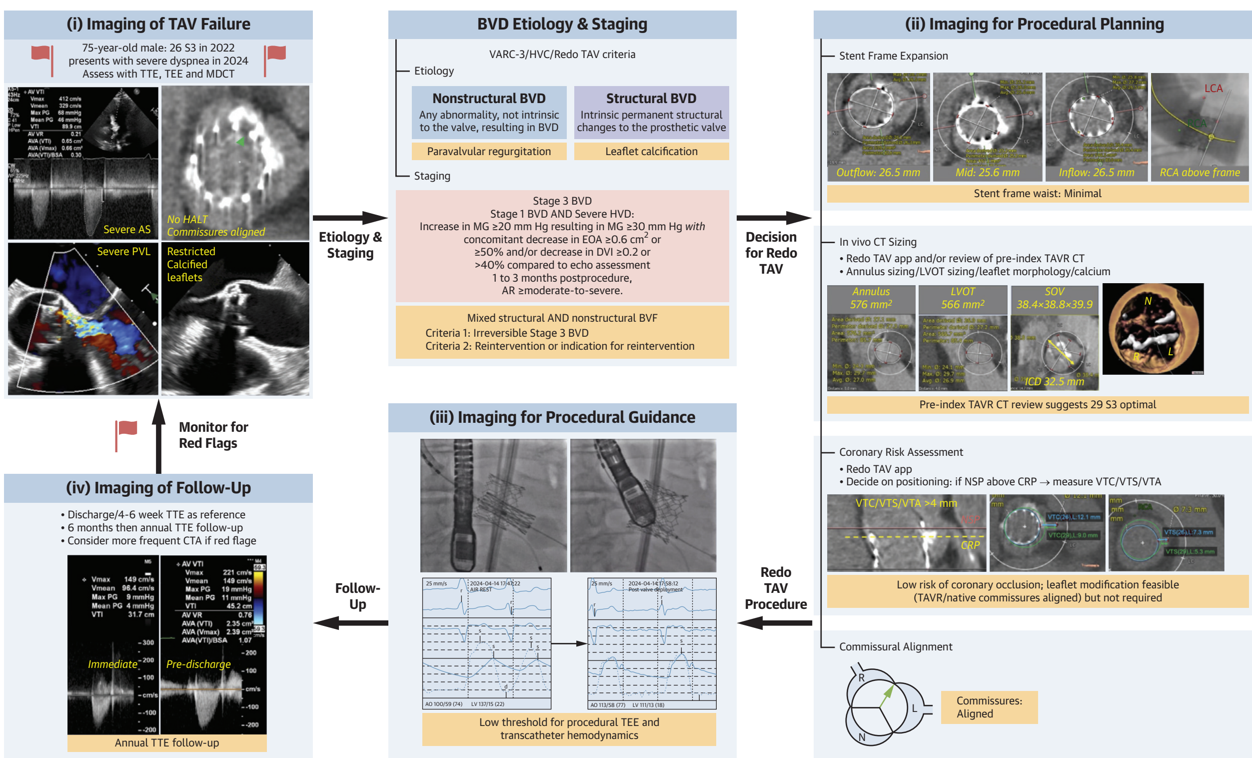


Nonstructural bioprosthetic valve dysfunction (BVD) and reversible forms of structural BVD (thrombosis and endocarditis) may evolve/progress to include parameters for (irreversible) structural BVD (shown). Different forms of BVD may coexist, resulting in mixed etiologies of BVD and hence mixed etiologies of BVF (Figure 2). Criteria for bioprosthetic valve failure (BVF) are clarified. *If BMI ≥30 kg/m². **BVF may be structural or nonstructural or a combination (mixed structural and nonstructural). †Baseline echocardiogram ideally performed 1 to 3 months postprocedure but, if not available, discharge echocardiogram may be used; if no baseline echocardiogram is available, normative data publications may be used for expected baseline function (see text). ‡Total AR; assessed by echocardiography or MRI. BMI = body mass index; EOA = effective orifice area.

Nonstructural BVD. Nonstructural BVD is defined as any abnormality, not intrinsic to the prosthetic valve, causing dysfunction. Examples include prosthesis-patient mismatch (PPM), paravalvular leak (PVL), pannus, and valve malpositioning (Figure 1, Table 1, Supplemental Table 1). Predicted PPM rates are significantly lower than measured PPM (Supplemental Table 1).[9-11] The association between severe PPM (measured or predicted) and mortality following TAVR has been variable.[12,13] Predicted PPM also uses echocardiographic measurements and cannot account for inadequate and asymmetric prosthesis expansion or shape, differences in leaflet material within the frame, or frame recoil.[14]

Since valve area is dependent on flow, the expected normal values for prosthetic valves may be larger in the setting of normal flow and lower in the setting of low-flow.[15] It is thus recommended to perform effective orifice area (EOA) measurements at 30 days post-TAVR as a baseline assessment, when

FIGURE 2 Imaging of TVF and for Redo-TAV: Case Example



Imaging approaches are shown for (i) transcatheter valve failure (TVF) identification, (ii) procedural planning, (iii) procedural guidance, and (iv) follow-up are illustrated for a patient presenting with TVF that ultimately underwent redo transcatheter aortic valve (redo-TAV). AS = aortic stenosis; CRP = coronary risk plane; CT = computed tomography; CTA = computed tomography angiography; DVI = Doppler Velocity Index; HALT = hypoattenuated leaflet thickening; HVC = Heart Valve Collaboratory; HVD = hemodynamic valve dysfunction; LVOT = left ventricular outflow tract; MDCT = multidetector computed tomography; MG = mean gradient; NSP = neoskirt plane; PVL = paravalvular leak; SOV = sinus of Valsalva; TAV = transcatheter aortic valve; TAVR = transcatheter aortic valve replacement; TEE = transesophageal echocardiography; TTE = transthoracic echocardiography; VARC-3 = Valve Academic Research Consortium 3; VTA = valve-to-aorta distance; VTC = valve-to-coronary distance; VTS = valve-to-sinus distance; other abbreviations as in Figure 1.

the highly prevalent low-flow state during and early after the procedure has improved, or to use the predicted indexed EOA instead.

Structural BVD. Structural BVD is defined as an intrinsic and permanent change to the prosthetic valve leaflets or stent, which may include wear and tear, disruption, leaflet flail, fibrosis or calcification, and stent fracture or deformation. Stages of structural BVD have been previously described[5,6] and are shown in Figure 1. Thrombosis and endocarditis are distinct forms of structural BVD. Importantly, they are potentially reversible and categorized as such, though they may progress to overt structural BVD if they become irreversible (Figure 1, Table 1). Given this potential reversible component, the "D" in BVD should denote "dysfunction" rather than "deterioration," and this nuance is stated consistently throughout this document, similarly for hemodynamic valve dysfunction. When assessing the presence and severity of hemodynamic valve dysfunction, the determination of dysfunction should be made, not only by looking at the absolute gradients, valve area calculations, and dimensionless index, but also on serial changes when compared with prior studies.

For structural BVD, some definitions reported in previous consensus documents or original research have included gradients or changes in gradients alone as criteria for structural (bioprosthetic) valve deterioration/dysfunction or BVD staging (supplement); specific examples include the 2017 European Association of Percutaneous Cardiovascular Interventions (EAPCI)/European Society of Cardiology (ESC)/European Association for Cardio-Thoracic Surgery (EACTS)

TABLE 1 Multimodality Imaging of Morphological Abnormalities of Valve Leaflets or Stent for Determination of the Type of Bioprosthetic Valve Dysfunction[6]

	Prosthesis-Patient Mismatch	Pannus	Valve Thrombosis	Valve Endocarditis	Structural BVD
TTE/TEE					
	Normal valve leaflet morphology and mobility	Dense fixed hyper-echogenic tissue involving periannular region or sewing ring	Diffuse or focal hypo-echogenic leaflet thickening (>2 mm) of at least 1 leaflet	Presence of vegetation(s)	Diffuse or focal hyper-echogenic leaflet thickening (>2 mm) of at least 1 leaflet
		Normal leaflet morphology	Normal or reduced leaflet mobility	Valve leaflet thickening	Reduced mobility and/or torn/avulsed/perforated leaflets
		Leaflet mobility may be normal or abnormal	Paucity (restriction) of color Doppler transvalvular flow	Possible torn/avulsed/ perforated leaflets or reduced leaflet mobility	Paucity (restriction) of color Doppler transvalvular flow
				Paravalvular complications: abscess, pseudo-aneurysm, fistula, dehiscence	
Multidetector CT					
Noncontrast CT	No leaflet calcification	No leaflet calcification	No leaflet calcification	No leaflet calcification	Leaflet calcification
Contrast-enhanced CT	Normal leaflet morphology and mobility	Hypodense semicircular or circular structure along and beneath the valve ring/stent	Hypoattenuation leaflet thickening (HALT)	Paravalvular complications: vegetations, abscess, pseudoaneurysm, fistula, dehiscence	Calcific or noncalcific hyper-dense leaflet thickening affecting leaflet motion
			Hypoattenuation affecting leaflet motion (HAM) (possible)		
			Reduced leaflet motion (RLM) (possible)		Reduced leaflet motion (RLM) (possible)
Nuclear imaging					
^{18}F-NaF PET/CT	No ^{18}F-NaF uptake at the level of the bioprosthetic valve leaflets [a]	Unknown	Increased ^{18}F-NaF uptake at the level of the bioprosthetic valve leaflets (possible)[a]	Increased ^{18}F-NaF uptake at the level of the bioprosthetic valve leaflets (possible)	Increased ^{18}F-NaF uptake at the level of the bioprosthetic valve leaflets (possible)[a]
^{18}F-FDG PET/CT	No increased ^{18}F-FDG uptake at the level of the valve or paravalvular region[a]	Unknown	Unknown	Increased ^{18}F-FDG uptake at the level of the bioprosthetic valve and paravalvular region	No increased ^{18}F-FDG uptake at the level of the bioprosthetic valve or paravalvular region[a]

[a]For research use.
^{18}F-FDG = 18F-fluorodeoxyglucose; CT = computed tomography; PET = positron emission tomography; TEE = transesophageal echocardiography; TTE = transthoracic echocardiography.

guidelines published by Capodanno et al[16] and several recent studies.[17,18] Undoubtedly, echocardiographic gradients are a simple and straightforward methodology to follow patients noninvasively. However, gradient alone does not correct for changes in flow, which may be influenced by multiple factors; hence, for complete staging criteria for BVD, we endorse the incorporation of specific echocardiographic parameters such as changes in EOA or Doppler Velocity Index (**Figure 1**).

Another important clarification in the staging of regurgitation-type dysfunction is that rather than valvular regurgitation alone, due to the potential coexistence of paravalvular and valvular aortic regurgitation (AR) (ie, nonstructural and structural BVD), total AR is graded rather than valvular AR alone that was mentioned in prior versions of this schema (**Figure 1**).

Bioprosthetic valve failure. BVF in general, and specifically TVF, is the end result of either structural or nonstructural BVD, or a combination, and summarizes the clinical impact to the patient (**Figure 1**). Although any stage of BVD associated with symptoms ("clinically expressive") was previously included in criterion 1 for BVF,[5,6] stage 1 and stage 2 BVD without reintervention (BVF criterion 2) or death (BVF criterion 2) are not included in the updated definition for BVF criterion 1 (**Figure 1**). Specific examples might include moderate PVL with hemolysis necessitating reintervention (which would be stage 2 BVD and BVF) or endocarditis in the setting of sepsis or embolization resulting in death despite only being only mild or moderate hemodynamic valve dysfunction (which would be stage 1 or 2 BVD and BVF). However, in the absence of reintervention, moderate PVL (stage 2 BVD) would not be regarded as BVF, even if "clinically expressive" with dyspnea (**Figure 1**), due to the challenges of interpretation of multifactorial symptoms that may or may not be valve-related. The presented practical schema (**Figure 1**) has been simplified

TABLE 2 Advantages, Limitations and Reasons for Discordance Between Noninvasive and Invasive Measures of Bioprosthetic Valve Hemodynamic Function

	Echocardiography Assessment	Invasive Hemodynamic Assessment
Advantages		
	Safe	Incorporates all valve, flow, and fluid components
	Widely accessible	Independent of incidence angle of ultrasound beam
	Repeatable	
	Multiple, confirmatory parameters	
	Differentiates stenosis and regurgitation	
	Measures correlate with outcomes	
	Can assess with normal loading conditions as well as during stress	
Limitations		
	Fails to account for flow acceleration, viscous forces	Invasive
	May not account for proximal LV pressure (pressure loss recovery)	Immediate post-TAVR measures not reflective of normal flow state and subsequent valve adaptation
	Requires alignment to flow	Errors of inaccurate zeroing, catheter calibration
		Catheters with multiple side holes may not capture maximal gradient
		Cardiac output measures not validated in elderly and post-AVR
Reasons for discordance		
	Failure to align probe parallel to max velocity	Inaccuracies of fluid-filled catheters, multiple side-holes, improper positioning
	Simplified Bernoulli equation fails to account for laminar/average flow, proximal LV velocity, variability of contraction coefficient, nonconvective forces	Timing of measurements immediately post-TAVR (low-flow)

Adapted from Tables 1 and 2 in Herrmann et al.[14]
AVR = aortic valve replacement; LV = left ventricular; TAVR = transcatheter aortic valve replacement.

but remains detailed, due to the need to capture multiple scenarios in the real world for patients presenting with BVD.

INVASIVE ASSESSMENT OF TVF

Although echocardiography remains the primary imaging modality for assessing TAV function,[19] invasive assessment of TVF is recommended in clinical situations where there is a significant discrepancy between echocardiographic findings and the patient's symptoms, or when the severity of valve dysfunction remains unclear. Immediate post-TAVR gradients by echo may be higher than invasive gradients, given flow characteristics of a normal TAV, and the discordance may vary by TAVR type.[20] Optimal invasive assessment demands careful methodologic technique (Table 2).[21]

An example of this utility is in the setting of pressure loss recovery, which is particularly pronounced in high-flow states, in small ascending aortas (<3 cm in diameter), or in the presence of eccentric jets.[22] At the vena contracta, the maximal velocity and gradient occur, but downstream pressure partially recovers, resulting in lower invasive gradients compared with echocardiographic measurements.[23]

CCTA POST-INDEX TAVR

CCTA ACQUISITION AND RECONSTRUCTION. Appropriate acquisition and reconstruction are critical for optimization of post-TAVR CT assessment. CCTA acquisition and reconstruction post-TAVR implantation are summarized in Table 3.

CCTA IMAGE ANALYSIS. CCTA is fundamental in the planning of redo-TAVR and is helpful to mitigate potentially serious complications such as root injury, coronary obstruction, and severe underexpansion of the redo-TAV. Assessment of index TAV expansion is performed at various levels including the inflow, leaflet level, and outflow. An underexpanded TAVR without leaflet pathology may signal an opportunity to perform a late balloon valvuloplasty,[24] albeit with the careful evaluation of risk and benefit based on native aortic root anatomy.

TABLE 3 Checklist for Cardiac Computed Tomography Angiography Acquisition Before Redo-TAVR

Patient preparation	
Heart rate control	Initiate heart rate control when feasible.
	Ideal heart rate: ∼60 beats/min.
	Higher heart rates up to ∼70 beats/min tolerated in newer high coverage or high temporal resolution scanners.
Significant TAV dysfunction	Caution with beta-blockade; weigh risks against benefits.
Scan acquisition	
Field of view	Adequate to cover entire heart and aortic root.
Noncontrast calcium score scan	Used to plan anatomic coverage and visualize bioprosthetic leaflet calcification.
Contrast scan protocol	Follow typical TAVR protocol, test bolus or bolus tracking with trigger in ascending or descending aorta.
	Full cardiac cycle acquisition.
	Volume scanners: entire cycle in 1 gantry rotation.
	Retrospective imaging without dose modulation for other scanners.
	Use thinnest scan collimation possible.
Scan reconstruction	
Slice thickness	Noncontrast: 2-3 mm and <1.0-mm slices to assess leaflet calcium. Contrast: reconstruct as thin as possible for maximal spatial resolution.
Phase reconstruction	Minimum of 10 phases (10%) increments; 5% increments (20 phases) preferred. In the presence of arrhythmias, at 50-ms increments intervals to the shortest R-R interval used for the scan acquisition. Use for best phase assessment of HALT and for RELM assessment.
Kernel reconstruction	Use several different kernels: sharp/stent for TAV frame edges, soft/medium/smooth for prosthetic leaflet tissue.
Metallic artifact reduction	Use sharp kernels and vendor-specific metallic artifact reducing reconstructions to reduce partial volume averaging.
Image analysis	Create thicker slices within multiplanar reconstructions (maximum, minimum, average intensity projections) for further analysis.

HALT = hypoattenuated leaflet thickening; RELM = reduced leaflet motion; TAV = transcatheter aortic valve; TAVR = transcatheter aortic valve replacement.

HALT is associated with leaflet thrombosis and is typically assessed in the best diastolic phase where there is the least motion artifact and leaflet coaptation is visualized; multiple phases should be reviewed as image quality may be superior in other phases.[25] HALT severity grading with assessment of reduced leaflet motion using multiphase CT have been described by Jilaihawi et al.[25] Typically, acute thrombus has a low CT tissue attenuation of <90 HU, whereas subacute and chronic thrombus will have values of 90 to 145 HU, though these cutoffs have been principally based on historical data from mechanical prosthesis thrombosis.[26] Importantly, chronic thrombus may be less likely to be resolved with anticoagulation.

In contrast, pannus generally has a higher CT tissue attenuation of >145 HU, reflective of different tissue characterization[26] and has a different distribution (**Figure 3**). Pannus onset in prosthetic valves usually occurs after 6 to 12 months of implantation and has a histopathology of dense fibrosis, myofibroblasts, inflammatory cells, and endothelial cells.

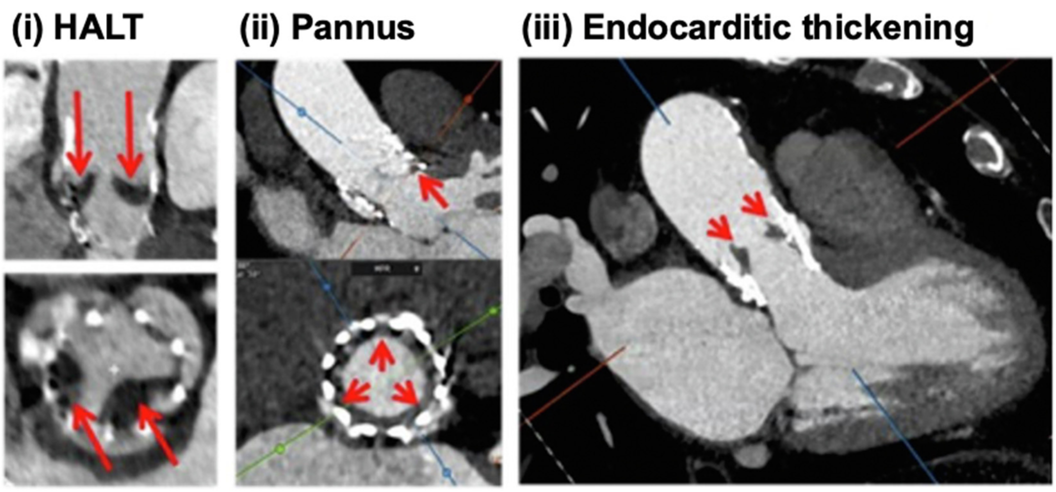
Endocarditis of the TAV appears as a thickening or irregular mass with low-to-intermediate CT tissue attenuation. Endocarditis may be associated with irregular leaflet thickening and mobile hypodensities attached to the leaflets, occasionally leaflet perforation, thickening surrounding the TAV device, pseudoaneurysm, abscess, fistulas, or dehiscence of the valve.

More relevant than degree of hypoattenuation post-TAVR are the specific and characteristic CT morphological appearances, with: 1) HALT, a crescentic hypoattenuation at the base of the leaflet on the aortic side at the periphery that may extend subsequently centrally towards the tip of the leaflets; 2) pannus as a circumferential hypoattenuation below the leaflets; and 3) endocarditis as hypoattenuated thickening at the tips of the leaflets (**Figure 3**). Importantly, resolution of HALT-type thickening following anticoagulation may often be seen in the setting of patients presenting with bioprosthetic stenosis, and a prolonged course of anticoagulation of >3 months may be required in some for resolution.[27]

CMR IMAGING POST-INDEX TAVR

One cannot reliably visualize leaflet thickening via CMR due to magnetic artifacts from the stent frame. CMR is helpful in assessing concomitant conditions such as cardiac amyloidosis or left ventricular dysfunction in patients undergoing TAVR[28]

FIGURE 3 Patterns of Hypoattenuation on CCTA, Reflecting Different Pathologies



(i) Hypoattenuated leaflet thickening (HALT) (thrombotic), a crescentic hypoattenuation at the base of the leaflet on the aortic side at the periphery and subsequently may extend centrally towards the tip of the leaflets (top panel shows a longitudinal view, lower panel an axial view); (ii) pannus as a circumferential hypoattenuation below the leaflets (top panel shows a longitudinal view, lower panel an axial view); and (iii) endocarditis as hypoattenuated thickening at the tips of the leaflets. Red arrows point to described abnormality.

(Figure 4). One of the most important clinical applications of CMR is in the quantification of AR, including PVL post-TAVR, with a cutoff of 30% regurgitant fraction for prognostically significant disease,[29] whereas the location and mechanism of regurgitation are better identified on CCTA or echocardiography. The most reliable assessment method on CMR is to prescribe a phase-contrast plane orthogonal to the aorta, just above the plane of the transcatheter heart valve and to directly measure forward and regurgitant flow.

PET/CT IMAGING POST-INDEX TAVR

PET imaging with ^{18}F sodium fluoride has shown potential for detecting early microcalcification activity and may help forecast valve dysfunction. The main current clinical utility of cardiac PET is to detect the presence of endocarditis. Like CCTA, the modality holds a Class IIa recommendation in the 2020 American College of Cardiology (ACC)/American Heart Association (AHA) valve guidelines.[19] and a Class I recommendation in the 2023 ESC endocarditis guidelines for investigation of suspected endocarditis in bioprosthetic valves.[30]

PRE-REDO-TAV CT ANALYSIS

Redo-TAVR requires meticulous preprocedural CT planning to guide redo-TAV type, size, implant position, and to predict the risk of coronary artery obstruction (Figure 5, Tables 4 and 5).

GENERAL PRINCIPLES. Every effort should be made to obtain the pre-index TAVR CT, which should be reanalyzed to measure native annulus and aortic root dimensions, and to identify key anatomical features that will impact the redo-TAV strategy, including bicuspid anatomy (with or without calcification of the raphe) and the presence of hostile calcification at the annulus or left ventricular outflow tract. These findings will inform the safety and sizing strategy for predilatation and post-dilatation, as well as the type and size of the redo TAV. If PVL is present, they will also enable distinction between underexpansion vs undersizing of the index TAVR. A high-quality repeat CCTA is essential for careful planning and safe execution of the redo-TAVR procedure.

STEP-BY-STEP APPROACH TO ANALYSIS OF THE PRE-REDO-TAV CT. To ensure accurate and reproducible assessment during pre-redo-TAV CT analysis, a structured approach is essential. Table 4 provides a step-by-step guide outlining the critical steps and measurements that should be undertaken.

CHOOSING THE TYPE OF REDO-TAV. The choice of TAV for the redo-TAVR is determined by multiple factors, including the type and size of the index TAV, the risk of root injury, the risk of coronary

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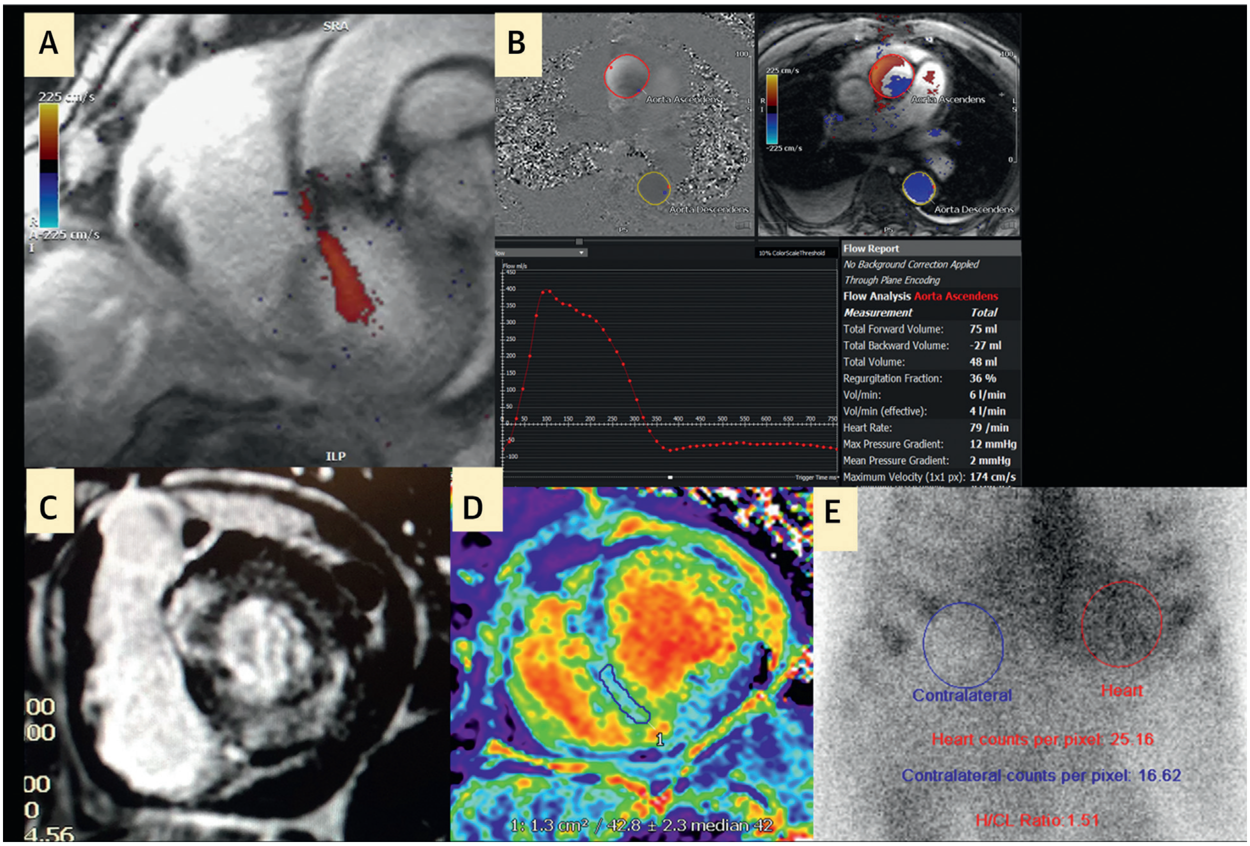
FIGURE 4 **CMR Imaging to Evaluate Aortic Regurgitation After TAVR**



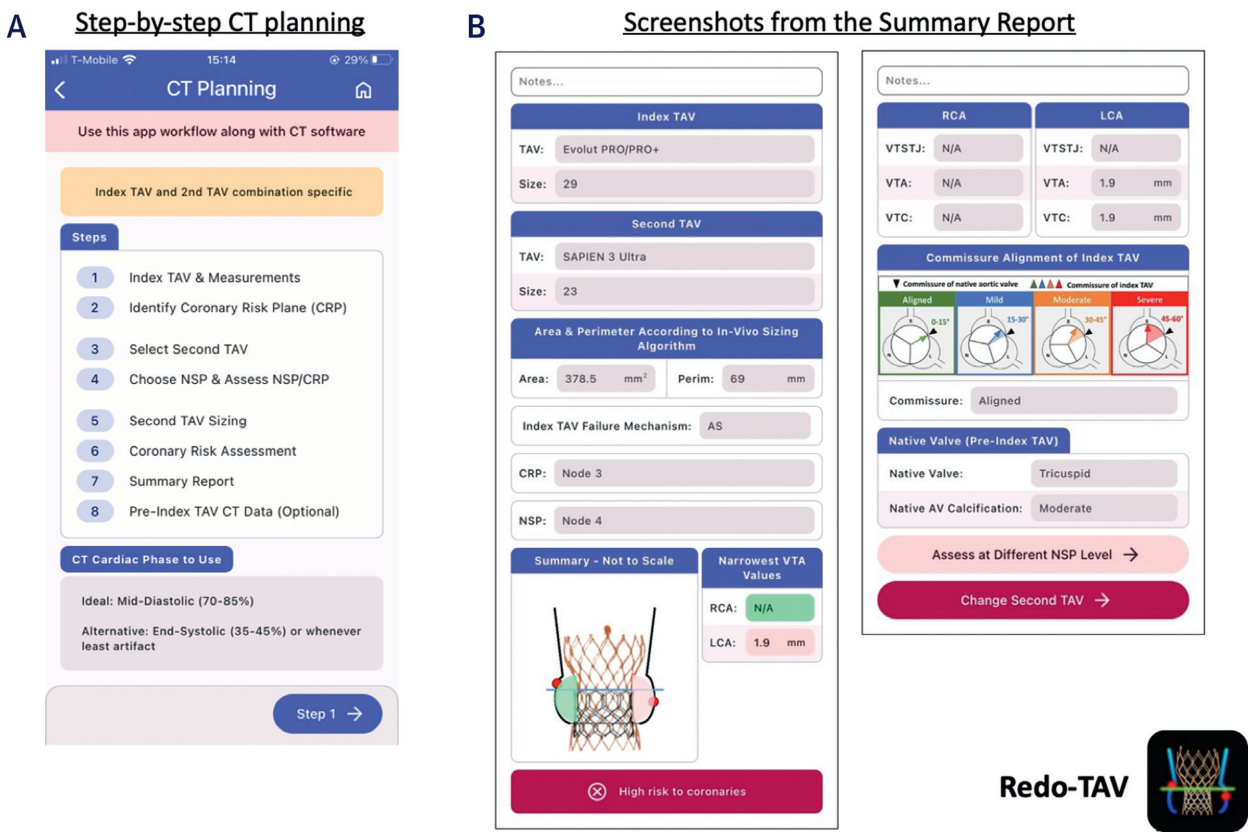
An 83-year-old male patient with recalcitrant heart failure episodes post-TAVR presenting for consideration of redo-TAVR. Preserved left ventricular ejection fraction and moderate aortic regurgitation seen on transthoracic echocardiogram, unable to determine mechanism. Cardiac magnetic resonance (CMR) imaging obtained to quantify severity of PVL and myocardial disease. (A) Severe posteromedial PVL. (B) Flow quantification with aortic regurgitation fraction = 36% and holodiastolic flow reversal. (C) Moderate concentric increased wall thickness with patchy diffuse nonischemic midwall fibrosis and concomitant pericardial effusion, raises the suspicion of concomitant cardiac amyloidosis. (D) Markedly elevated myocardial extracellular volume (42%) is consistent with cardiac amyloidosis, which is then confirmed by technetium pyrophosphate (Tc-PYP) scan. (E) Perugini Grade 3 uptake and increased heart/contra-lateral ratio (H/CL) = 1.51. Abbreviations as in Figure 2.

obstruction, ease of coronary access, risk of PPM, and operator experience with each type of TAV.

SIZING THE REDO-TAV. We reiterate that incorporation of not only the pre-redo-TAVR CCTA analysis but also review of the prior pre-index TAVR CCTA is preferred as the gold standard for redo-TAV sizing, especially if any PVL is present. In particular, the risk of root injury, often related to TAV sizing in relation to the native annulus size, and to patterns of native leaflet, annular and subannular calcification, is best assessed on the pre-index TAVR CCTA. In the absence of PVL, sizing of the redo-TAV is primarily determined by the dimensions of the index TAV within the intended landing zone on the post-TAVR CCTA. However, if the index TAV is underexpanded, it is important to consider, based on the pre-index TAVR CT, how much to safely expand the index TAV before implanting the second TAV, and if appropriate, to upsize the redo TAV accordingly (Figure 2). Measuring the internal dimensions of the index TAV at multiple levels within the intended landing zone can further help size the redo-TAV, especially if the index TAV is eccentric and/or underexpanded. Excessive pannus or calcification of the index TAV leaflets should be considered as this will reduce the available area for the redo TAV.

ASSESSING CORONARY OBSTRUCTION RISK. Following the initial analysis detailed above, a thorough assessment of coronary obstruction risk is essential to guide procedural feasibility and strategy. Table 5

FIGURE 5 **The Redo TAV App**



(A) Steps for the step-by-step CT planning. (B) Screenshots from the Summary Report of CT planning section, summarizing all important data points with a summary image. VTSJ = valve-to-sinus of Valsalva distance; other abbreviations as in Figure 2.

outlines the steps required to evaluate this risk, including the identification of key anatomical planes and measurements that inform the likelihood of coronary obstruction.

There are several caveats to this analysis. First, the imaging quality of the postindex TAVR CCTA can impact the analysis and risk assessment of sinus sequestration and coronary obstruction. When in doubt, perform left heart catheterization with aortic root angiography at a left anterior oblique/cranial view, with parallax of the TAV frame removed to assess left coronary obstruction risk. Second, the ability of the operator to precisely position the redo-TAV may not be as accurate as desired. If the coronary risk and neoskirt planes are very close, then a small difference in redo-TAV implantation depth may risk coronary obstruction. Moreover, when implanting a short balloon-expandable TAV inside a tall self-expanding supra-annular TAV, coronary perfusion/access may rely on a degree of leaflet overhang. However, the degenerated/calcified leaflets of the failed TAV may not overhang as much as normal, noncalcified leaflets.[31]

REDO TAV APP

The Redo TAV app (available on iOS and Android) offers a patient-specific, combination-specific, step-by-step guide for CT analysis before redo-TAV, eliminating the need to consult multiple sources. It provides details on TAV design, combination-specific procedure guides, coronary interactions, and TAV explantations, and allows users to document data after redo-TAV, for integration into the electronic medical record. The app is based on pre-redo-TAVR CT imaging, assuming optimal sizing of the index TAVR. Therefore, it is crucial to review the pre-index TAVR CT before redo-TAVR, especially when PVL, frame underexpansion or distortion, or PPM are present.

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TABLE 4 Step-by-Step Approach for Pre-Redo-TAV CT Analysis

Steps	
1	Set the annular plane on CT at the inflow of the index TAV, not the native annulus.
2	Adjust the centerline along the central axis of the index TAV.
3	Assess commissural alignment, best seen in diastolic phase images, with respect to the coronary arteries and the native sinuses/commissures.
4	Measure the index TAV internal dimensions, applying the following principles: a) Perform center-to-center tracing (ie, with the tracing through the middle of the stent struts, rather than the inner or outer margins); this approach reduces the effect of blooming artifact on sizing, and as a consequence is more reproducible. b) Measure area and perimeter, with derived diameters, at multiple levels. c) The levels at which measurements should be made are specific for each index TAV, and for some TAV-in-TAV combinations, but will include a minimum of 3 levels between the nadir of the leaflets and the commissure tabs. d) Detailed guidance on measurements of the index TAV is provided in the Redo TAV app.
5	Measure STJ and SOV dimensions.
6	Mark the lower aspect of the ostia of both left and right coronary artery ostia and measure the heights of the coronary arteries and the STJ from the inflow of the index TAV.

STJ = sinotubular junction; SOV = sinus of Valsalva; other abbreviations as in Tables 1 and 3.

The main sections of the Redo TAV app include redo-TAV CT planning, procedure guide, and procedure data and outcome. The algorithms behind the app have been derived after extensive bench and CT simulation work.

The Redo-TAV CT planning section provides a step-by-step combination-specific guide to record important measurements of the index TAV, select the second TAV (type and size), and calculate the coronary risk of the procedure (**Figure 5**). Other submenus in the Redo TAV app are described in Supplemental Table 2.

CT-BASED SIMULATION IN REDO-TAV ASSESSMENT

CT-based simulations involve various methods for virtual valve implantation in the Redo-TAV app. Simple implantation of an embedded geometry or virtual valve can be performed using a dedicated TAV module within software such as TeraRecon, Circle (Circle Cardiovascular Imaging), and 3mensio (Pie Medical Imaging). Basic measurements sufficient for redo-TAVR assessment can be performed as already described. The advantage of these is simplicity and availability.

Advanced computer simulations create a "digital twin" of the patient to evaluate virtual implants and various strategies. DASI simulations (U.S. Food and Drug Administration-approved and reimbursable in the United States through a "software as a device" pathway) and FEops are 2 presently available technologies in this category. These simulations use various software engineering technologies including finite element analysis, advanced registration, and

TABLE 5 Step-by-Step Assessment of Coronary Obstruction Risk

Steps		
1	Identify the CRP	Defined as the bottom of the lowest coronary ostium (most often, but not always, the left coronary artery).
2	Identify the NSP	Determined by the top of the index TAV pinned leaflets and redo TAV skirt.
3	Determine the relationship between the NSP and CRP	If the NSP is below the CRP, then the risk of coronary obstruction is low. If the NSP is above the CRP, simulate a virtual valve to account for outward expansion of the index TAV. The diameter of the virtual valve is determined by the sizing assessment performed above, taking into account the size of the index TAV, the size of the redo TAV, and whether or not predilatation and/or postdilatation will be performed.
4	Record the minimum virtual VTA distance	Measure the VTA at multiple levels from the NSP to the CRP. Record the minimum VTA, the VTC and the VTSTJ if the NSP is above the STJ. These measurements should be performed for each coronary at risk. If the VTC is <4 mm, there is a high risk of coronary obstruction. If the VTA/VTSTJ is <2 mm, there is a high risk of sinus sequestration.[a]

[a]It should be noted that these cutoffs are at present empiric, and a similar valve to aorta distance (VTA) may project different risk in self-expanding valves in balloon-expandable valves than in balloon-expandable valves in self-expanding valves; the stated cutoffs require systematic validation in prospective series and registries.

CRP = coronary risk plane; NSP = neoskirt plane; VTC = valve to coronary distance; VTSTJ = valve to sinotubular junction distance; other abbreviations as in Tables 3 and 4.

reduced order modeling.[32] Although further validation is needed, advanced preprocedural planning holds promise for a precision-medicine approach to test multiple different device, size, and positioning options in any given patient's anatomy with the prediction of, not only acute procedural complications, but also longer-term outcomes such as thrombosis and degeneration.[33]

FOLLOW-UP

The 2020 ACC/AHA valvular heart disease guidelines recommend echocardiographic imaging at baseline post-TAVR and annually thereafter.[19] Based on current data, CCTA is reasonable when there is suspicion of HALT from increased transvalvular gradients or when symptoms are present. However, if gradients are normal or symptoms absent, there is currently no supporting evidence for and, indeed, the potential for harm from, a regimented strategy of anticoagulation following subclinical HALT detected by routine CCTA.[34]

Post-redo-TAV imaging may require a greater frequency than previously recommended, particularly in the first-year postprocedure, due to potential changes in flow as well as the potential predisposition to HALT. After the redo-TAV procedure, a baseline predischarge echocardiogram should be obtained. Given the theoretically higher risk of HALT and-potentially-structural BVD in this setting, it is reasonable to perform echocardiography at more frequent intervals for comparison, at 4 to 6 weeks and at 6-month follow-up, then annually thereafter (**Figure 2**). For clinical purposes, it would be reasonable to perform a CCTA when an increase in echocardiographic gradient occurs.

A recent publication reported outcomes from the STS/ACC TVT (Society of Thoracic Surgeons/American College of Cardiology Transcatheter Valve Therapy) Registry from 2011 to 2022, of patients who underwent redo-TAVR with balloon-expandable valves in failed TAV vs native aortic valve.[35] It noted, in 1,320 propensity-matched pairs, low procedural complication rates, and death and stroke rates similar to those in patients undergoing TAVR for native aortic valve stenosis, but the redo-TAV arm had more aortic valve reinterventions at 1 year, which raises some concern.

The ongoing multicenter ReTAVI (ReTAVI Prospective Observational Registry) and REVALVE (REdo Transcatheter Aortic VALVE Implantation for the Management of Transcatheter Aortic Valve Failure) registries in Europe should contribute to some much-needed granularity. Indeed, a U.S. national multicenter imaging-centered redo-TAV registry would capture the basic parameters of the STS/ACC TVT registry but also offer the granularity of core-lab-adjudicated multimodality imaging data and long-term follow-up. In addition to standard-of-care imaging data, such a collaborative registry would also be the foundation for nested registries incorporating novel multimodality imaging modalities such as PET/CT, novel devices, or software planning tools, and innovative approaches such as leaflet modification.

CONCLUSIONS

TVF presents specific challenges different to those seen following failure of surgical bioprostheses. Its identification, treatment with redo-TAV or surgical explantation, and follow-up are fundamentally directed by imaging. This updated Heart Valve Collaboratory framework represents an attempt by a coalition of multidisciplinary experts in the field to standardize best practices on the application of multimodality imaging in the diagnosis of TVF, anatomical evaluation for reintervention, mitigation of the risk of complications from redo-TAV, and finally, optimization of long-term outcomes. The relative importance of the specific imaging modalities and methodologies stated requires a concerted collaborative effort for systematic validation in international multicenter prospective series and registries.

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Dr Yakubov has received institutional grants from Boston Scientific and Medtronic; and has received personal fees from Medtronic during the conduct of the study. Dr Delgado has received speaker fees from Abbott Vascular, Edwards Lifesciences, GE Healthcare, JenaValve, Medtronic, Novartis, Philips, and P&F Products & Features; and has received consulting fees from Edwards Lifesciences, Merck Sharp & Dohme, and Novo Nordisk. Dr Hahn has received speaker fees from Abbott Structural, Baylis Medical, Edwards Lifesciences, Medtronic, Philips Healthcare, and Siemens Healthineers; and has institutional consulting contracts for which she receives no direct compensation with Abbott Structural, Boston Scientific, Edwards Lifesciences, Medtronic, and Novartis. Dr Jilaihawi has received institutional grants for clinical research in Pi-Cardia; holds equity and serves on the scientific advisory board for DASI simulations; and has served as a consultant to Edwards Lifesciences and Medtronic. 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KEY WORDS cardiac computed tomography angiography, structural valve deterioration, transcatheter aortic valve replacement, transesophageal echocardiography, transthoracic echocardiography

APPENDIX For supplemental tables, please see the online version of this paper.

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