JACC: CARDIOVASCULAR IMAGING
VOL. 8, NO. 3, 2015

ISSN 1936-878X/$36.00
PUBLISHED BY ELSEVIER INC.
http://dx.doi.org/10.1016/j.jcmg.2015.01.008

Assessment of Paravalvular Regurgitation Following TAVR

A Proposal of Unifying Grading Scheme

Philippe Pibarot, DVM, PhD,* Rebecca T. Hahn, MD,† Neil J. Weissman, MD,‡ Mark J. Monaghan, PhD§

JACC: CARDIOVASCULAR IMAGING CME

CME Editor: Ragavendra R. Baliga, MD

This article has been selected as this issue's CME activity, available online at http://imaging.onlinejacc.org by selecting the CME tab on the top navigation bar.

Accreditation and Designation Statement

The American College of Cardiology Foundation (ACCF) is accredited by the Accreditation Council for Continuing Medical Education (ACCME) to provide continuing medical education for physicians.

The ACCF designates this Journal-based CME activity for a maximum of 1 *AMA PRA Category 1 Credit(s)* ™. Physicians should only claim credit commensurate with the extent of their participation in the activity.

Method of Participation and Receipt of CME Certificate

To obtain credit for this CME activity, you must:

1. Be an ACC member or *JACC: Cardiovascular Imaging* subscriber.
2. Carefully read the CME-designated article available online and in this issue of the journal.
3. Answer the post-test questions. At least 2 out of the 3 questions provided must be answered correctly to obtain CME credit.
4. Complete a brief evaluation.
5. Claim your CME credit and receive your certificate electronically by following the instructions given at the conclusion of the activity.

CME Objective for This Article: At the end of this activity the reader should be able to: 1) recognize the strengths and weaknesses of each imaging modality (cineangiography, invasive hemodynamics, echocardiography, and CMR) for the identification and quantitation of PVR following TAVR; 2) describe the different views and parameters to be obtained for comprehensive assessment of PVR by transthoracic and transesophageal echocardiography; and 3) discuss the added value of the unifying 5-class scheme proposed for the grading PVR severity.

CME Editor Disclosure: *JACC: Cardiovascular Imaging* CME Editor Ragavendra R. Baliga, MD, has reported that he has no relationships to disclose.

Author Disclosures: Dr. Pibarot holds the Canada Research Chair in Valvular Heart Disease, and his research program is funded by the Canadian Institutes of Health Research (grant numbers: MOP 126072, MOP 114997; MOP 102737). Dr. Pibarot has Core Lab contracts with Edwards Lifesciences, for which he receives no direct compensation; and is a speaker for St. Jude Medical. Dr. Hahn has Core Lab contracts with Edwards Lifesciences for which she receives no direct compensation; and is a speaker for Philips Healthcare, St. Jude Medical, and Boston Scientific. Dr. Weissman has Core Lab contracts with Edwards Lifesciences, St. Jude Medical, Boston Scientific, Medtronic, Biostable, Sorin, Abbott Vascular, Direct Flow, and Mitralign, for which he receives no direct compensation. Dr. Monaghan is proctor for Edwards Lifesciences; and is a speaker for Philips Medical Systems and GE Medical.

Medium of Participation: Print (article only); online (article and quiz).

CME Term of Approval

Issue Date: March 2015
Expiration Date: February 29, 2016

From the *Institut Universitaire de Cardiologie et de Pneumologie de Québec/Québec Heart & Lung Institute, Department of Medicine, Laval University, Québec, Canada; †Department of Medicine, Columbia University Medical Center/NY Presbyterian Hospital, New York, New York; ‡Department of Medicine, Medstar Health Research Institute and Georgetown University, Washington, DC; and the §Department of Cardiology, King's College Hospital, London, United Kingdom. Dr. Pibarot holds the Canada Research Chair in Valvular Heart Disease, and his research program is funded by the Canadian Institutes of Health Research (grant numbers: MOP 126072, MOP 114997; MOP 102737). Dr. Pibarot has Core Lab contracts with Edwards Lifesciences, for which he receives no direct compensation; and is a speaker for St. Jude Medical. Dr. Hahn has Core Lab contracts with Edwards Lifesciences for which she receives no direct compensation and is a speaker for Philips Healthcare, St. Jude Medical, and Boston Scientific. Dr. Weissman has Core Lab contracts with Edwards Lifesciences, St. Jude Medical, Boston Scientific, Medtronic, Biostable, Sorin, Abbott Vascular, Direct Flow, and Mitralign, for which he receives no direct compensation. Dr. Monaghan is proctor for Edwards Lifesciences; and is a speaker for Philips Medical Systems and GE Medical.

Manuscript received December 21, 2014; revised manuscript received January 22, 2015, accepted January 25, 2015.

Assessment of Paravalvular Regurgitation Following TAVR

A Proposal of Unifying Grading Scheme

ABSTRACT

Paravalvular regurgitation (PVR) is a frequent complication of transcatheter aortic valve replacement that has been shown to be associated with increased mortality. The objective of this article is to review the most up-to-date information about the assessment and management of PVR and to propose a new more comprehensive and unifying scheme for grading PVR severity. A multimodality, multiparametric, integrative approach including Doppler echocardiography, cineangiography, hemodynamic assessment, and/or cardiac magnetic resonance is essential to accurately assess the severity of PVR and the underlying etiology. Corrective procedures such as balloon post-dilation, valve-in-valve, or leak closure may be considered, depending on the severity, location, and etiology of PVR. (J Am Coll Cardiol Img 2015;8:340–60) © 2015 by the American College of Cardiology Foundation.

Transcatheter aortic valve replacement (TAVR) is a rapidly expanding alternative to surgical replacement for patients with high operative risk. Paravalvular regurgitation (PVR) is, however, an important complication of TAVR that has been shown to be associated with increased mortality for both the balloon-expandable and the self-expanding transcatheter heart valves (THV) (1,2). Thus, the accurate measurement of this complication becomes an important means for determining the effectiveness of various corrective interventions (such as post-dilation or valve-in-valve) as well as the effectiveness of various valve iterations or designs. The objective of this article is to review the most up-to-date information about the assessment and management of PVR and to propose a new unifying scheme for grading PVR severity, which would bring clarity and uniformity to grading of PVR.

INCIDENCE AND CLINICAL IMPACT OF PVR

INCIDENCE OF PVR. The incidence of moderate or severe PVR following TAVR varies from 0% to 24% and that of mild PVR from 7% to 70%, depending on the studies (Online Figure 1, Online Appendix) (1-4). These important inconsistencies in reported incidences of PVR are multifactorial and may be due to differences in: 1) the baseline risk profile of the populations; 2) the type of THV and approach used for TAVR; 3) the method of assessment of PVR (cineangiography versus hemodynamics versus cardiac magnetic resonance [CMR] versus echocardiography) (5); 4) the parameters and criteria relied upon to grade PVR; 5) the type of grading (i.e., 3- vs. 4-class) scheme used to classify PVR severity; and 6) the standardization of the assessment of PVR (i.e., site vs. core lab reported) (**Table 1**).

CLINICAL IMPACT OF PVR. In a meta-analysis (4), moderate/severe PVR was associated with a 3-fold increase in 30-day mortality and a 2.3-fold increase in 1-year mortality following TAVR. The studies on the impact of mild PVR on outcomes have yielded conflicting results (1,4,6-8). In the PARTNER-IA (Placement of AoRTic TraNscathetER Valves) study randomized TAVR arm, the impact of mild PVR on survival was as important as that of moderate/severe PVR (~2-fold increase in the risk of mortality) (1). In a recent analysis of the PARTNER-IA randomized and nonrandomized continued access cohorts, mild PVR was independently associated with a 1.37-fold increase in all-cause mortality after adjustment for other comorbidities (6). However, in several large registries, moderate or greater PVR, but not mild PVR, was shown to have a significant impact on survival (2,7,8). Several factors may explain the intriguing association between mild PVR and mortality: 1) the pitfalls in the grading of PVR and the possibility that it may have been underestimated in a substantial number of patients (or that moderate PVR may have been overestimated); and 2) the worse baseline risk profile of patients with mild PVR versus those with none or trace PVR (6,9). Furthermore, even a mild PVR may have a detrimental impact in patients with small, thick, and noncompliant ventricles, such as is often the case in the population with severe aortic stenosis (AS) undergoing TAVR (7,10).

ABBREVIATIONS AND ACRONYMS

AR = aortic regurgitation

AS = aortic stenosis

ASE = American Society of Echocardiography

CMR = cardiac magnetic resonance

LV = left ventricle/ventricular

LVOT = left ventricular outflow tract

PVR = paravalvular regurgitation

RV = right ventricle/ventricular

TAVR = transcatheter aortic valve replacement

TEE = transesophageal echocardiography

THV = transcatheter heart valve

TTE = transthoracic echocardiography

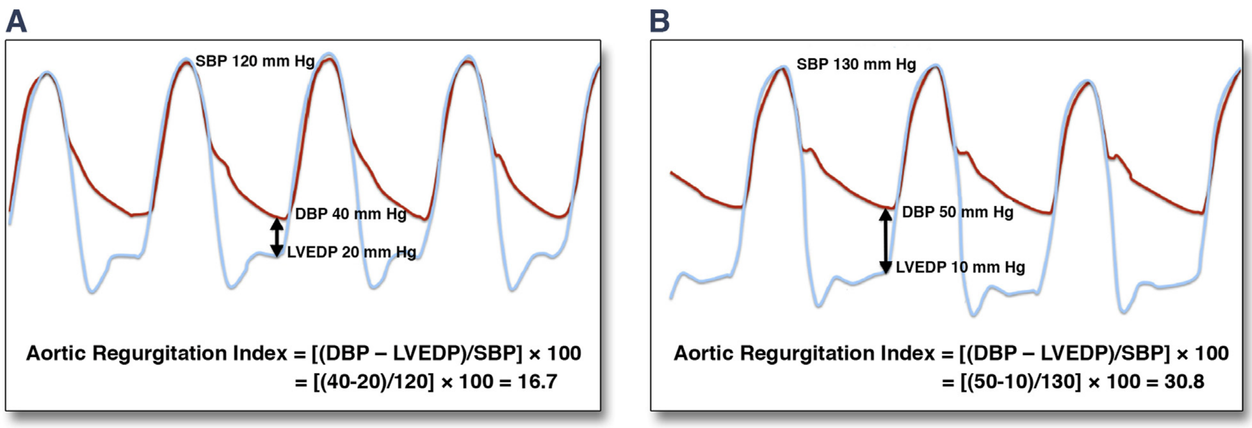
PROPOSAL OF A NEW UNIFYING SCHEME FOR GRADING PVR BY ECHOCARDIOGRAPHY

Several studies have used the 3-class grading scheme (mild, moderate, severe) proposed in the most recent guidelines (11-14) to report the severity of PVR, whereas other studies have employed the 4-class scheme (Grades 1, 2, 3, 4) often used clinically to grade native or prosthetic aortic regurgitation (AR) (Table 1). Among the studies that have applied this 4-class scheme, there is often ambiguity or even frank differences in Grades 2 and 3; the Grade 2 class is considered as an equivalent to mild AR in some studies, whereas it is considered as moderate in others, and Grade 3 is considered moderate in some studies and moderate to severe in others.

To better understand the possible contribution to differences in grading attributable to the broad categories of mild, moderate, and severe, and to align the grading scheme with the commonly used clinical scheme that uses "between-grade" options, we propose using an expanded grading scheme. When the reader is only offered a grading scheme with 3 broad classes, he or she would have a tendency to select the class in the middle (i.e., the moderate class) if there is a hesitation between 2 classes (mild vs. moderate or moderate vs. severe). We believe that the 5-class scheme will provide more flexibility for the grading of PVR and will therefore have the potential to improve the overall accuracy and reproducibility of PVR grading by echocardiography (15).

This proposed grading scheme follows clinical practice to divide: 1) mild PVR into 2 separate grades: mild and mild-to-moderate; and 2) moderate PVR into moderate and moderate-to-severe. This results in a 5-class grading scheme. The intent is that the 5 classes of grading would then be easily collapsed and reported with the 3-class scheme recommended by the American Society of Echocardiography (ASE)-European Association of Cardiovascular Imaging guidelines (11,14). It is recognized that more grades would initially produce greater variability but if the additional grades are used only as an interim step and then collapsed to the grades used in the guidelines, it may derive the benefits from clinical application and ultimately reduce variability. Furthermore, it also allows unification and clarification of several different grading scales. Table 1 presents the proposed qualitative, semiquantitative, and quantitative parameters of each class of this new grading scheme, as well as the correspondence with other existing schemes (3-class and 4-class). The echocardiographic parameters and criteria used to support this 5-class grading scheme are presented in the next section. Obviously, this new scheme will

FIGURE 1 AR Index for the Assessment of PVR Severity



The aortic regurgitation (AR) index can be used for quantitating AR severity following transcatheter heart valve (THV) deployment; it is calculated as the ratio of the diastolic transvalvular pressure gradient to the systolic blood pressure measured by left heart catheterization. In the patient with moderate paravalvular regurgitation (PVR) **(A)**, the AR index is 16.7, whereas in the patient with trace PVR **(B)**, the index is 30.8. Adapted with permission from Sinning et al. (16). DBP = end-diastolic blood pressure in the aorta; LVEDP = left-ventricular end-diastolic pressure; SBP = systolic blood pressure in the aorta.

TABLE 1 Scheme, Modalities, Parameters, and Criteria for Grading the Severity of PVR

3-Class Grading Scheme	Trace	Mild	Mild	Moderate	Moderate	Severe
4-Class Grading Scheme	**1**	**1**	**2**	**2**	**3**	**4**
Unifying 5-Class Grading Scheme	**Trace**	**Mild**	**Mild-to-Moderate**	**Moderate**	**Moderate-to-Severe**	**Severe**
Cineangiography	Grade 1	Grade 1	Grade 1	Grade 2	Grade 3	Grade 4
Invasive hemodynamics						
Aortic regurgitation index*	>25	>25	>25	10-25	10-25	<10
Doppler echocardiography						
Structural parameters						
● Valve stent	Usually normal	Usually normal	Normal/abnormal†	Normal/abnormal†	Usually abnormal†	Usually abnormal†
○ LV size‡	Normal	Normal	Normal	Normal/mildly dilated	Mildly/moderately dilated	Moderately/severely dilated
Doppler parameters (qualitative or semiquantitative)						
● Jet features§						
Extensive/wide jet origin	Absent	Absent	Absent	Present	Present	Present
Multiple jets	Possible	Possible	Often present	Often present	Usually present	Usually present
Jet path visible along the stent	Absent	Absent	Possible	Often present	Usually present	Present
Proximal flow convergence visible	Absent	Absent	Absent	Possible	Often present	Often present
○ Vena contracta width (mm): color Doppler‖	<2	<2	2-4	4-5	5-6	>6
○ Vena contracta area (mm^2): 2D/3D color Doppler¶	<5	5-10	10-20	20-30	30-40	>40
● Jet width at its origin (%LVOT diameter): color Doppler‖	Narrow (<5)	Narrow (5-15)	Intermediate (15-30)	Intermediate (30-45)	Large (45-60)	Large (>60)
○ Jet density: CW Doppler	Incomplete or faint	Incomplete or faint	Variable	Dense	Dense	Dense
○ Jet deceleration rate (PHT, ms): CW Doppler*‡	Slow (>500)	Slow (>500)	Slow (>500)	Variable (200-500)	Variable (200-500)	Steep (<200)
○ Diastolic flow reversal in the descending aorta: PW Doppler*‡	Absent	Absent or brief early diastolic	Intermediate	Intermediate	Holodiastolic (end-diast. vel. >20 cm/s)	Holodiastolic (end-diast. vel. >25 cm/s)
● Circumferential extent of PVR (%): color Doppler‖	<10	<10	10-20	20-30	>30	>30
Doppler parameters (quantitative)						
○ Regurgitant volume (ml/beat)#	<15	<15	15-30	30-45	45-60	>60
○ Regurgitant fraction (%)	<15	<15	15-30	30-40	40-50	>50
○ Effective regurgitant orifice area (mm^2)**	<5	<5	5-10	10-20	20-30	>30
Cardiac magnetic resonance imaging						
Regurgitant fraction (%)††	<10 <15	<10 <15	10-20 15-25	20-30 15-25	20-30 25-50	>30 >50

● Parameters that are most frequently applicable and used to grade PVR severity by echocardiography. ○ Parameters that are less often applicable due to pitfalls in the feasibility/accuracy of the measurements and/or to the interaction with other factors. Online Videos 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, and 36 provide Doppler color images (parasternal short- and long-axis, apical 5- and 3-chamber views) of representative cases for each class (except none and severe PVR) of the unifying 5-class grading scheme proposed in this table. *These parameters are influenced by LV and aortic compliance. In particular, low transvalvular end-diastolic aorta to LV pressure gradient that is due to concomitant moderate/severe LV diastolic dysfunction may lead to false-positive results. The high dependency of aortic flow reversal on aortic compliance considerably limits the utility of this parameter in the elderly population undergoing TAVR. These parameters are also influenced by chronotropy. †Abnormalities of stent position (too low or too high), deployment, and/or circularity. ‡Applies to chronic PVR but is less reliable for periprocedural or early post-procedural assessment. §See **Figure 9** for illustrative images. ‖These parameters are generally assessed visually. ¶The vena contracta area is measured by planimetry of the vena contracta of the jet(s) on 2D or 3D color Doppler images in the short-axis view (**Figure 8**). #Regurgitant volume is calculated as the difference of stroke volume measured in the LV outflow tract minus the stroke volume measured in the right ventricular outflow tract (see **Figure 10**). **The effective regurgitant orifice area is calculated by dividing the regurgitant volume by the time-velocity integral of the AR flow by CW Doppler. ††There are important variability in the cutpoint values of regurgitant fraction and volume reported in the published studies to grade AR by cardiac magnetic resonance imaging.

2D = 2-dimensional; 3D = 3-dimensional; AR = aortic regurgitation; CW = continuous wave; end diast. vel. = end-diastolic velocity; LV = left ventricular; LVOT = left ventricular outflow tract; PHT = pressure half-time; PVR = paravalvular regurgitation; PW = pulsed wave; RV = right ventricular; TAVR = transcatheter aortic valve replacement.

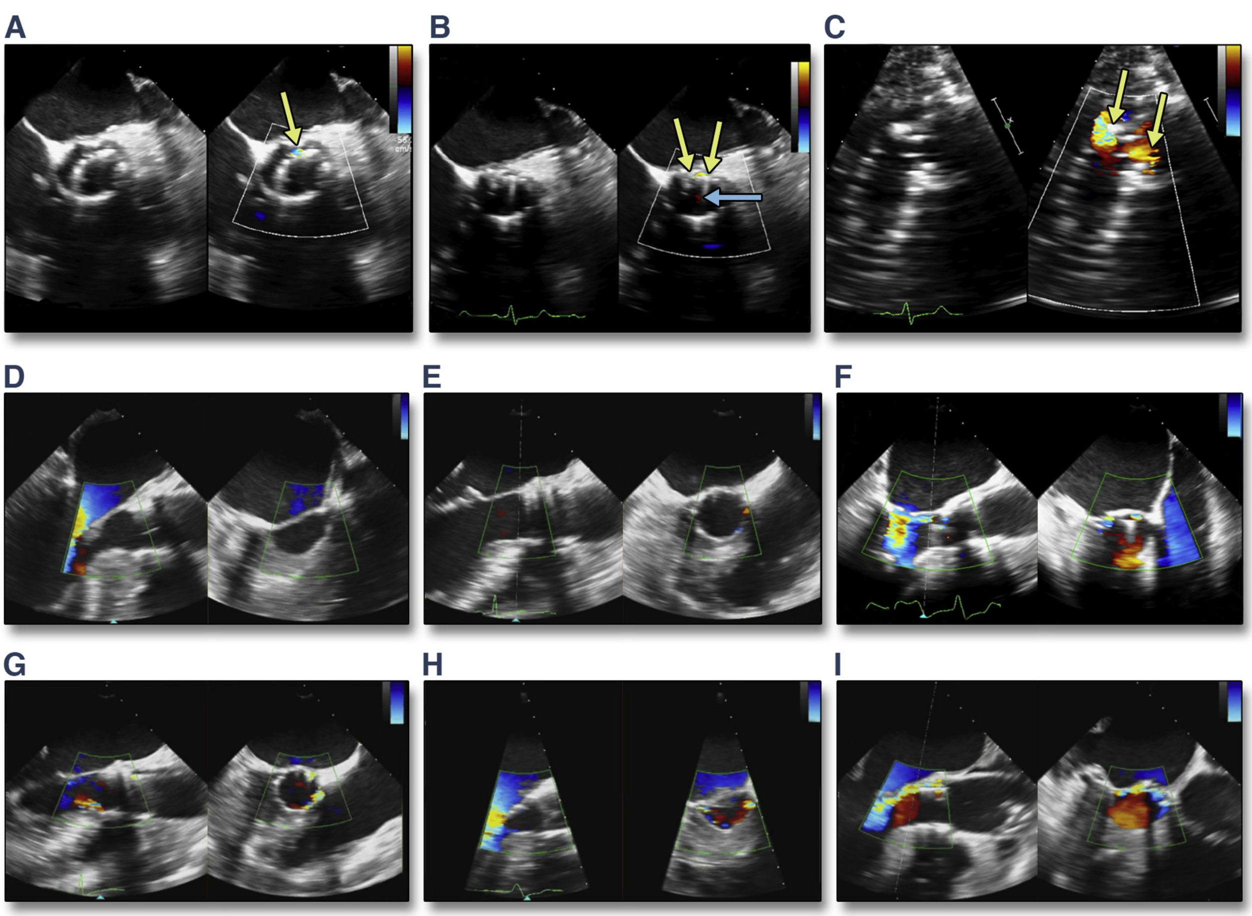
have to be validated with PVR severity data determined by other modalities (e.g., CMR) and, more importantly, with outcome data.

IDENTIFICATION AND QUANTITATION OF PVR

Several modalities may be used to identify and quantitate PVR, and each of these modalities has inherent limitations and technical pitfalls. Echocardiography remains the most frequently used modality to detect, grade, and follow PVR. During the procedure, transesophageal echocardiography (TEE), cineangiography, and/or invasive hemodynamics are utilized to assess PVR, whereas transthoracic echocardiography (TTE) is generally used for the assessment and follow-up of PVR after the procedure. TTE is also used in place of TEE for periprocedural assessment when TAVR is performed under conscious sedation only.

CINEANGIOGRAPHY. Semiquantitative assessment of AR can be obtained during the procedure by assessing the relative density of contrast media in the left ventricle by cineangiography (16,17). AR severity is classified according to the visually estimated density of opacification of the left ventricle (LV) into 4 grades (13,16). However, cineangiography is highly subjective and dependent on observer's experience as well as the numerous technical factors (i.e., the intensity

FIGURE 2 Transesophageal Color Doppler Echocardiographic Views for the Assessment of PVR

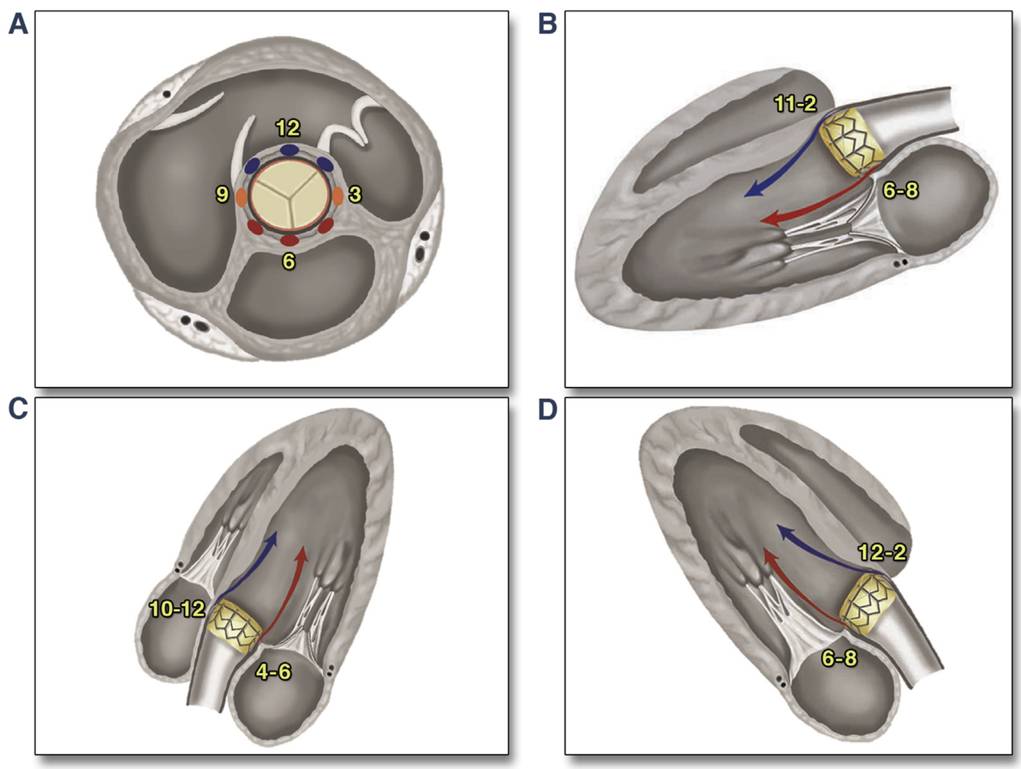


Multiple views should be used to assess paravalvular regurgitation (PVR) by transesophageal echocardiography (TEE). **A** is a mid-esophageal short-axis view with simultaneous 2-dimensional (2D) and color Doppler imaging at the mid-transcatheter heart valve (THV) level. A small jet of color **(yellow arrow)** represents flow in the sinus of Valsalva. **B** is at the level of the leaflets with color jet between the **yellow arrows** likely representing turbulent flow between the native calcified cusps and THV. The **blue arrow** indicates trivial central aortic regurgitation (AR). **C** is from the deep transgastric view, and multiple jets of PVR are seen **(yellow arrows)**. Note: from these views, jet length and area may exaggerate the severity of the PVR. **D to I** present representative cases of none **(D)**, mild **(E)**, mild-to-moderate **(F)**, moderate **(G)**, moderate-to-severe **(H)**, and severe **(I)** PVR.

of fluoroscopy, the use of single or biplane imaging, the volume of the contrast medium injected, the type and position of the catheter tip), which result in significant variability in grading. In addition, this method has not been validated for the post-TAVR population, where atypical, multiple, localized jets may influence the density of contrast seen in the ventricle. Recently, quantitative densitometry has been proposed as a more reproducible measure of AR following TAVR by comparing the density of the contrast in the aorta with that in the ventricle (18). Many patients undergoing TAVR have renal insufficiency, and therefore, it is prudent to minimize the contrast load; this is another reason why cine-angiography may not be the modality of choice in this setting.

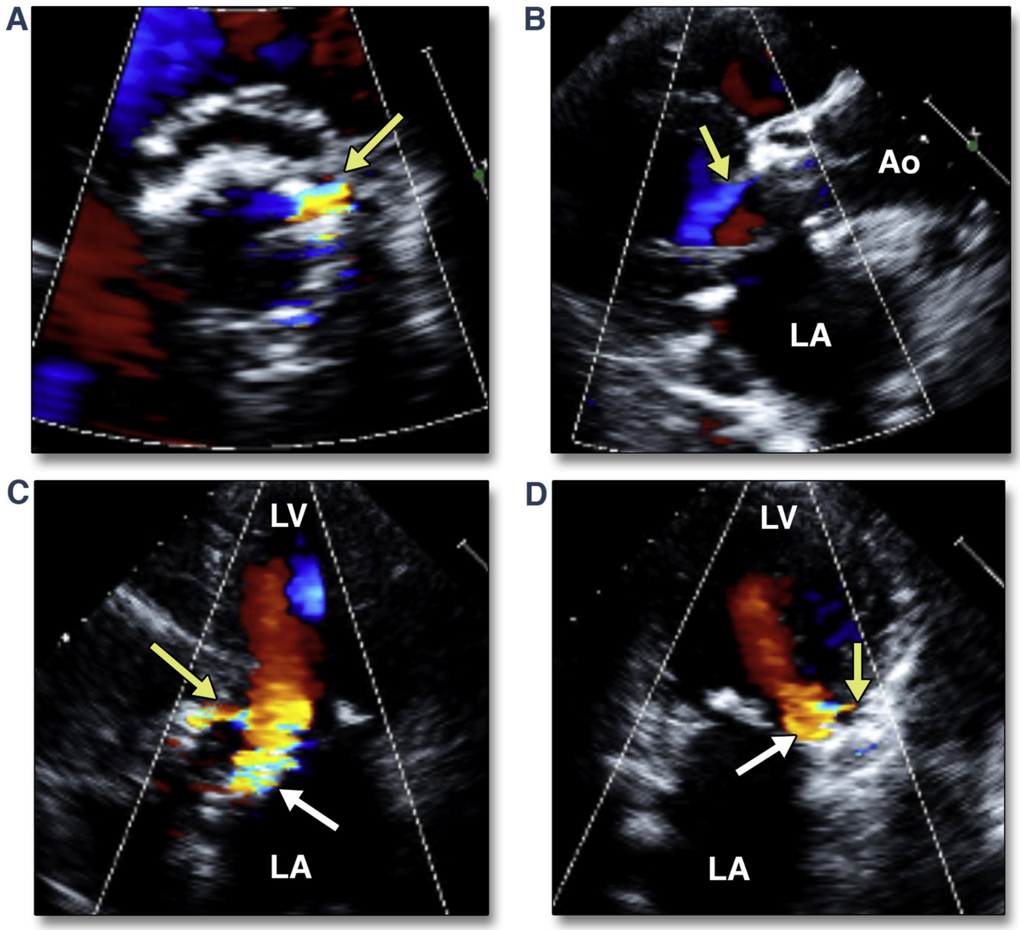
HEMODYNAMIC ASSESSMENT. Invasive hemodynamic measurements may provide additional information on the severity of AR during the procedure. Sinning et al. (16) proposed calculating the AR index to assess the severity of PVR during TAVR: AR index = [(DBP − LVEDP)/SBP] × 100, where DBP and SBP are diastolic and systolic blood pressures, and LVEDP is the LV end-diastolic pressure (Figure 1). An index of <25% was predictive of increased 1-year mortality in both patients with none/mild PVR and those with moderate/severe PVR, suggesting that the severity of regurgitation may not be the only determinant of the AR index. A false-positive AR index can be seen with abnormal ventricular or aortic compliance. Nonspecific elevation of the LV end-diastolic pressure in the setting of severe LV diastolic dysfunction, as well as increased aortic stiffness resulting in diastolic reversal of flow, may lead to a low end-diastolic transvalvular gradient in the absence of significant AR. Similar to angiographic grading, there is a significant overlap

FIGURE 3 Location of the PVR Jets in the Different Transthoracic Echocardiographic Views



Schematic representations of transthoracic echocardiographic (TTE) views: parasternal short-axis view **(A)**; parasternal long-axis view **(B)**; apical 5-chamber view **(C)**; apical 3-chamber view **(D)** (see Figure 4 for representative TTE images and videos). The location of the jets are described according to the face of a clock applied on the short-axis view with the insertion of the tricuspid valve leaflet set as the 9 o'clock reference **(A)**. The jets with anterior location (10 to 2 o'clock) are represented in **blue** in all views; the jets with posterior location (4 to 8 o'clock) in **red**, and the jets with lateral or medial locations (8 to 10 and 2 to 4 o'clock) are in **orange**. PVR = paravalvular regurgitation. Adapted with permission from Gonçalves et al. (23).

FIGURE 4 **Multiview, Multiplane TTE Imaging for the Assessment of PVR**



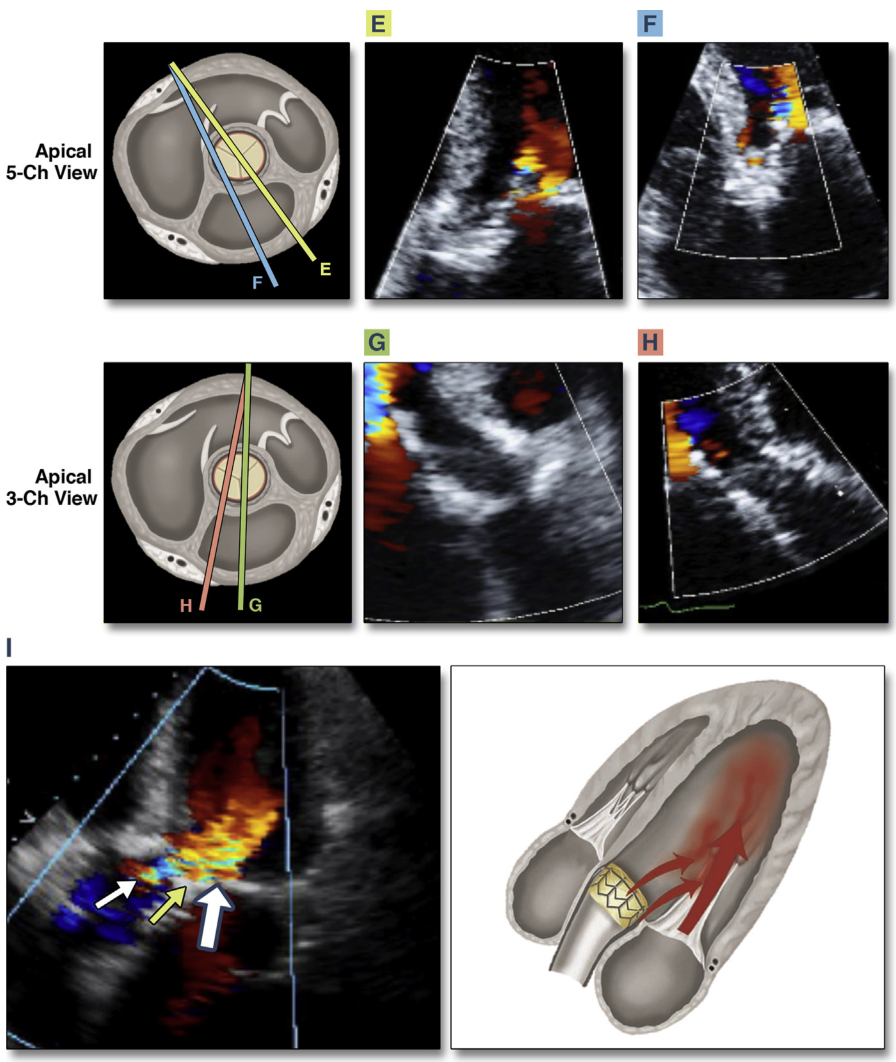
Parasternal short-axis view **(A)** (Online Video 1); parasternal long-axis view **(B)** (Online Video 2); apical 5-chamber view **(C)** (Online Video 3); apical 3-chamber view **(D)** (Online Video 4). The **yellow arrow** indicates a small anterior jet, and the **white arrow** a larger posterior jet. The posterior jet is not well visualized and largely underestimated in the parasternal views **(A and B)**. **E, F, G, and H** (Online Videos 5, 6, 7, and 8) underline the importance of rotational sweeps in the apical 5- and 3-chamber views to obtain multiplane imaging and therefore optimize the visualization and assessment of PVR jet(s). The schematic representation in the **left panels** shows the location of the image plane in the short-axis view. **I** shows a color Doppler TTE image and a schematic representation of a case with a central regurgitation **(thin white arrow)** and a posterior PVR **(thin yellow arrow)** (Online Video 9). The posterior jet merges with the systolic mitral flow **(large white arrow)**, making difficult the visualization of the origin of this jet and the grading of PVR severity. Abbreviations as in **Figure 3**.

Continued on the next page

between grades, and the AR index does not differentiate between central or paravalvular regurgitation. Another pitfall of the AR index is that it is dependent on heart rate. In many respects, it is analogous to the continuous-wave Doppler pressure half-time method (see the following text) and carries similar limitations. Hence, intraprocedural decision making using this index should integrate this index with other imaging modalities such as echocardiography.

ECHOCARDIOGRAPHY. PVR jets are often multiple, eccentric, and of irregular shape (**Figures 2 to 6**, Online Videos 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12) (9,11). Furthermore, they are confined along the left ventricular outflow tract (LVOT) wall, and they may be masked partially or totally as a result of acoustic shadowing from the calcifications of the native aortic annulus or from the THV stent. These features render the echocardiographic imaging, detection, and quantification of PVR particularly challenging. Several parameters and criteria have been proposed in the recent ASE-European Association of Cardiovascular Imaging and Valve Academic Research

FIGURE 4 Continued

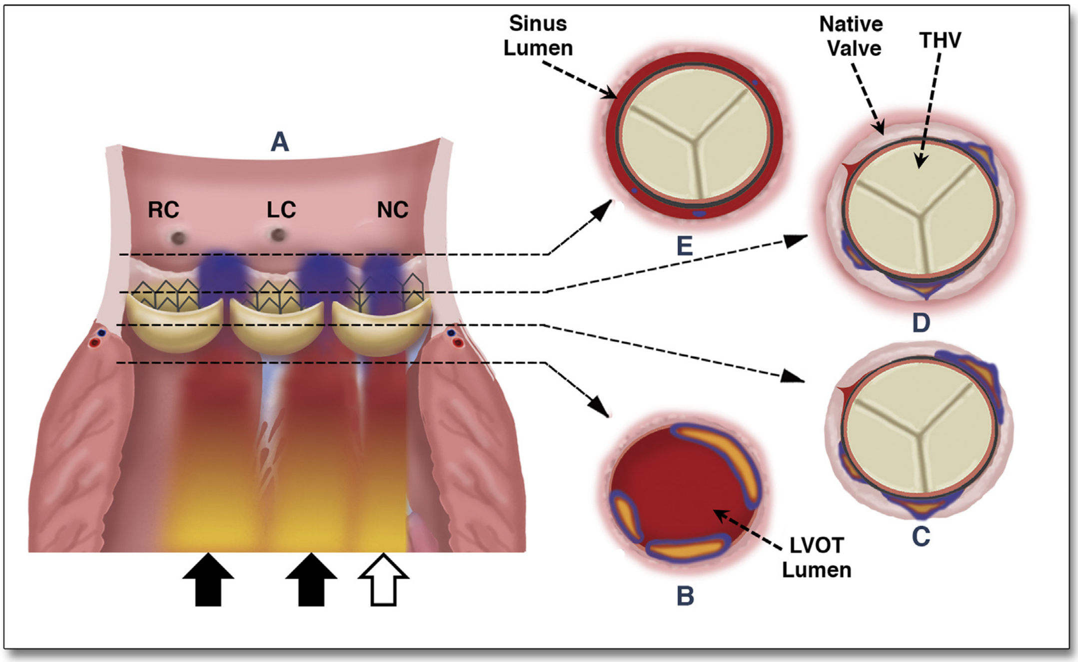


Consortium 2 guidelines (11,13,14) to assess PVR by echocardiography (Table 1). However, because of the particular nature of PVR jet(s), several of the semi-quantitative or quantitative parameters that are generally used to grade native AR (12) are difficult or impossible to apply to the context of PVR (11,13,14). In the following subsections, we present the parameters proposed in the guidelines, as well as other additional parameters that can be used to support the classification of PVR severity according to the 3-class, 4-class, and proposed 5-class grading schemes (Table 1).

Structural parameters. *THV stent position and shape.* Although the presence of abnormalities of THV stent position or shape provides supportive findings to identify and grade PVR, these findings lack sensitivity and specificity. The parasternal long- and short-axis views are generally the best views to assess THV stent position and shape. PVR that is moderate or greater is often associated with: 1) inappropriate low (or high) stent position; 2) noncircular/irregular stent shape; and 3) clearly visible free space between stent and native aortic annulus. Real-time 3-dimensional (3D) echocardiography may help to identify and assess abnormalities of THV stent shape and position.

LV size and function. In the periprocedural and early post-procedural (<3 months) period, a significant increase in LV diameter and/or deterioration in LV ejection fraction compared with pre-procedural echocardiography should raise the level of concern with regard to the presence of significant PVR. However, these findings have a relatively low

FIGURE 5 **Circumferential Extent of the PVR According to the Jet Location and Plane of Interrogation**



(A) Shows a longitudinal unfold view of the left ventricular outflow tract (LVOT), transcatheter heart valve (THV), native valve, and aortic root. **(B, C, D, E)** Show the short-axis cross sections at different levels: LVOT **(B)** and lower **(C)**, mid **(D)**, and upper **(E)** portions of the THV. The extent of the paravalvular circumference occupied by the regurgitant jet(s) can be used to assess the severity of the regurgitation **(C, D)**. **(A, C, D)** The paravalvular regurgitation (PVR) most frequently occurs at the location of the native valve commissures (i.e., between right and left coronary cusps: 1 to 2 o'clock on the short-axis view; left and non-coronary cusps: 5 to 6 o'clock; and non- and right coronary cusps: 10 to 11 o'clock). Given that the extension of these jets at the commissures is determined by the size of the native intervalvular triangle, they tend to splay widely as they flow toward the lower portion of the THV stent and LVOT **(black arrows)**. The circumferential extent of these jets may thus vary markedly depending on the plane of interrogation used for the short-axis view. The jets arising from malapposition of the THV stent, most frequently due to bulky calcification of the native cusp, are generally more restricted with less splaying in the LVOT **(white arrow)**. **(F, G, H)** In this example, the size of the PVR jet is dependent on the level of imaging. **Panel F** is a short-axis image at the level of the aortic root near the left main coronary artery **(red arrow)**. **Panel G** is at the level of the THV leaflets **(blue arrow)** and shows a small PVR jet **(yellow arrow)**. **H** is slightly lower, near the ventricular edge of the THV stent and the aortic regurgitant jet is much larger. **(I and J)** In this example, the size of the PVR jet is also dependent on the level of imaging. **I** is a simultaneous multiplane image with the long axis showing the level of the orthogonal short-axis view **(blue arrow)**. The short-axis view has 2 turbulent color Doppler jets associated with the stent frame. In **J**, the orthogonal view is within the LVOT and no PVR is seen. **A, B, C, D, and E** are adapted with permission from Tuzcu et al. (20).

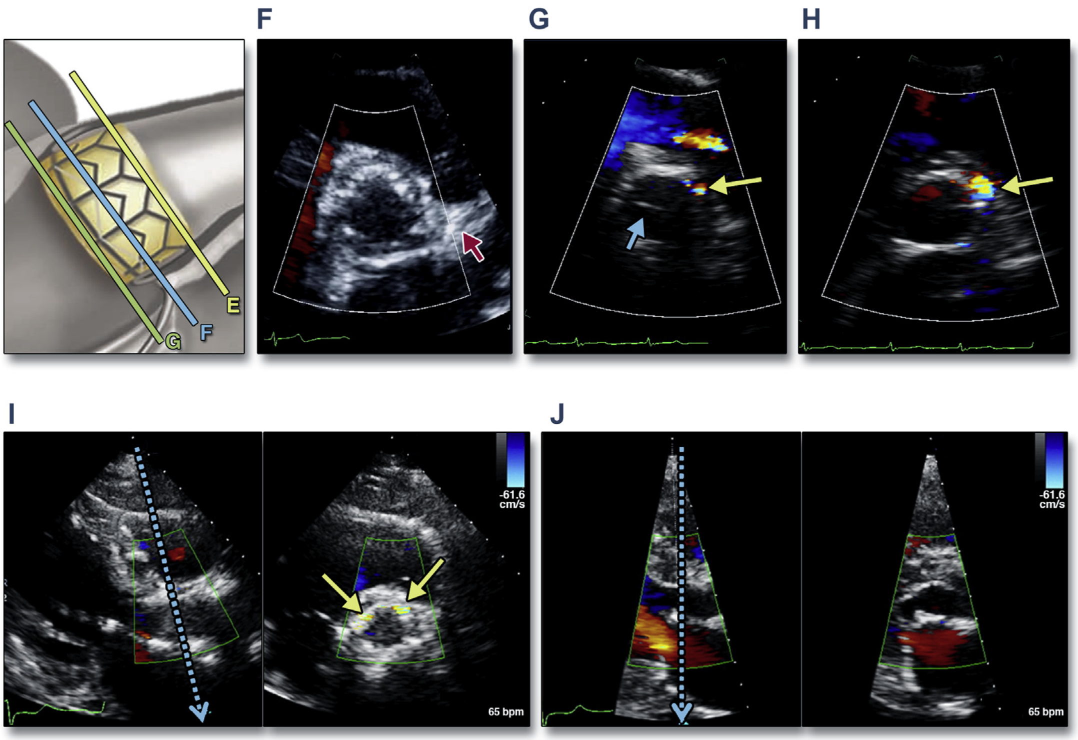
Continued on the next page

specificity and, more importantly, a low sensitivity in the acute post-TAVR phase. Indeed, immediately after procedure, a large proportion of patients with moderate or greater PVR have no significant LV dilation. The consideration of the LV cavity size becomes more useful in the context of chronic THV regurgitation (**Table 1**). In the late (>3 to 6 months) post-TAVR phase, the presence of moderate or greater PVR is expected to be associated with significant LV dilation during follow-up, and its absence should, in most situations, preclude the diagnosis of significant regurgitation, whereas its presence should increase the level of suspicion.

Color Doppler parameters. For both TEE and TTE evaluation of PVR, it is essential to obtain color Doppler images in multiple views and multiple planes (**Figures 2 to 6**, Online Videos 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 12) to ensure complete visualization of the paravalvular region and proper detection and assessment of all PVR jets.

With TEE, the PVR jets are best visualized in the mid-esophageal long-axis view of the THV, mid-esophageal short-axis view just below the level of the stent, and transgastric views (**Figure 2**). Multiple short-axis levels of the THV (from the level of the leaflets to below the stent frame) should be evaluated. Deep transgastric views of the THV allow for a multiangle rotation to assess the entire circumference of the valve (**Figure 2**). Although jet length and width should not be used to assess severity, the number of

FIGURE 5 Continued



jets and the size of the jet origin may be helpful in determining PVR severity.

With TTE, the 4 main views that should be acquired are the parasternal short-axis, parasternal long-axis, apical 5-chamber, and apical 3-chamber views (**Figures 3 and 4**, Online Videos 1, 2, 3, and 4). For the short-axis view, it is very important to do an aorta-to-LVOT sweep and acquire images at several levels of the valve stent (**Figure 5**). A lateral-to-medial sweep is also useful in the parasternal long-axis view. For the apical views, it is important to perform translational (lateral to medial, anterior to posterior) and rotational (5-chamber to 4-chamber to 3-chamber) sweeps and acquire off-axis and intermediary (e.g., between 5- and 4-chamber) views (**Figures 4E, 4F, 4G, and 4H**, Online Videos 5, 6, 7, and 8).

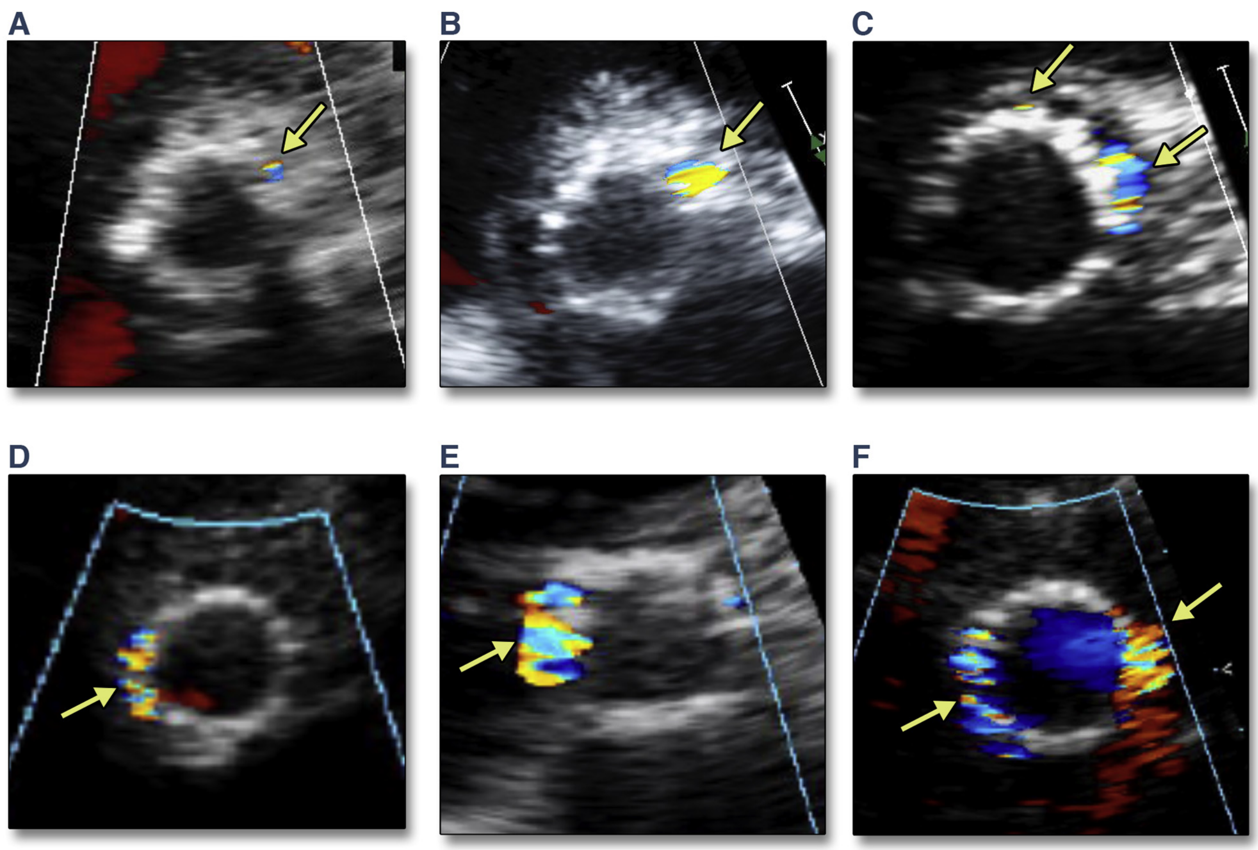
Detection and localization of the PVR jets: Because of the shadowing caused by the native aortic valve calcifications and the THV stent, the PVR jets located posteriorly are often totally or partially masked in the parasternal long-axis or short-axis TTE views (**Figures 3, 4A, 4B, 4C, and 4D**, Online Videos 1, 2, 3, and 4). Apical views should thus be carefully examined to properly detect and quantitate these posterior jets. Conversely, with TEE, the anterior jets may be underdetected or underestimated in some views as a result of this shadowing phenomenon. The PVR jets located on the lateral or medial aspects of the THV are often difficult to visualize in the standard parasternal long-axis and apical TTE views, and it is necessary to obtain off-axis/intermediary views to reveal these jets.

To provide a more precise description of the localization of the PVR jets, the face of a clock can be applied to the short-axis view using the tricuspid valve septal leaflet insertion as the 9 o'clock reference (**Figure 3**). The most frequent locations of PVR following TAVR are at the 1 to 2, 5 to 6, and 9 to 11 o'clock positions (19), which correspond to the commissures of the native aortic valve (**Figure 5**). Indeed, at these locations, the stent, which has a circular shape with limited flexibility, does not conform to the triangular configuration of the commissure (20). These PVR jets arising from the native commissures often splay widely when they enter into the LVOT (**Figure 5**). PVR may also occur at other locations because of malapposition of the stent, which is often related to bulky calcifications. These jets tend to be more restricted and splay less as they enter into the LVOT.

The circumferential extent of the PVR jet(s) estimated in the parasternal short-axis view is the main

JACC: CARDIOVASCULAR IMAGING, VOL. 8, NO. 3, 2015
MARCH 2015:340–60

FIGURE 6 Circumferential Extent of the PVR for Assessment of Regurgitation Severity



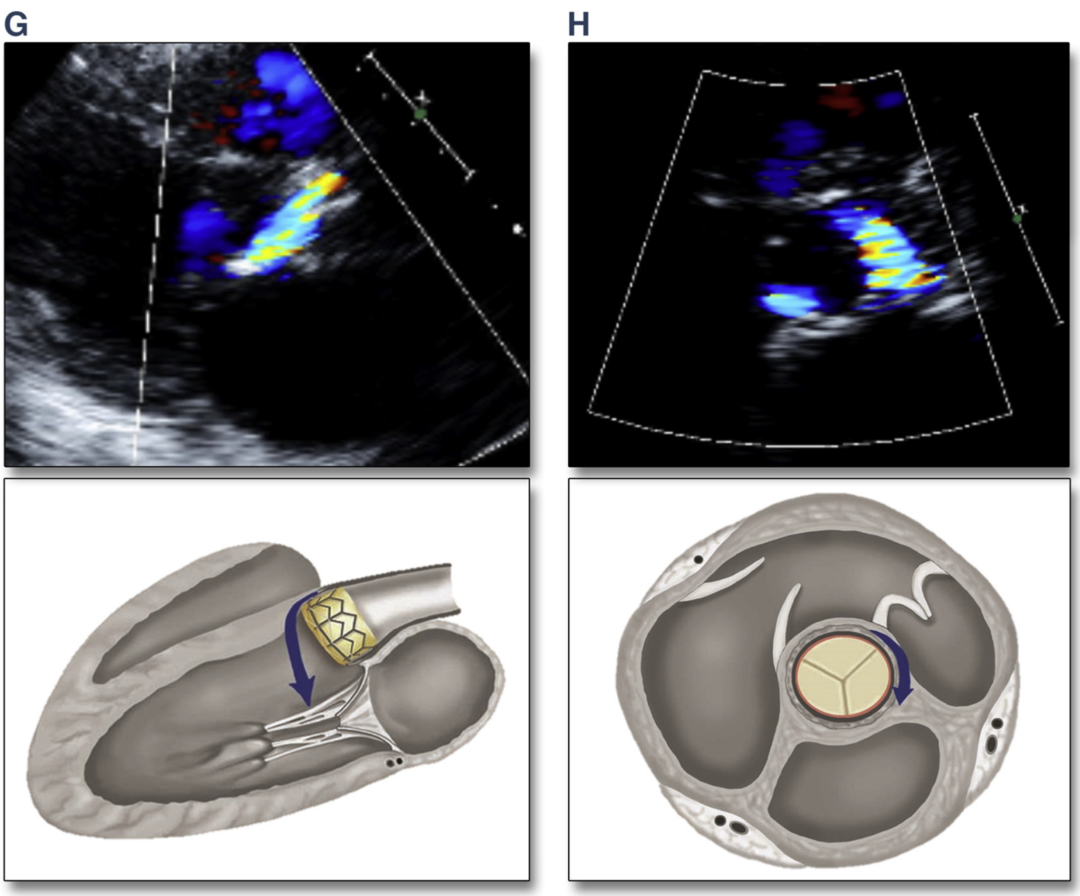
This figure shows TTE short-axis images with various degrees of regurgitant jet circumferential extent and PVR severity (**yellow arrows** show PVR jets): <5%, trace PVR **(A)**; 5% to 15%, mild PVR **(B)**; 15% to 25%, mild-to-moderate PVR **(C and D)**; 15% to 25% but larger jet width, moderate PVR **(E)**; >30%, moderate-to-severe PVR **(F)**. **(G and H)** Show TTE parasternal long-axis **(G)** (Online Video 10) and short-axis **(H)** (Online Videos 11 and 12) views and schematic representations of an eccentric anterior PVR jet. On the short-axis view **(H)**, the circumferential extent of this eccentric jet may easily be overestimated (see Online Videos 11 vs. 12). There is also a small posterior jet visible in the parasternal long- and short-axis views (Online Videos 10 and 11). The anterior jets are often eccentric because when they enter into the LVOT, they are deviated posteriorly by the prominent septal bulge (see schematic representation in the **left bottom panel**). Abbreviations as in **Figures 3 and 5**.

Continued on the next page

parameter that has been proposed in the guidelines for semiquantitative assessment of PVR severity (**Table 1**, **Figures 4 and 6**, Online Videos 1, 11, and 12) (11,14). This parameter is assessed by estimating visually the approximate number of minutes occupied by the PVR jet(s) according to the face of a clock and by dividing this number by 60 min (**Figures 5 and 6**). The circumferential extent is then expressed as a percentage and, according to the 2009 ASE guidelines (11), a value between 10% and 20% would correspond to moderate PVR, and a value >20% to severe PVR. However, these cutpoint values have been revised in the 2012 Valve Academic Research Consortium 2 recommendations (13) and an extent between 10% and 30% corresponds to moderate PVR, and >30% to severe PVR, to correspond to the grading scheme used by the PARTNER-I trial (1,2). However, the PVR circumferential extent may vary substantially depending on the plane of interrogation (**Figure 5**). It is thus important to scan the entire height of the stent and use the short-axis plane where the vena contracta of the jet is the smallest. An image plane that is too high (above the stent or upper portion of the stent) may underestimate the regurgitation, whereas a plane that is too low in the LVOT may overestimate the regurgitation severity as a result of rapid broadening of the jet downstream of the vena contracta (**Figure 5**).

The circumferential extent of the jet becomes even more complex and less reliable when multiple and/or eccentric jets are present. In case of multiple-jet PVR,

FIGURE 6 Continued



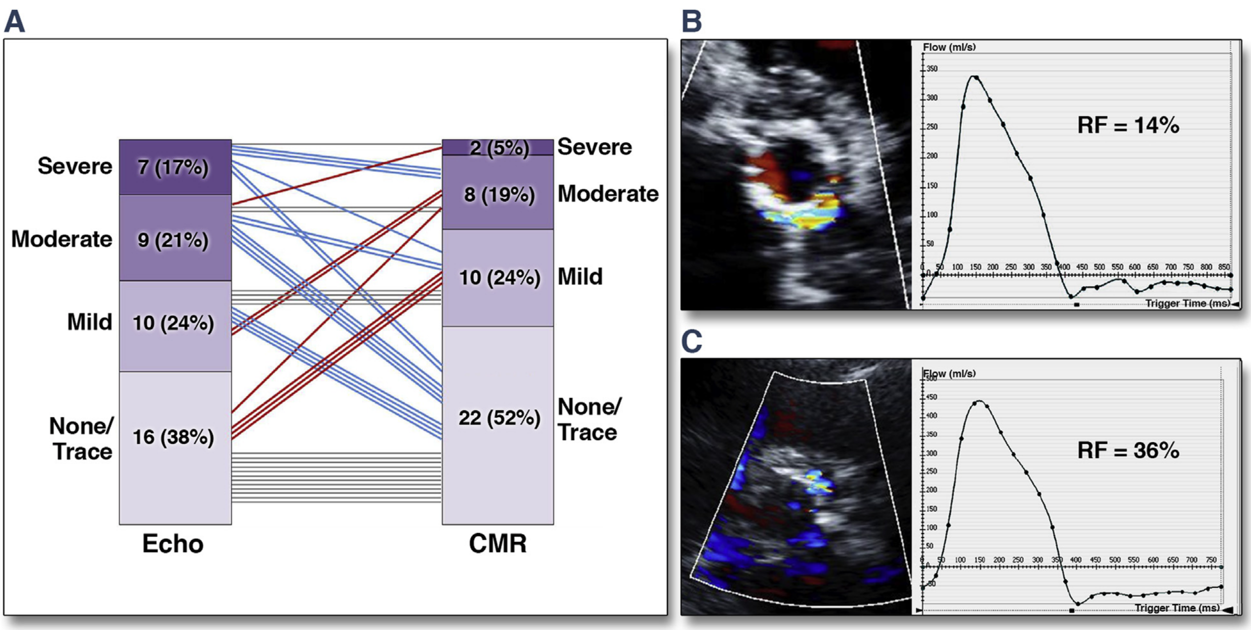
the vena contracta may be at different levels depending on the jets, and this may, therefore, require several image planes to assess the overall circumferential extent of PVR. Moreover, the PVR jets, and particularly the anterior jets may be very eccentric and in such case, the jet may be directed across the short-axis plane, which may lead to an overestimation of the circumferential extent and thus of the severity of PVR (**Figures 6G and 6H**, Online Videos 10, 11, and 12). Inversely, the severity of PVR may be underestimated when a jet does not occupy a large circumferential extent but has a greater radial width (**Figure 6E**). Recent studies revealed that this parameter correlates poorly with the severity of PVR measured by CMR (**Figure 7**) (21,22).

Hence, the grading of PVR should not rely solely on the examination of the short-axis view and estimation of circumferential extent. This measure should be integrated with other views and parameters, as described below.

The width of the jet at its origin is probably the most important parameter to consider for grading the severity of PVR. It is assessed visually in the parasternal and apical views, and an estimate of the ratio of the jet width to the LVOT diameter may be provided and expressed in percentage (**Table 1**). It is important to visualize the origin of the jet(s) just underneath the apical border of the stent before the jet dispersion, which can be challenging (**Figures 4 and 5**). The PVR jets located posteriorly may be difficult to visualize and assess because they tend to merge with the mitral flow (**Figure 4I**, Online Video 9).

The vena contracta of the PVR jets is often difficult to visualize and measure by 2-dimensional color Doppler echocardiography. Furthermore, as opposed to native AR or central prosthetic AR, the vena contracta of PVR is not circular and is often irregular (**Figure 5**). 3D echocardiography may eventually overcome the limitations of 2-dimensional and standard Doppler measurements for quantifying PVR.

FIGURE 7 Comparison of PVR Severity Assessed With the Jet Circumferential Extent by Doppler-Echocardiography vs. the Regurgitation Fraction by CMR Imaging



(A) Shows the comparison of AR severity based on the PVR circumferential extent by Doppler echocardiography versus the regurgitant fraction (RF) by cardiac magnetic resonance (CMR). **(B and C)** Show 2 examples where circumferential extent overestimated **(B)** and underestimated **(C)** the AR severity as assessed by CMR RF. Adapted with permission from Ribeiro et al. (21). Abbreviations as in **Figure 1**.

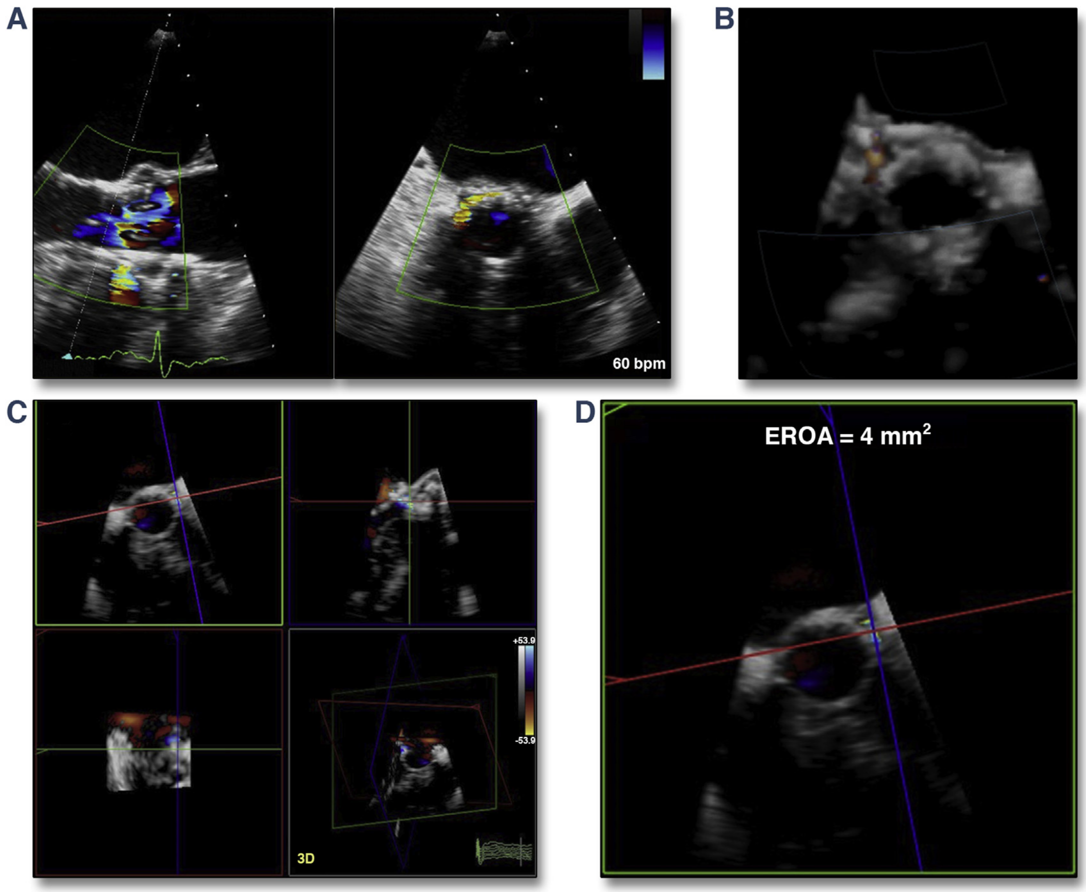
Studies using 3D TTE have shown the feasibility of measuring the 3D vena contracta of PVR following TAVR (**Figure 8**, **Table 1**) (23,24).

PVR jet features. Besides the size and circumferential extent of the jet at its origin, other characteristics may be used to grade the severity of PVR, including the number of jets and the visualization of the jet path along the stent and/or of the proximal flow convergence (**Figure 9**, **Table 1**). The number of jets visualized at echocardiography correlates with the regurgitant fraction measured by CMR (21). Nevertheless, a single jet can be severe if it has a large vena contracta. On the other hand, 3 mild jets may correspond to moderate PVR or more. When the path of the PVR jet is clearly visible along the whole length of the stent, this is often associated with moderate or greater PVR (**Figure 9**). The proximal flow convergence is rarely visible in the case of PVR, but when it is, this is often a marker of significant PVR. As for native AR, the use of regurgitant jet area and length are no longer recommended because these parameters are unreliable indicators of AR severity, given their dependence on blood pressure and aortic and ventricular compliance. Very short jets are rarely greater than mild, but longer jets can be mild to severe depending on the size of their vena contracta and other hemodynamic variables. Online Videos 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, and 36 provide color Doppler images of representative cases for each class (except none and severe PVR) of the 5-class grading scheme proposed in **Table 1**.

Doppler parameters. Doppler parameters, including the signal intensity and pressure half-time of the continuous-wave envelope of the regurgitant jet(s) and the timing and velocity of the diastolic flow reversal in the descending aorta, may also be determined to corroborate PVR severity (**Figure 10**, **Table 1**). However, the accuracy of these parameters is limited in the early post-procedural period because of the acute nature of PVR and the frequent coexistence of moderate-severe diastolic dysfunction. Furthermore, pressure half-time is highly heart-rate dependent.

The flow reversal in the descending aorta and the end-diastolic velocity measured by pulsed-wave Doppler is strongly influenced by aorta compliance,

FIGURE 8 Usefulness of 3D Color Doppler to Assess PVR

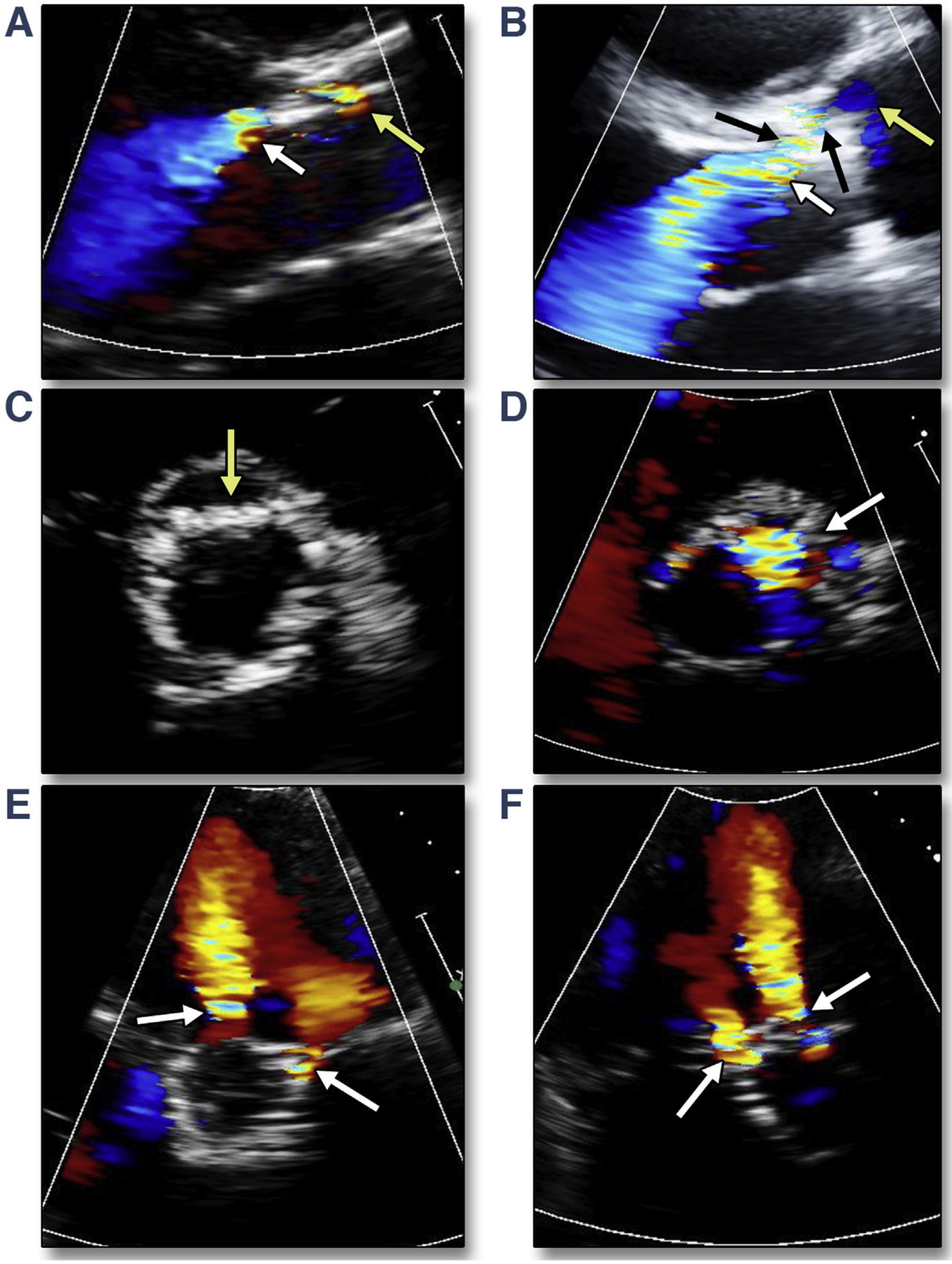


In this case, the patient has a PVR jet along the posterolateral aspect of the THV stent that is imaged on simultaneous multiplane imaging **(A)**. However, the level of imaging is just above the lowest edge of the THV stent. On 3-dimensional (3D) color Doppler **(B),** the regurgitant jet does not appear as significant. Using multiplanar reconstruction **(C),** the vena contracta can be imaged and the effective regurgitant orifice area (EROA) measured **(D)**. Abbreviations as in Figure 5.

and increased arterial stiffness may result in false-positive results. Indeed, several studies reported that holodiastolic and rapid flow reversal can occur in elderly patients with stiff aorta, even in the absence of significant AR (25). This considerably limits the usefulness of aortic flow reversal in the TAVR population, given that these patients are generally old and the majority have markedly reduced arterial compliance.

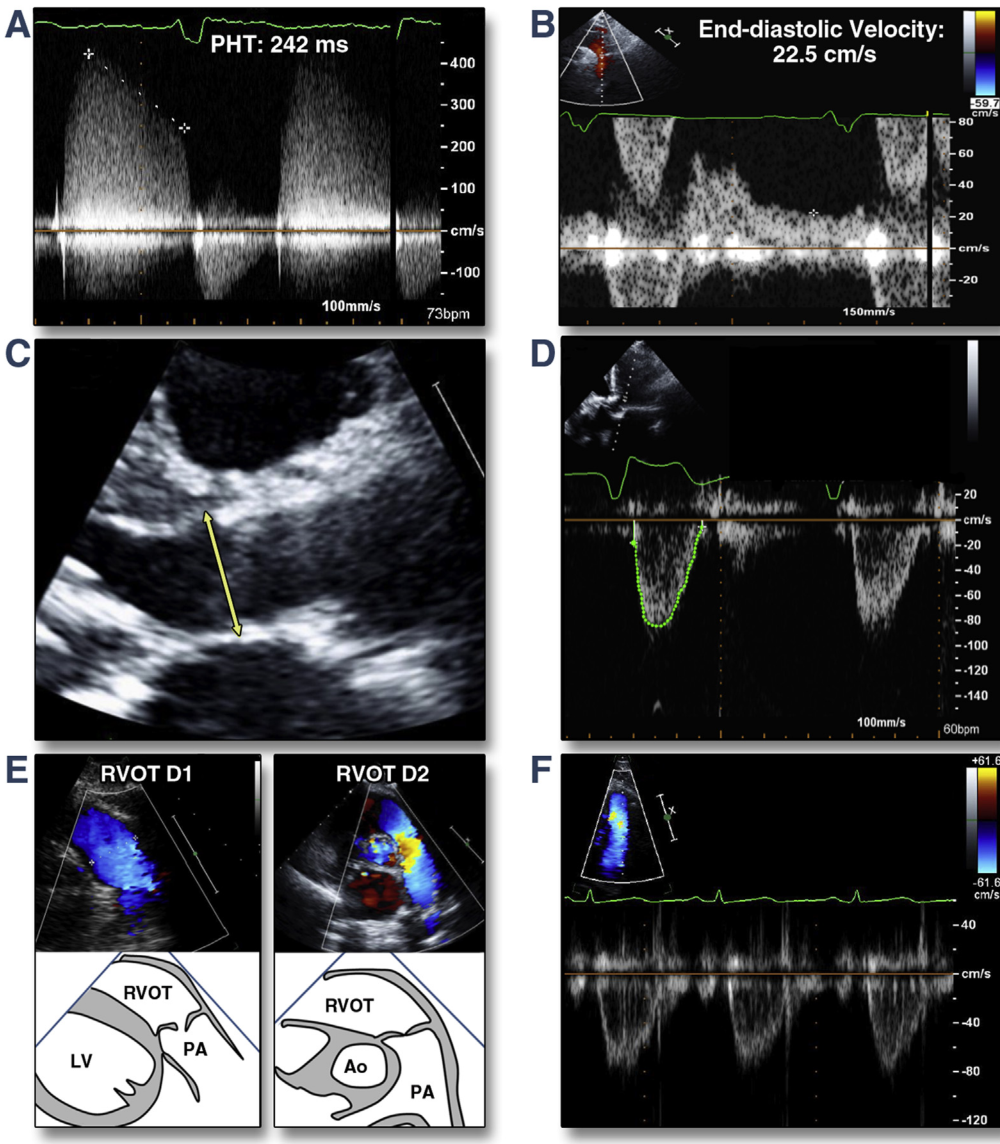
Quantitative parameters. Quantitative methods such as the Proximal Isovelocity Surface Area method are rarely applicable to PVR (11). The regurgitant volume may, however, be estimated by calculating the difference between the left and right ventricular (RV) stroke volumes, providing that there is no significant pulmonary regurgitation (Figure 10, Table 1). This parameter is, however, subject to significant interobserver and intraobserver measurement variability, which is, in large part, related to the difficulty of measuring the RV outflow tract diameter by TTE (24). Newer methods based on real-time 3D velocity color flow Doppler echocardiography allow automated quantification of the velocity, flow rate, and flow volume in any given region of the heart from color Doppler images (26). This method provides excellent feasibility, accuracy, and reproducibility for the quantitation of mitral inflow and aortic stroke volumes. The application of this method to the measurement of LV and RV stroke volumes would potentially permit one to obtain a more accurate measure of the PVR regurgitant volume.

FIGURE 9 **PVR Jet Features Associated With Regurgitation Severity**



This figure shows some of the PVR jet features often associated with moderate or greater PVR: large width of the jet at its origin **(white arrow)**, visible path of the PVR jet along the stent **(black arrows)**, visible proximal flow convergence **(yellow arrows) (A and B)**; abnormal THV stent shape with mal-apposition **(yellow arrow)** and large vena contracta of the PVR jet **(white arrow)** in the short-axis views **(C and D)**; multiple jets with large width at the origin in multiple views **(white arrows) (E and F)**. Online Videos 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, and 36 present representative color Doppler images of the different classes of PVR severity. Abbreviations as in **Figure 5**.

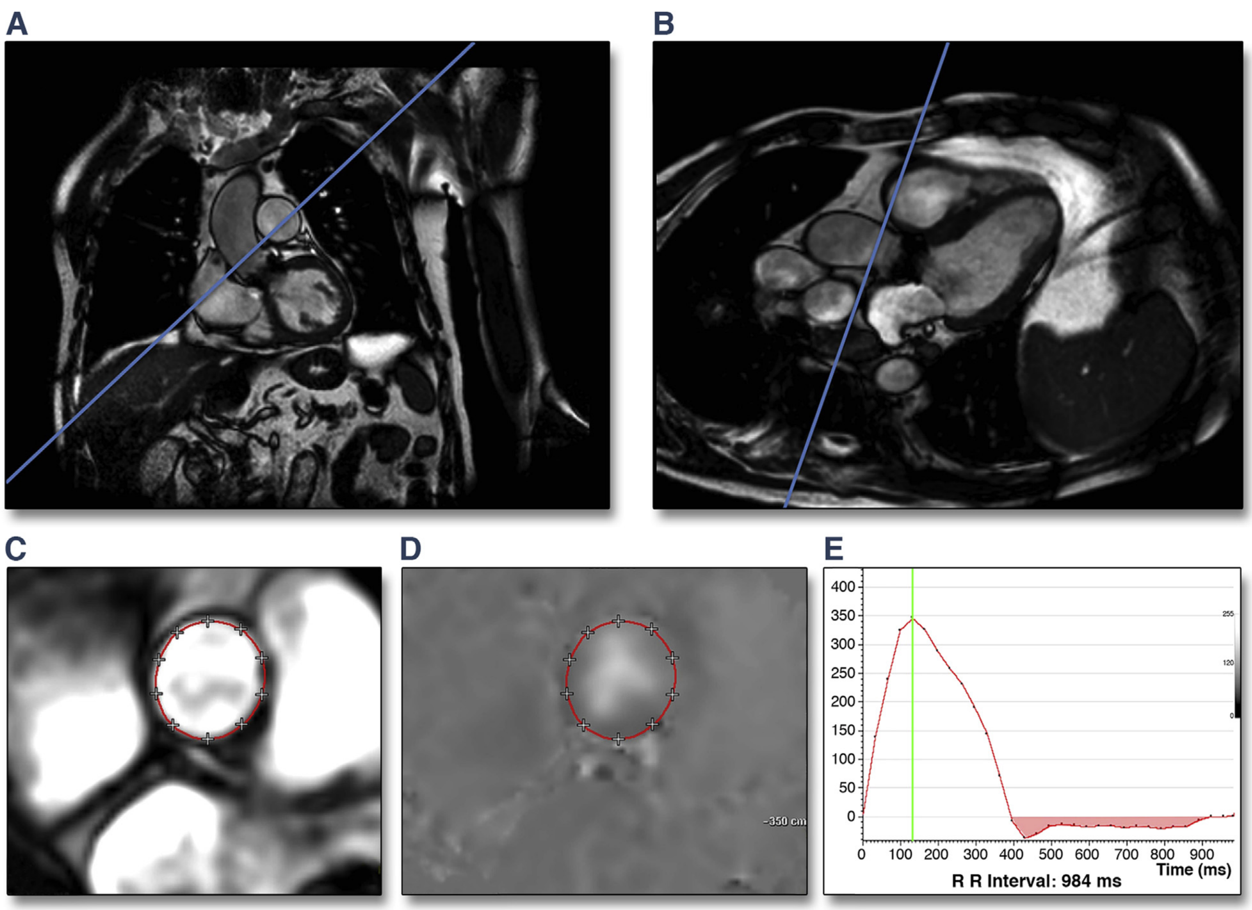
FIGURE 10 Doppler Parameters for the Assessment of PVR



(A) The pressure half-time (PHT) measured on the continuous-wave Doppler aortic regurgitant signal may be used to corroborate the AR severity: in the example shown, the PHT is short (242 ms), consistent with severe AR. **(B)** The flow reversal and end-diastolic velocity obtained by pulsed-wave Doppler in the descending aorta may be used to differentiate moderate from severe AR: in the example shown, there is holodiastolic flow reversal with high end-diastolic velocity (22.5 cm/s), consistent with severe AR. However, in the elderly patients with noncompliant aorta and/or left ventricular (LV) diastolic dysfunction, there are often false-positive cases with both pressure half time and aortic flow reversal. **(C, D, E, F)** A quantitative assessment of the aortic regurgitant volume may be obtained by calculating the difference of the stroke volume measured in the LV outflow tract **(C and D)** minus the stroke volume measured in the right ventricular outflow tract (RVOT) **(E and F)**. To measure RVOT diameter, it is recommended to use both the RV outflow view and the short-axis view **(E)**. Color Doppler may be useful to better delineate the borders of the RVOT. Abbreviations as in Figure 1.

CMR IMAGING. There are a number of advantages of CMR for assessing PVR post-TAVR including the ability to measure regurgitant volumes irrespective of regurgitant jet number or morphology (24), high reproducibility of measurements (27), and the ability to measure regurgitant volume for multiple valve types (5,17,28). The consequences of PVR on LV volumes and function can also be assessed using

FIGURE 11 Assessment of PVR Severity by CMR



(A and B) This is an example of CMR images obtained with steady-state free precession acquisition (**blue lines** = planning lines for imaging planes of velocity-encoded CMR) in a patient with PVR. **(C and D)** Magnitude image **(C)** and phase velocity map **(D)**. **(E)** Time-velocity curve of aortic flow rate, the **red area** between the curve and the x-axis represents regurgitant flow. Adapted with permission from the BMJ Publishing Group, Ltd., from Orwat et al. (22). Abbreviations as in **Figures 1 and 7**.

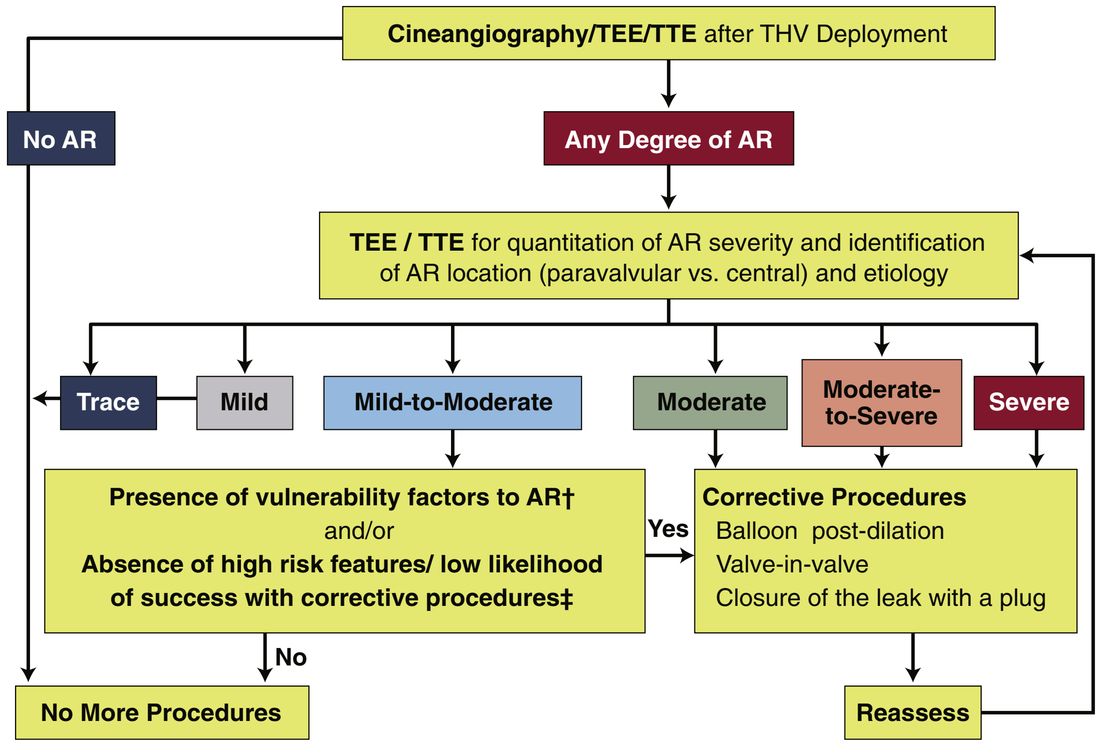
standard cine CMR sequences. Unfortunately, the pitfalls of the technique discussed below, as well as cost and access to scanners, continues to be major barriers to widespread use.

Phase-contrast velocity mapping has become the primary mode for assessing regurgitant volume by CMR. For this purpose, phase-contrast imaging is obtained in a short-axis plane cutting the aorta just above the THV stent to measure the antegrade and retrograde aortic flows and then to calculate the regurgitant volume and fraction (**Figure 11**) (22).

Although CMR consistently shows low variability of measurements, numerous pitfalls also exist (27). Studies are typically gated, and arrhythmias may reduce the accuracy of measurement. Patient discomfort and movements may cause motion artifacts and reduce the quality of the image acquisition. The accuracy of CMR to grade PVR may also be altered by flow turbulences and loss of signal in the vicinity of the THV stent. Finally, because the coronary artery diastolic flow is included in the final regurgitant volume assessment, CMR may lead to a slight overestimation of AR and does not allow precise separation between mild, trace, and no AR.

Recent studies reported that the incidence of moderate/severe PVR as evaluated by CMR is 2- to 3-fold higher compared with TTE. These discrepancies might be, in part, related to an underestimation of PVR by TTE as a result of the fact that PVR jets are often multiple, eccentric, irregular, confined against the LVOT wall, and potentially masked by the

FIGURE 12 Algorithm for the Intraprocedural Management of PVR



†No pre-procedural AR, severe LV concentric hypertrophy with small LV cavity, and moderate-to-severe diastolic dysfunction. ‡High-risk features: bulky calcific nodules within the sinuses of Valsalva or annulus which threaten the integrity of the aortic root/annulus, or left main coronary artery; low likelihood of success: severely malpositioned valves, or bulky calcium adjacent to the lower skirt that prevent apposition of the stent frame with native tissue. Abbreviations as in Figures 1, 2, 3, and 10.

acoustic shadowing (9,11). On the other hand, the inherent pitfalls of CMR may also lead to an overestimation of PVR with this technique. Furthermore and importantly, the cutoff values of CMR regurgitation volume and fraction used to grade AR severity (Table 1) are not well validated and vary substantially from one study to another. Gelfand et al. (29) reported that the CMR regurgitant fractions that optimized the correlation with echocardiographic grades (using an integrative approach) of mild, moderate, moderate-severe, and severe, were: ≤15%, 16% to 25%, 26% to 48%, and >48%, respectively (Table 1). Gabriel et al. (30), however, reported significantly lower CMR regurgitant fraction cutpoints for the same echocardiographic grades: Grade 0 to 1, <8%; Grade 2, 8% to 19%; Grade 3, 20 to 29%; and Grade 4, 30%. The studies that have compared the severity of PVR by echocardiography versus CMR (9,11) used the lower cutpoint values proposed by Gabriel et al. (30), and this may have contributed to the discrepancies observed between these 2 modalities.

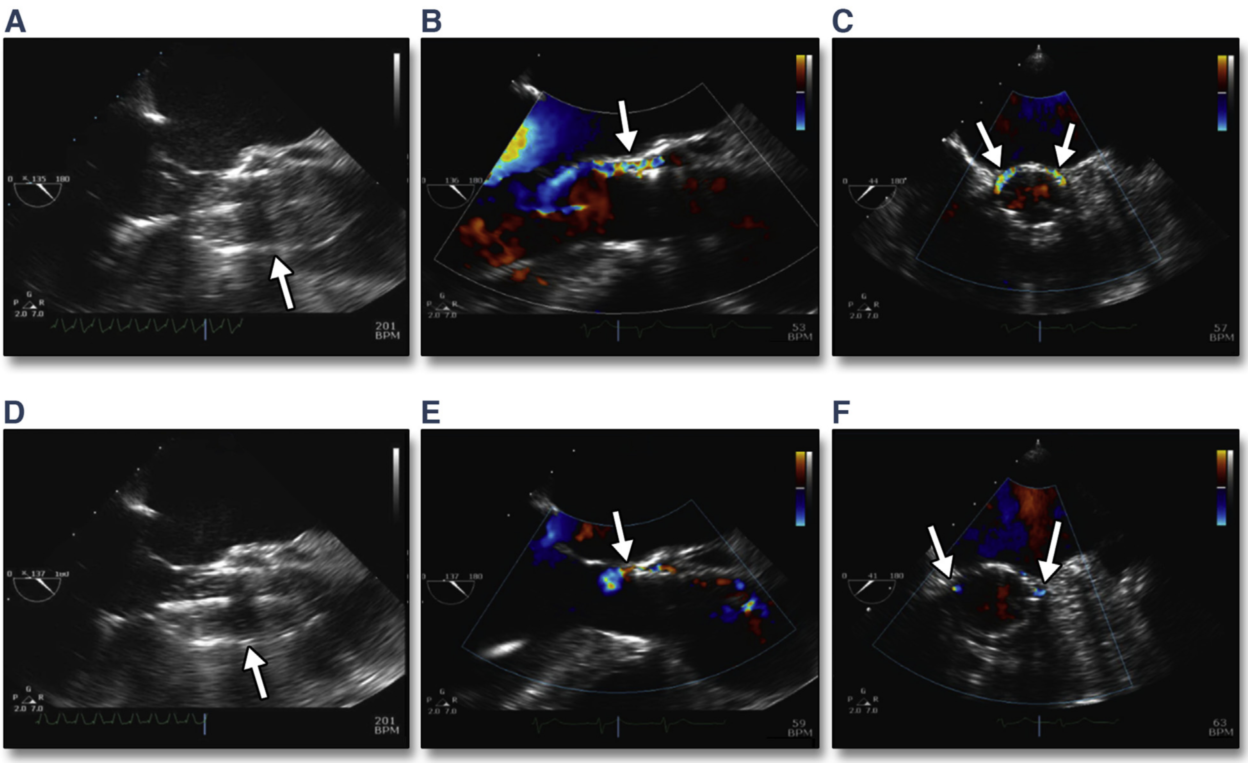
Hence, CMR may help to corroborate the severity of regurgitation in cases where echocardiography remains inconclusive and/or when there is discordance between the echocardiographic grading of PVR severity and patient's symptomatic status and/or degree of LV dilation/dysfunction. However, further outcome studies are urgently needed to validate the cut-point values of CMR regurgitant volume and fraction that should be used to grade the severity of AR, including PVR. Until such studies are conducted, caution is warranted using CMR regurgitant volumes and/or fractions in isolation.

MANAGEMENT OF PVR

Despite the improvements in THV design, sizing, and positioning, a substantial proportion of the patients undergoing TAVR still present with significant PVR

JACC: CARDIOVASCULAR IMAGING, VOL. 8, NO. 3, 2015
MARCH 2015:340-60

FIGURE 13 Balloon Post-Dilation to Correct PVR



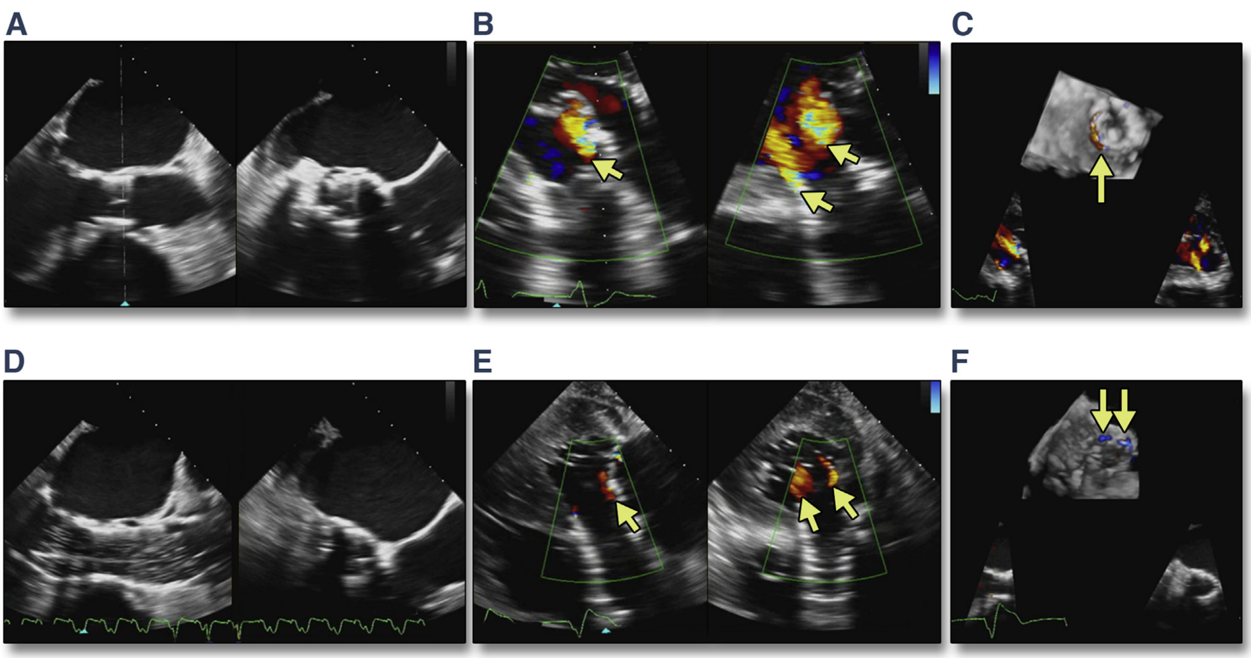
(A) TEE long-axis view of valve prosthesis implantation; the **white arrow** indicates balloon inflation. **(B and C)** TEE long- and short-axis images immediately after THV deployment; **white arrows** indicate moderate PVR. **(D)** TEE long-axis image of balloon post-dilation with a slightly larger balloon; **white arrows** indicate balloon inflation. **(E and F)** TEE long- and short-axis images immediately after balloon post-dilation showing a marked reduction in PVR **(white arrows)**. Reproduced with permission from Nombela-Franco et al. (31). Abbreviations as in Figures 1 and 2.

following deployment of the THV, and corrective interventions, including post-dilation, valve-in-valve, or leak closure, may be considered during or after the procedure.

INTRAPROCEDURAL MANAGEMENT OF PVR. Accurate assessment of the presence and severity of PVR immediately after THV implantation is key for optimal utilization of additional procedures (Figure 12). In the presence of moderate or greater PVR or of mild-to-moderate PVR in some specific situations (Figure 12), balloon post-dilation should be considered to reduce PVR (Figure 13). This procedure is currently performed in about 10% to 20% of patients following TAVR, and it reduces the severity of PVR by at least 1 grade in more than two-thirds of the patients, with the achievement of mild or less than mild AR in about one-half of them (31). However, balloon post-dilation may be associated with increased risk of cerebrovascular events and annular trauma, as well as with increased incidence of central regurgitation (31,32). Hence, a rational utilization of this procedure is recommended (Figure 12). A valve-in-valve procedure (i.e., implantation of a second THV within the first one) is generally used to correct central regurgitation. However, this procedure may also be considered for PVR when the balloon post-dilation fails to reduce a moderate/severe PVR that is likely caused by inadequate positioning of the THV (i.e., too low or too high implantation depth) (Figure 14).

POST-PROCEDURAL MANAGEMENT OF PVR. Patients with PVR should receive a close clinical and echocardiographic follow-up. If there is uncertainty regarding the grading of PVR at TTE and/or TEE, CMR may be used to corroborate PVR severity (21,22). Patients with PVR should have aggressive control of systemic arterial hypertension because it may worsen the regurgitant volume leading to a negative impact on LV geometry and function.

FIGURE 14 **Valve-in-Valve Procedure to Correct PVR**



TEE image showing an undersized SAPIEN 26 mm (Edwards Lifesciences, Irvine, California) **(A)**; deep gastric color Doppler image with severe PVR **(yellow arrows) (B)**; 3D color Doppler image showing severe PVR **(C)**; CoreValve (Medtronic, Minneapolis, Minnesota) implanted in the SAPIEN valve with post-dilation to maximally expand, particularly the lower skirt (see low position of the balloon) **(D)**; 2D and 3D color Doppler images showing mild PVR **(yellow arrows) (E and F)**. Abbreviations as in Figures 2 and 8.

Transcatheter closure of paravalvular leaks may be performed during the TAVR procedure if balloon post-dilation and/or valve-in-valve fail to correct a moderate/severe PVR or it can be done after TAVR if symptoms persist/recur or if LV dilation/dysfunction occurs (33).

CONCLUSIONS

PVR is frequent following TAVR and has a negative impact on outcomes. Because PVR jets are often multiple, irregular, and eccentric, the imaging and grading of PVR by echocardiography is challenging. Hence, a multiwindow, multiparametric, integrative approach is essential to accurately assess the severity of PVR. Variations of PVR grading scales have added to the confusion. A proposed unifying and clarifying grading scale may help to ultimately improve the accuracy of the echocardiographic grading of PVR severity. The proposed 5-class scheme will have to be validated with outcome data. Newer approaches based on 3D color Doppler methods should improve the feasibility, accuracy, and reproducibility of PVR quantitation in the near future. Other modalities such as cineangiography, invasive hemodynamic, and CMR may also be useful to complement or corroborate echocardiography for the grading of PVR during and after the procedure but should not be used in isolation. The use of corrective procedures such as balloon post-dilation, valve-in-valve, and/or leak closure may be considered depending on the severity of PVR and the anticipated risk of complications associated with these procedures.

ACKNOWLEDGMENT The authors would like to thank Marie Dauenheimer, MA, CMI, FAMI, for her assistance in the preparation of the figures.

REPRINT REQUESTS AND CORRESPONDENCE: Dr. Philippe Pibarot, Institut Universitaire de Cardiologie et de Pneumologie de Québec, 2725 Chemin Sainte-Foy, Québec G1V-4G5, Canada. E-mail: philippe.pibarot@med.ulaval.ca.

REFERENCES

1. Kodali SK, Williams MR, Smith CR, et al. Two-year outcomes after transcatheter or surgical aortic-valve replacement. N Engl J Med 2012;366:1686–95.

2. Gilard M, Eltchaninoff H, Iung B, et al. Registry of transcatheter aortic-valve implantation in high-risk patients. N Engl J Med 2012;366:1705–15.

3. Adams DH, Popma JJ, Reardon MJ, et al. Transcatheter aortic-valve replacement with a self-expanding prosthesis. N Engl J Med 2014;370:1790–8.

4. Athappan G, Patvardhan E, Tuzcu EM, et al. Incidence, predictors, and outcomes of aortic regurgitation after transcatheter aortic valve replacement: meta-analysis and systematic review of literature. J Am Coll Cardiol 2013;61:1585–95.

5. Abdel-Wahab M, Mehilli J, Frerker C, et al. Comparison of balloon-expandable vs self-expandable valves in patients undergoing transcatheter aortic valve replacement: the CHOICE randomized clinical trial. JAMA 2014;311:1503–14.

6. Kodali S, Pibarot P, Douglas PS, et al. Paravalvular regurgitation after transcatheter aortic valve replacement with the Edwards Sapien valve in the PARTNER trial: characterizing patients and impact on outcomes. Eur Heart J 2015;36:449–56.

7. Van Belle E, Juthier F, Susen S, et al. Postprocedural aortic regurgitation in balloon-expandable and self-expandable TAVR procedures: Analysis of predictors and impact on long-term mortality: insights from the FRANCE2 Registry. Circulation 2014;129:1415–27.

8. Dworakowski R, Wendler O, Halliday B, et al. Device-dependent association between paravalvar aortic regurgitation and outcome after TAVI. Heart 2014;100:1939–45.

9. Hahn RT, Pibarot P, Stewart WJ, et al. Comparison of transcatheter and surgical aortic valve replacement in severe aortic stenosis: a longitudinal study of echocardiography parameters in cohort A of the PARTNER trial (Placement of Aortic Transcatheter Valves). J Am Coll Cardiol 2013;61:2514–21.

10. Jerez-Valero M, Urena M, Webb JG, et al. Clinical impact of the presence of aortic regurgitation following transcatheter aortic valve implantation: insights into the degree and acuteness of presentation. J Am Coll Cardiol Intv 2014;7:1022–32.

11. Zoghbi WA, Chambers JB, Dumesnil JG, et al. Recommendations for evaluation of prosthetic valves with echocardiography and Doppler ultrasound: a report from the American Society of Echocardiography's Guidelines and Standards Committee. J Am Soc Echocardiogr 2009;22:975–1014.

12. Lancellotti P, Tribouilloy C, Hagendorff A, et al. European Association of Echocardiography recommendations for the assessment of valvular regurgitation. Part 1: aortic and pulmonary regurgitation (native valve disease). Eur J Echocardiogr 2010;11:223–44.

13. Kappetein AP, Head SJ, Genereux P, et al. Updated standardized endpoint definitions for transcatheter aortic valve implantation: the Valve Academic Research Consortium-2 consensus document. Eur J Cardiothorac Surg 2012;42:S45–60.

14. Zamorano JL, Badano LP, Bruce C, et al. EAE/ASE recommendations for the use of echocardiography in new transcatheter interventions for valvular heart disease. J Am Soc Echocardiogr 2011;24:937–65.

15. Hahn RT, Pibarot P, Weissman NJ, Rodriguez L, Jaber WA. Assessment of paravalvular aortic regurgitation after transcatheter aortic valve replacement: intra-core laboratory variability. J Am Soc Echocardiogr 2015 Feb 10 [E-pub ahead of print].

16. Sinning JM, Vasa-Nicotera M, Chin D, et al. Evaluation and management of paravalvular aortic regurgitation after transcatheter aortic valve replacement. J Am Coll Cardiol 2013;62:11–20.

17. Sherif MA, Abdel-Wahab M, Beurich HW, et al. Haemodynamic evaluation of aortic regurgitation after transcatheter aortic valve implantation using cardiovascular magnetic resonance. EuroIntervention 2011;7:57–63.

18. Schultz CJ, Tzikas A, Moelker A, et al. Correlates on MSCT of paravalvular aortic regurgitation after transcatheter aortic valve implantation using the Medtronic CoreValve prosthesis. Catheter Cardiovasc Interv 2011;78:446–55.

19. Khalique O, Hahn RT, Gada H, et al. Quantity and location of aortic valve complex calcification predicts severity and location of paravalvular regurgitation and frequency of post-dilation after balloon-expandable transcatheter aortic valve replacement. J Am Coll Cardiol Intv 2014;7:885–94.

20. Tuzcu EM, Kapadia SR, Svensson LG. Valve design and paravalvular aortic regurgitation: new insights from the French registry. Circulation 2014;129:1378–80.

21. Ribeiro HB, Le Ven F, Larose É, et al. Cardiac magnetic resonance versus transthoracic echocardiography for the assessment and quantification of aortic regurgitation in patients undergoing transcatheter aortic valve implantation. Heart 2014;100:1924–32.

22. Orwat S, Diller GP, Kaleschke G, et al. Aortic regurgitation severity after transcatheter aortic valve implantation is underestimated by echocardiography compared with MRI. Heart 2014;100:1933–8.

23. Gonçalves A, Almeria C, Marcos-Alberca P, et al. Three-dimensional echocardiography in paravalvular aortic regurgitation assessment after transcatheter aortic valve implantation. J Am Soc Echocardiogr 2012;25:47–55.

24. Altiok E, Frick M, Meyer CG, et al. Comparison of two- and three-dimensional transthoracic echocardiography to cardiac magnetic resonance imaging for assessment of paravalvular regurgitation after transcatheter aortic valve implantation. Am J Cardiol 2014;113:1859–66.

25. Svedlund S, Wetterholm R, Volkmann R, Caidahl K. Retrograde blood flow in the aortic arch determined by transesophageal Doppler ultrasound. Cerebrovasc Dis 2009;27:22–8.

26. Thavendiranathan P, Liu S, Datta S, et al. Automated quantification of mitral inflow and aortic outflow stroke volumes by three-dimensional real-time volume color-flow Doppler transthoracic echocardiography: comparison with pulsed-wave Doppler and cardiac magnetic resonance imaging. J Am Soc Echocardiogr 2012;25:56–65.

27. Cawley PJ, Hamilton-Craig C, Owens DS, et al. Prospective comparison of valve regurgitation quantitation by cardiac magnetic resonance imaging and transthoracic echocardiography. Circ Cardiovasc Imaging 2013;6:48–57.

28. Merten C, Beurich HW, Zachow D, et al. Aortic regurgitation and left ventricular remodeling after transcatheter aortic valve implantation: a serial cardiac magnetic resonance imaging study. Circ Cardiovasc Interv 2013;6:476–83.

29. Gelfand EV, Hughes S, Hauser TH, et al. Severity of mitral and aortic regurgitation as assessed by cardiovascular magnetic resonance: optimizing correlation with Doppler echocardiography. J Cardiovasc Magn Reson 2006;8:503–7.

30. Gabriel RS, Renapurkar R, Bolen MA, et al. Comparison of severity of aortic regurgitation by cardiovascular magnetic resonance versus transthoracic echocardiography. Am J Cardiol 2011;108:1014–20.

31. Nombela-Franco L, Rodés-Cabau J, DeLarochellière R, et al. Predictive factors, efficacy, and safety of balloon post-dilation after transcatheter aortic valve implantation with a balloon-expandable valve. J Am Coll Cardiol Intv 2012;5:499–512.

32. Hahn RT, Pibarot P, Webb J, et al. Outcomes with post-dilation following transcatheter aortic valve replacement: The PARTNER I trial (placement of aortic transcatheter valve). J Am Coll Cardiol Intv 2014;7:781–9.

33. Gafoor S, Franke J, Piayda K, et al. Paravalvular leak closure after transcatheter aortic valve replacement with a self-expanding prosthesis. Catheter Cardiovasc Interv 2014;84:147–54.

KEY WORDS aortic regurgitation, aortic stenosis, cardiac magnetic resonance, Doppler echocardiography, transcatheter aortic valve replacement, transcatheter heart valve

APPENDIX For a supplemental figure and videos, please see the online version of this paper.

CME Go to http://cme.jaccjournals.org to take the CME quiz for this article.