11-19-2020

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JACC: CARDIOVASCULAR IMAGING VOL. ■, NO. ■, 2020

PUBLISHED BY ELSEVIER

iREVIEW

STATE-OF-THE-ART PAPER

Neo-LVOT and Transcatheter Mitral Valve Replacement

Expert Recommendations

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ABSTRACT

With the advent of transcatheter mitral valve replacement (TMVR), the concept of the neo–left ventricular outflow tract (LVOT) was introduced and remains an essential component of treatment planning. This paper describes the LVOT anatomy and provides a step-by-step computed tomography methodology to segment and measure the neo-LVOT while discussing the current evidence and outstanding challenges. It also discusses the technical and hemodynamic factors that play a major role in assessing the neo-LVOT. A summary of expert-based recommendations about the overall risk of LVOT obstruction in different scenarios is presented along with the currently available methods to reduce the risk of LVOT obstruction and other post-procedural complications. (J Am Coll Cardiol Img 2020;■:■–■) © 2020 by the American College of Cardiology Foundation.

Mitral regurgitation is highly prevalent, reported in almost 10% of patients >75 years of age (1), with at least one-half of these patients are not suitable for surgical intervention given comorbidities. Left untreated, 90% of these will experience at least 1 heart failure hospitalization, with a mortality rate of 50% within 5 years (2,3). Thus, transcatheter mitral valve replacement (TMVR) has gained much interest as a new, less invasive treatment option for patients with significant mitral regurgitation and high surgical risk (4–6).

In addition to numerous clinical trials and devices specifically designed for the native mitral space (4–6), TMVR also includes previously approved transcatheter aortic valve replacement (TAVR) valves for use in the mitral space, principally for use in valve-in-valve (ViV), valve-in-ring (ViR), or valve-in-mitral annulus calcification (ViMAC).

The structure and function of the mitral valve is complex, comprising a nonplanar, noncircular annulus, variable leaflet lengths and heights, and heterogeneous anatomy of the subvalvular apparatus. These lie in close proximity to adjacent anatomic structures such as the left circumflex artery and the left ventricular outflow tract (LVOT). Fundamental to TMVR procedural success is a valve

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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.

Manuscript received August 5, 2020; revised manuscript received September 23, 2020, accepted September 24, 2020.

ISSN 1936-878X/$36.00 https://doi.org/10.1016/j.jcmg.2020.09.027

ABBREVIATIONS AND ACRONYMS

AML = anterior mitral valve leaflet

CTA = computed tomography angiography

LV = left ventricle/ventricular

LVOT = left ventricular outflow tract

LVOTO = left ventricular outflow tract obstruction

MAC = mitral annular calcification

MVARC = Mitral Valve Academic Research Consortium

TAVR = transcatheter aortic valve replacement

TMVR = transcatheter mitral valve replacement

ViMAC = valve-in-mitral annular calcification

ViR = valve-in-ring

ViV = valve-in-valve

prosthesis that allows for adequate anchoring and sealing, while being able to accommodate the dynamic deformation of the mitral annulus during the cardiac cycle (7,8). Such a device, however, carries a risk of narrowing the LVOT and displacing the native anterior mitral valve leaflet (AML), resulting in LVOT obstruction (LVOTO) (9,10). Historically, LVOTO has been considered a rare but recognized complication following surgical mitral valve interventions in cases in which the AML is preserved, or in which the surgical valve was positioned with the stent post angulated toward the LVOT. TMVR-related LVOTO, however, is feared and is potentially fatal, and is reported in approximately 7% to 9% of TMVR procedures (7). For these reasons, and building on experience with transcatheter aortic valve implantation, contrast-enhanced multiphasic computed tomography angiography (CTA) has quickly become embedded as an essential complementary tool in treatment planning, device selection, and patient-specific procedural risk stratification prior to TMVR (8,9). Given that threatened LVOTO is an exclusion criteria for approximately 50% of patients in contemporary clinical trials (10), our capability for accurate modelling of the post-procedure neo-LVOT with CTA is crucial for procedural success. This document aims to provide practical recommendations for current protocols and techniques used in the assessment of risk of LVOTO post-TMVR (**Central Illustration**).

THE CONCEPT OF THE NEO-LVOT

ANATOMY OF THE NATIVE LVOT AND THE NEO-LVOT. The native LVOT is the anatomic tract confined by the region of potential interaction between a proposed implanted device and the opposing basal to mid anteroseptal wall of the LV (**Figure 1**). TMVR devices comprise fabric-covered stent struts that protrude into the basal LV cavity. After implantation, the TMVR pins the native AML open, displacing it toward the septum, thereby creating a "neo-LVOT," confined by the displaced AML, the stent of the TMVR, and the basal-mid anteroseptal LV wall (11), similar in concept to "fixed" systolic anterior motion of the mitral valve.

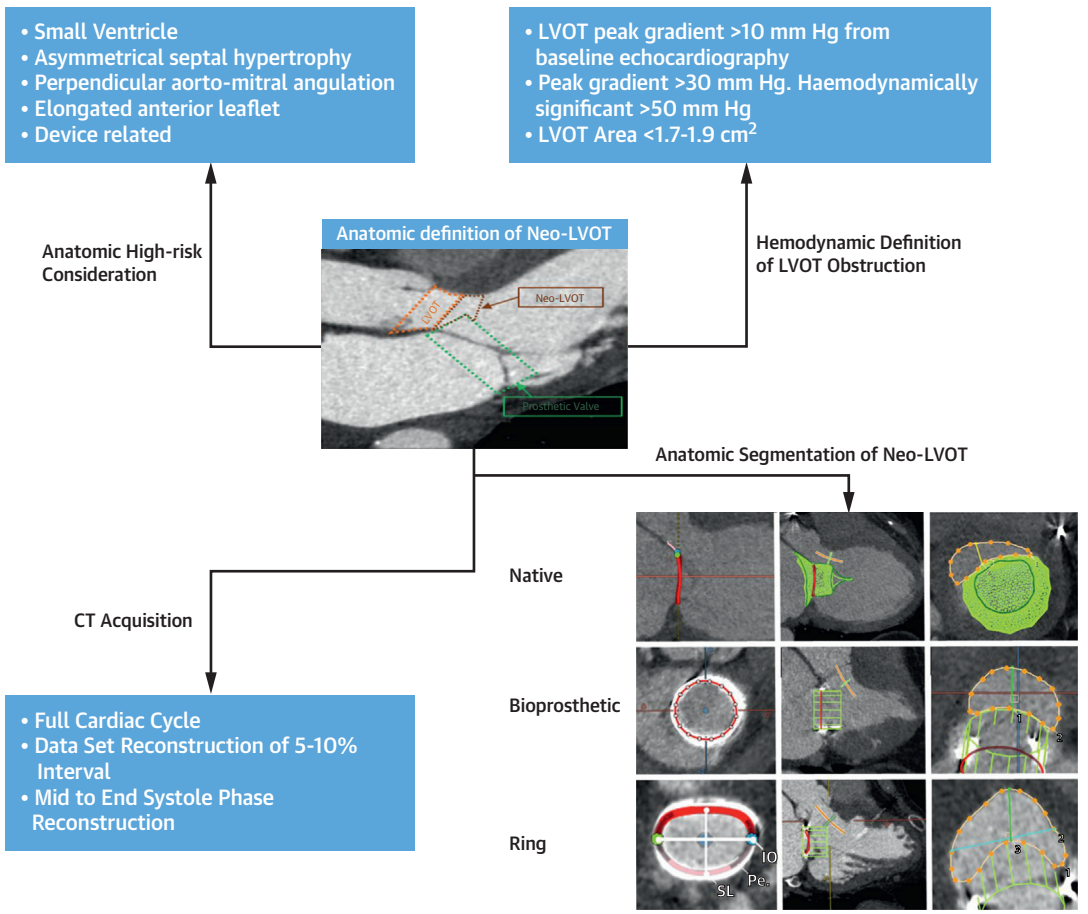
Implantation of an artificial valve into a native mitral annulus landing zone decreases the available surface area for blood to flow into the patient's native LVOT. In the transcatheter world, implantation of a closed-cell TMVR device necessitates an in-depth understanding of the entire threatened LVOT, because of the potential of fixed obstruction post-device implantation. Contrary to open-cell technology, in which leaflets open and close, allowing blood flow into the LVOT during systole, closed-cell TMVR devices created a fixed LVOTO, with the depth of protrusion of the prosthetic valve into the LVOT being the main predictor of obstruction (12). The risk of LVOTO post-TMVR is greater in the presence of an elongated native AML, which can produce dynamic LVOTO due to systolic anterior motion of the AML (**Figure 2**).

Acute LVOTO can be a catastrophic complication occurring immediately following TMVR, causing hemodynamic collapse and potential periprocedural death (10). More chronic LVOTO may also be seen as a consequence of LV reverse remodeling after mitral regurgitation correction, and patients are typically preload dependent and sensitive to volume changes. Chronic LVOTO increases LV afterload and may introduce adverse hypertrophic LV remodeling, predisposing to subsequent ventricular failure, particularly in the context of underlying LV dysfunction (13).

SEGMENTATION AND MEASUREMENT OF THE NEO-LVOT. Given the dynamicity and complex interplay of the mitral prosthesis, LVOT, and LV in the generation of neo-LVOTO, contrast-enhanced CTA data acquisition should cover the entire systolic cardiac cycle, either by means of retrospectively electrocardiography-gated data acquisition, or by prospective electrocardiography-triggered data acquisition with "whole-heart" detector coverage. Datasets should be reconstructed at minimum of 10% R-R interval (preferably at 5% of R-R intervals [i.e., 20 phases]), and optimally without dose modulation. Presence of atrial fibrillation or faster heart rates can compromise data quality, and absolute millisecond reconstruction at 50-ms intervals can improve image quality when compared with % of R-R intervals.

A 3-step method for neo-LVOT measurement in native mitral valve disease is described in detail in **Figure 3**. Methods of segmentation of the native D-shaped mitral valve annulus using CTA have been comprehensively described previously. In brief, the D-shaped annulus is formed by truncating the anterior horn from the saddle-shaped annulus at the level of the fibrous trigones, facilitating and standardizing the sizing for TMVR. Typically, pre-TMVR, 3-dimensional segmentation of the mitral annulus is performed in end-diastole by measuring the intersection of the left atrium and LV blood flow, commonly identified by the basal insertion points of the anterior and posterior mitral leaflets. Post-processing provides the annular area and perimeter,

CENTRAL ILLUSTRATION **Key Elements of Computed Tomography Acquisition and Evaluation for Neo-LVOT Obstruction Risk During Transcatheter Mitral Valve Replacement**



Reid, A. et al. J Am Coll Cardiol Img. 2020;■(■):■-■.

Approach to computed tomography imaging and analysis for left ventricular outflow tract (LVOT) obstruction during transcatheter mitral valve replacement.

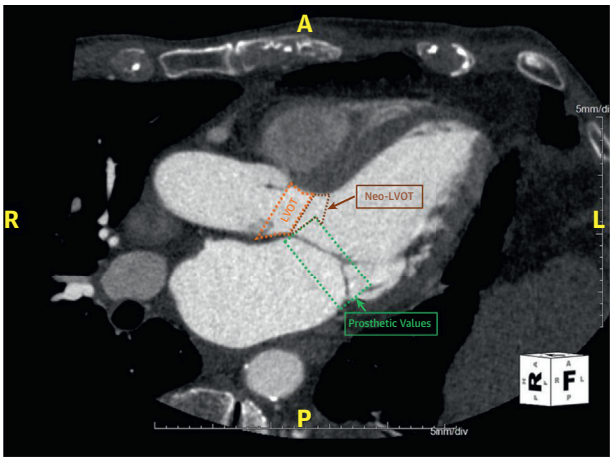
and major and minor dimensions. This step can be done with standard post-processing CTA software (8).

This same segmentation is repeated in mid- or end-systole, which serves as the anatomic landmark for CTA-based virtual simulation of device implantation, by embedding either a device-specific contour (using a stereolithographic file) or a generic cylindrical or D-shaped contour. The minimal cross-sectional area of the neo-LVOT at the site of the greatest encroachment and narrowing can be planimetered using a multiplanar reformat plane orthogonal to a centerline plotted through the LVOT. This step requires a dedicated TMVR modulus, which allows the simulation of the residual neo-LVOT, while accounting for the prosthesis characteristics.

HEMODYNAMIC DEFINITION OF LVOTO POST-TMVR.

The upper bound for acceptable LVOT gradients post-TMVR has not yet been defined. According to the Mitral Valve Academic Research Consortium (MVARC) criteria, surgical device-related, iatrogenic LVOTO is defined as an increment in peak LVOT gradient of >10 mm Hg from baseline, derived from echocardiography (14). Varying thresholds of peak LVOT gradient post-TMVR have been proposed. In clinical trials evaluating novel investigational TMVR devices not yet approved for commercial implantation, the general accepted definition for early signs of LVOTO and gradient adhere to MVARC recommendations of 10 mm Hg. In patient populations at risk of critical LVOTO who are ineligible for investigational

FIGURE 1 Chamber Reconstruction of a Cardiac Computed Tomography Angiogram Defining the Anatomical Neo-LVOT



The left ventricular outflow tract (LVOT) is defined by the basal-mid anteroseptal wall and the mitral intervalvular fibrosa **(orange dotted line)**. Following valve placement, the prosthetic valve is protruding into the basal left ventricular cavity **(green dotted line)** to produce the neo-LVOT **(red dotted line)**.

TMVR devices due to complex anatomy (i.e., off-label use of commercially available devices such as the Edwards SAPIEN transcatheter heart valve [Edwards Lifesciences, Irvine, California]) LVOTO has been proposed as a peak gradient of >30 mm Hg, with hemodynamically significant LVOTO as a peak gradient of >50 mm Hg (15). To date, there is no consensus. Early technologies have demonstrated the presence of potential positive and negative LVOT remodeling post-TMVR device implantation. Our understanding of clinically relevant obstruction being >30 mm Hg has been inferred from data defined in the setting of hypertrophic obstructive cardiomyopathy, and the ability to apply this in a dynamically remodeling LV in the TMVR population is not yet well studied (16).

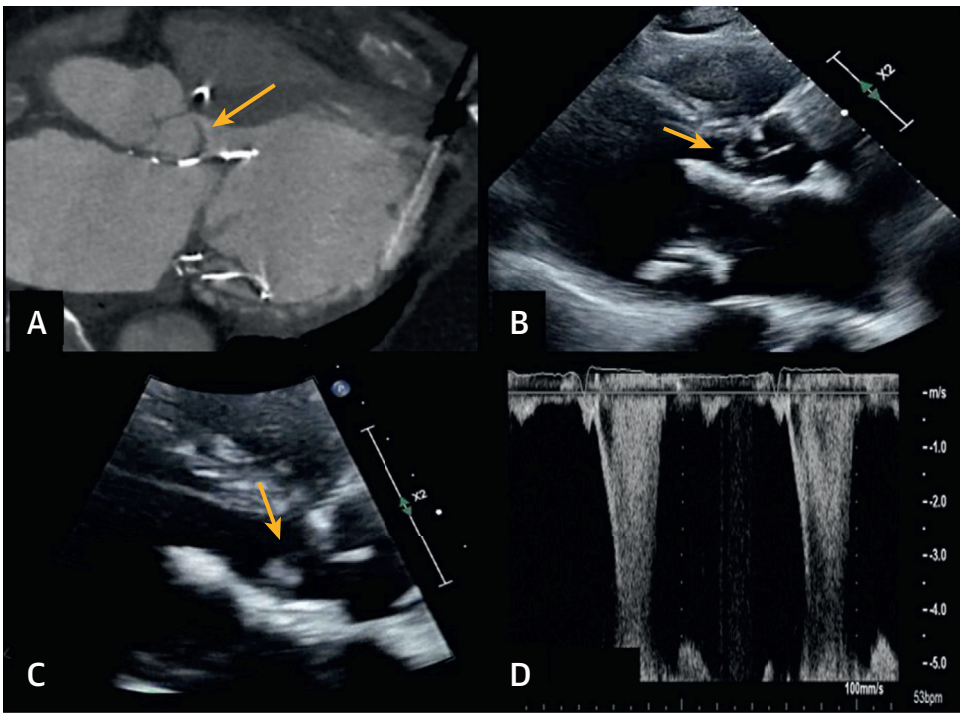
There is an inverse correlation between LVOT gradient and neo-LVOT area post-TMVR (17). Interestingly, computational models using CT datasets, facilitating simulation of different virtual valves and LVOT flows, confirm the relationship between LVOT area and pressure gradient in TMVR. A reduction of 35% in LVOT area has been shown to generate exponential increases in LVOT pressure gradients and reduced LV emptying, inducing low cardiac output (18). The finding of a nonlinear relationship between neo-LVOT area and pressure gradient has been supported by other computational models. Alharbi et al. (19) recently confirmed that the neo-LVOT area is the most important factor to influence the pressure gradient. Pre-procedural estimation of the neo-LVOT area is therefore a fundamental aspect of the patient-specific risk stratification, but uncertainties still exist. The lack of early prospective and TMVR-specific data generated a reliance on extrapolated hypertrophic obstructive cardiomyopathy data to derive conservative consensus threshold of a minimal neo-LVOT cross-sectional area of 2 cm^2 in mid-systole (20), which has been used in several clinical trials but has resulted in high rates of screening failure and ineligibility for TMVR (10).

The current TMVR literature comprises small, heterogeneous studies, including a mixed population of patients undergoing TMVR for native valve disease, failed surgical replacements or repair, and calcific mitral valve disease. Nevertheless, these data have allowed for the validation of the technique by demonstrating excellent correlation between predicted and with actual neo-LVOT area on post-procedural CTA (17). Furthermore, small pre-procedural simulated neo-LVOT area has been shown correlate with post-procedural adverse clinical outcomes (17). Despite this, the threshold for the smallest neo-LVOT area that will generate acceptable post-implantation outcomes and gradients has been challenging to establish and likely not as dichotomous and binary as proposed. Thresholds of neo-LVOT area of 1.7 to 1.9 cm^2 have been demonstrated to predict LVOTO according to MVARC criteria, with high sensitivities and specificities, but it is important to note that these studies used different TMVR technologies (17,21). Current neo-LVOT cutoffs of 1.7 to 1.9 cm^2 have largely been studied on closed cell-TMVR technologies such as the Edwards SAPIEN 3 and Tendyne (Tendyne, Roseville, Minnesota) valves. This neo-LVOT cut-off is not yet well understood for hybrid cell technologies including the Evoque and Medtronic Apollo device (Edwards Lifesciences) where there is an open frame docking system external to an internal closed valve design. Furthermore, mid-systolic neo-LVOT area is not the sole determinant of LVOTO, and more thoughtful integration of ventricular and device geometry, as well as LV function and AML, are required.

KEY CONSIDERATIONS IN THE ASSESSMENT OF THE NEO-LVOT AREA

PHASE SELECTION. Both the native mitral valve complex (leaflet, annulus, and subvalvular apparatus) and neo-LVOT are dynamic structures, changing size and shape throughout the cardiac cycle. Echocardiographic and CTA-derived data identify the LVOT area

FIGURE 2 **Echocardiographic Evaluation of Dynamic LVOT Obstruction**

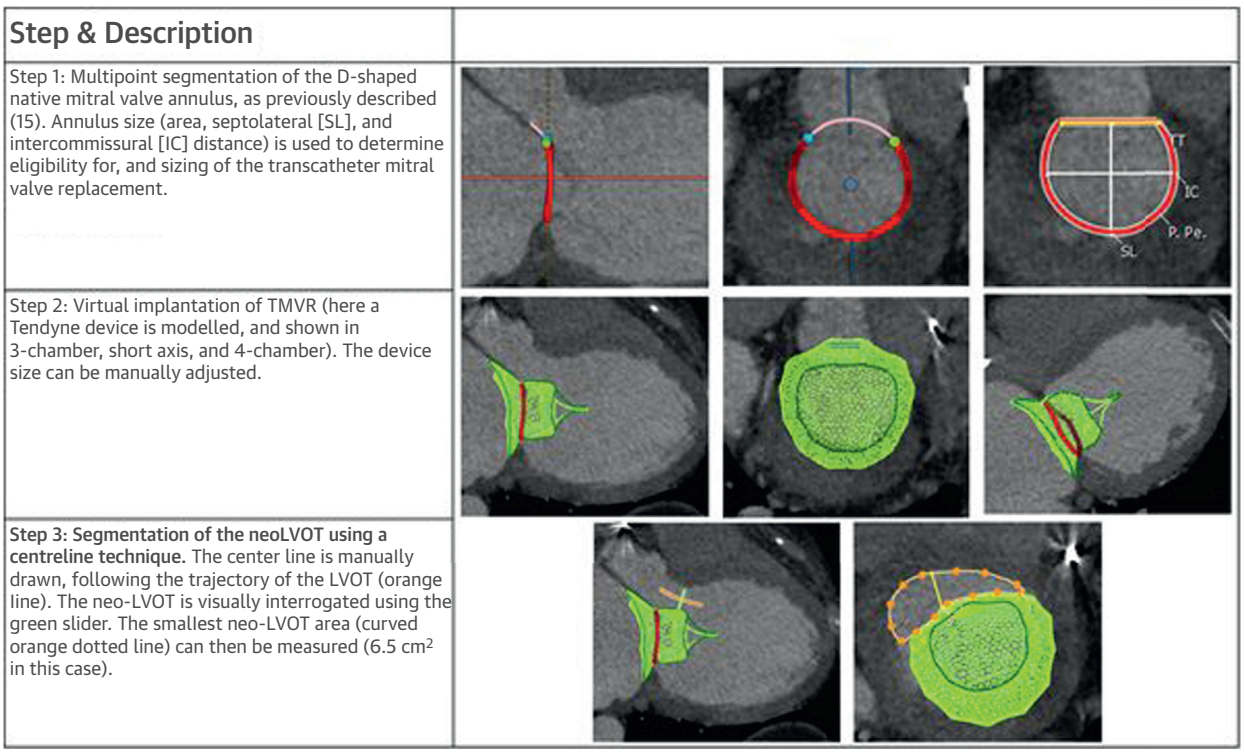


An example of dynamic left ventricular outflow tract (LVOT) obstruction. Following transcatheter mitral valve replacement, there is systolic anterior motion of the residual native anterior mitral leaflet **(arrow)** as demonstrated in **(A)** computed tomography and **(B, C)** 2-dimensional echocardiography. **(D)** The resulted dynamic LVOT obstruction is seen with the LVOT continuous-wave Doppler.

as being smallest at end-systole. However, there is confusion in terminology between echocardiographic and CTA datasets. Owing to the inherent delay between electrocardiography sensing and echocardiographic contract, the end-systole on a parasternal long-axis view of the LV most commonly correlates to 55%, or early diastole on CTA. CTA does not suffer from electrocardiography sensing delays long documented in echocardiography, although the timing of phase reconstruction does vary across vendors, meaning 50% of the R-R interval is not the same thing across CT scan platforms. Safe TMVR planning must include an understanding of the dynamism of the structures within the LVOT during systole. LV cavity size as a sole indicator of phase selection is additionally not an adequate predictor of neo-LVOT risk, as early diastole is commonly when LV volume is smaller on CTA and echocardiography. Safety checks must be employed to ensure that in systolic phases the aortic valve is open, and not closed, as physiologically, in a nondiseased aortic valve, systole is defined as the phase when the valve is open.

In the Intrepid Global Pilot Study cohort, Meduri et al. (22) identified that pre-procedural end-systolic prediction of neo-LVOT area was found to be smaller than the true post-procedure neo-LVOT area (in ascending size) at end-systole, multiphasic, and early systole. This study emphasized the importance of understanding TMVR device technology and potential presence or absence of device conformational changes with relation to the patient's native mitral annulus. In the presence or absence of TMVR device deformation, there would be potentially associated neo-LVOT prediction modeling changes that would need to be accounted for. Additionally, multiphasic and early systolic neo-LVOT allowed better discrimination of post-procedure LVOT gradient and better prediction of the post-procedure neo-LVOT, with the added potential for increasing eligibility for TMVR (22). It is essential to recognize that the majority of patient screening to date has relied on adjudication of the neo-LVOT in mid- and end-systole, and while hypothesis generating, the recent work with the Intrepid device may be device specific, and there is not

FIGURE 3 **Stepwise Approach to Neo-LVOT Segmentation in Native Mitral Regurgitation With CT**



IC = intercommisure; LVOT = left ventricular outflow tract; SL = septolateral; TMVR = transcatheter mitral valve replacement.

enough evidence to transition to early systolic measurements for risk prediction. This work does also emphasize the need to improve our pre-procedural measurements by learning from post-TMVR CTA datasets, which are invaluable to refine our understanding of device-specific post-implant remodeling and its impact on the neo-LVOT geometry.

ANATOMICAL HIGH-RISK FEATURES. LVOT area is affected by LV size, thickness, right ventricular size, function, dynamism, and loading conditions. Previous studies of patients following surgical mitral valve replacement have shown that LVOT area and the risk of LVOTO is increased in patients with small, hypercontractile LV as well as with the presence of septal hypertrophy or an asymmetrical septal bulge (>15 mm) (16,18,20,23,24). Similar physiology is anticipated in TMVR. It is, of course, impossible to completely predict and incorporate a patient's physiologic response to a TMVR insertion, changes in their cardiac output once the degree of mitral regurgitation is reduced, and the degree of the post-procedural LV remodeling and changes in dynamism into the pre-procedural risk assessment of LVOTO. However, conceptually, small end-systolic LV dimensions are likely to predict neo-LVOTO and thus obviate the need for time-consuming image post-processing (25).

Mitral valve and chordal anatomy vary between patients but is an important consideration in the prediction of LVOTO. An elongated AML with redundant chordae is an accepted risk factor for dynamic LVOTO, although there are no currently accepted thresholds (26). The current available TMVR simulation software do not account for the residual AML, which can protrude toward the neo-LVOT, causing dynamic LVOTO. Bulky calcification in the AML has the potential to displace the LVOT following valve placement (27). Native mitral annular dynamicity influences LVOT area throughout the cardiac cycle; however, this is lost following prosthetic valve implantation. Thus, the current method of neo-LVOT area analysis still has room for improvements.

Aortomitral angulation describes the angle between the annular planes of the aortic and mitral valve and is typically measured in end-systole. Conceptually, a mitral annular trajectory (and therefore TMVR trajectory) running parallel to the LVOT

long axis would result in minimal risk of LVOTO, whereas a perpendicular orientation, and subsequent canting of the TMVR trajectory toward the septum, would result in maximal risk. It is recommended that aortomitral angulation is considered together with LVOT, septal, and LV geometry, rather than as a single, stand-alone factor. The importance of the aortomitral angle more commonly affects valve depth deployment, valve coaxiality, and feasibility of different transcatheter or surgical approaches to maximize LVOT area post-TMVR. Furthermore, quantification may be limited by subjective assessment of the LVOT long axis, although facilitated workflows may improve this observer variability (8).

DEVICE FEATURES. The varying features of individual TMVR prosthesis plays a key role in estimation of the neo-LVOT. The currently available devices have different structures, which is outside the scope of this paper, but in general, the greater the depth of device protrusion into the LV and extent of device flaring at LVOT level will lead to narrower and smaller neo-LVOT area (11,12). Moreover, it is currently impossible to predict the end position and shape of the implant, and the degree of compression the device will undergo, particularly in nitinol-based devices. For this reason, in borderline cases, the true neo-LVOT area may be larger (if greater compression occurs) or smaller (if there is significant LV protrusion) than that predicted.

LVOT OBSTRUCTION RISK IN SPECIFIC PATIENT POPULATIONS

MITRAL ViV AND ViR. In the context of a failing bioprosthesis, mitral ViV implantation is typically performed with a transcatheter aortic valve into the mitral position. The risk of neo-LVOTO in this group is higher than that compared with native TMVR, occurring in 2.2% to 2.6% of cases (17,28). The new prosthesis pins the failing valve leaflets open, enveloping the open valve stent cells of the TMVR, and creating a covered cylinder which may induce a fixed obstruction (12,28). Risk of neo-LVOTO may vary depending on the intrinsic features of the original implant. Because the failing leaflets will only extend at most to the tip of the original stent posts, the height, rather than size, of the failing prosthesis is an important factor in determining the risk of neo-LVOT anatomy and obstruction. Canting of the surgical valve toward the septum, as opposed to parallel, may also predispose to neo-LVOTO (12,29). Orientation of the stent struts within the native mitral valve annulus may not influence the neo-LVOT area but may influence the ability to achieve adequate skirt-neo-LVOT area in high-risk patient populations requiring the LAMPOON procedure. Bench testing indicates a tendency of porcine valve leaflets to crumple, compared with pericardial valve leaflets, which remain rigid and upright. Pericardial valve leaflets are also longer, and therefore likely to cover more surface area of the TMVR stent. These are, then, conceptually more likely to form a covered cylindrical stent and neo-LVOTO (12). A method for neo-LVOT area using double oblique, multiplanar reformation is described in **Figure 4**. Alternatively, dedicated software with virtual valve implantation may be performed (**Figure 5**). Measurements of the surgical prosthesis should be performed to confirm the surgical report and be done along the inner border, taking care to optimize image acquisition (using body size appropriate tube voltage and tube current), image reconstruction (using thin slices and without cardiac motion), and wide grayscale display settings to minimize beam hardening and blooming artifacts.

Similar to ViV, mitral ViR is performed using a transcatheter aortic valve (**Figure 6**); however, ViR is associated with relatively higher rates of LVOTO, occurring in 5% to 8% of procedures (28,30,31). Longer AML length appears to be a particularly relevant anatomic risk factor for LVOTO; further study and integration of other anatomic and procedural risk factors are likely to be required to define specific thresholds.

Conceivably, the type of previous annuloplasty ring affects the degree of risk of LVOTO in ViR cases (28). Rigid rings do not allow for full expansion of the percutaneous valve; instead, the valve deforms to fit the oval shape of the ring, risking valve malfunction. By contrast, flexible and semi-rigid rings will conform to match the circular shape of the percutaneous valve. While preferred for valve function, ViR displaces the AML toward the LVOT and septum, thereby increasing the risk of LVOTO (32,33). Recent data, however, identified no difference in outcomes amongst the varying ring types, but in small numbers (31). Last, it bears repeating that current TMVR simulation software for the ViR TMVR procedure do not account for the residual AML, which can protrude toward the neo-LVOT, causing dynamic LVOTO.

Common to both procedures is the interplay between the sewing ring annular plane and LV. Recent published data suggest that in addition to an anticipated neo-LVOT area of <1.9 cm^2, an annulus-to-septal distance of <17.8 mm, an LV end-diastolic

FIGURE 4 **Stepwise Approach to Neo-LVOT Segmentation in the Setting of a Bioprosthetic Mitral Valve**

Step 1: Starting with multi-planar images in the default axial (red box), sagittal (green box) and coronal (blue box) orientation, center the cross-hairs onto the center of the mitral valve.

Step 2: Rotate the cross-hairs in the axial and sagittal views to intersect the LV apex and align with the long axis of the left ventricle to depict a double oblique short axis view of the sewing ring of the surgical valve prosthesis.

Step 3: Rotate the crosshairs clockwise on the short axis plane of the valve prosthesis to intersect the aortic valve and run parallel to the aortic root. This will generate a 3-chamber view in the formally axial view (red box).

Step 4: Increase the maximal intensity projection to visualise the three stent posts of the valve prosthesis in the long axis views (orange arrows).

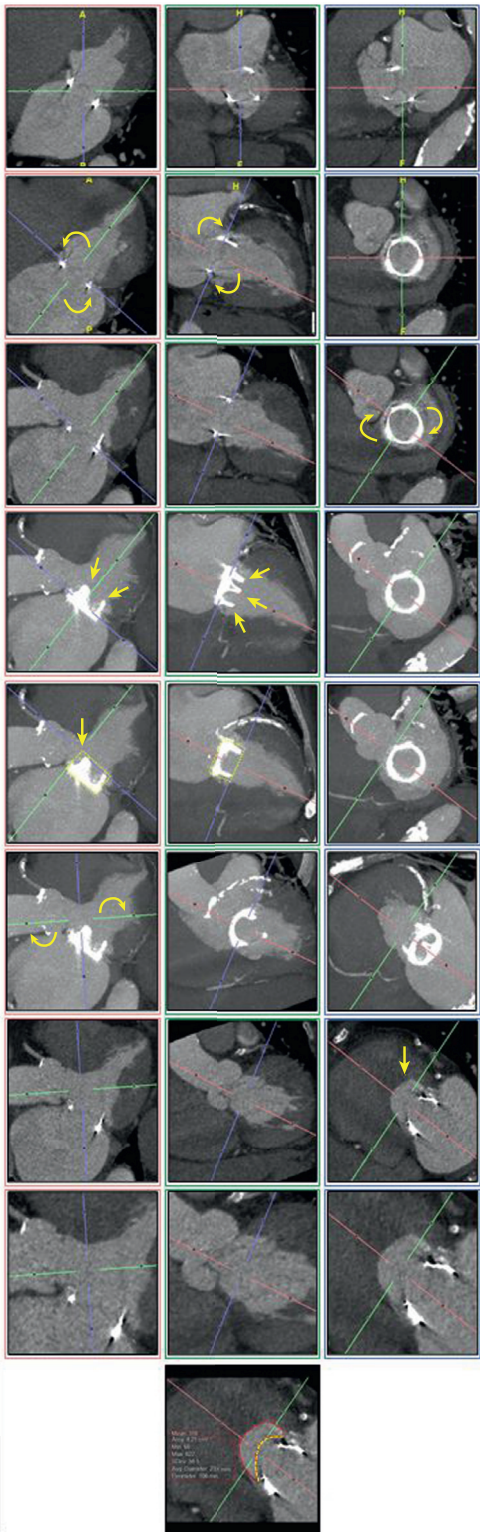
Step 5: On the 3-chamber view, position and align the crosshairs on the intersection of the level stent post tips and septal edge of the prosthesis (yellow arrow). The dashed rectangle represents the conceptual prosthesis 'space'.

Step 6: Rotate the crosshairs clockwise in the 3-chamber view to align with the LVOT trajectory.

Step 7: Reduce the maximal intensity projection to visualize the LVOT in short axis (yellow arrow, blue box).

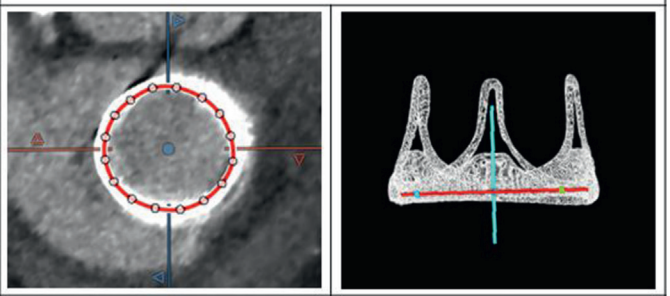
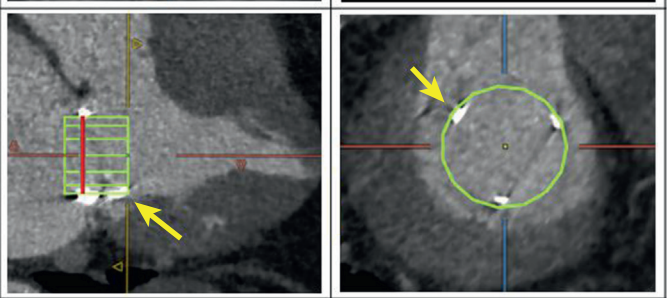
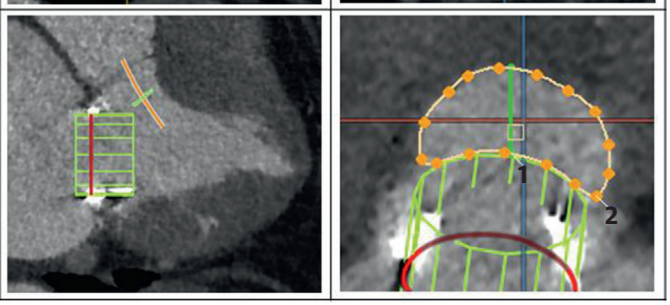
Step 8: Zoom in to optimize the working view.

Step 9: The neoLVOT area can be planimetered. The center of the crosshair represents the most distal point of the septal aspect of the prosthesis, which will form the inferior border of the neo-LVOT (yellow dashed line).



LV = left ventricle; LVOT = left ventricular outflow tract.

FIGURE 5 **Stepwise Approach to Neo-LVOT Segmentation in the Setting of a Mitral Bio-Prosthesis**

Step & Description	
Step 1: Segmentation of the prosthetic valve basal ring. A 31mm Magna was segmented in mid-late systole (40% in this case). The true internal diameter (measured with the automatically generated SL or Ie dimension) was 28.5 mm.	
Step 2: Virtual implantation of a TMVR. A 29mm Sapien S3 was modelled, and offset to the level of the stent posts (yellow arrows).	
Step 3: Segmentation of the neo-LVOT. The center line is manually drawn as in native valves. The smallest neo-LVOT area was measured as 4.2 cm^2 in this case.	

LVOT = left ventricular outflow tract; TMVR = transcatheter mitral valve replacement.

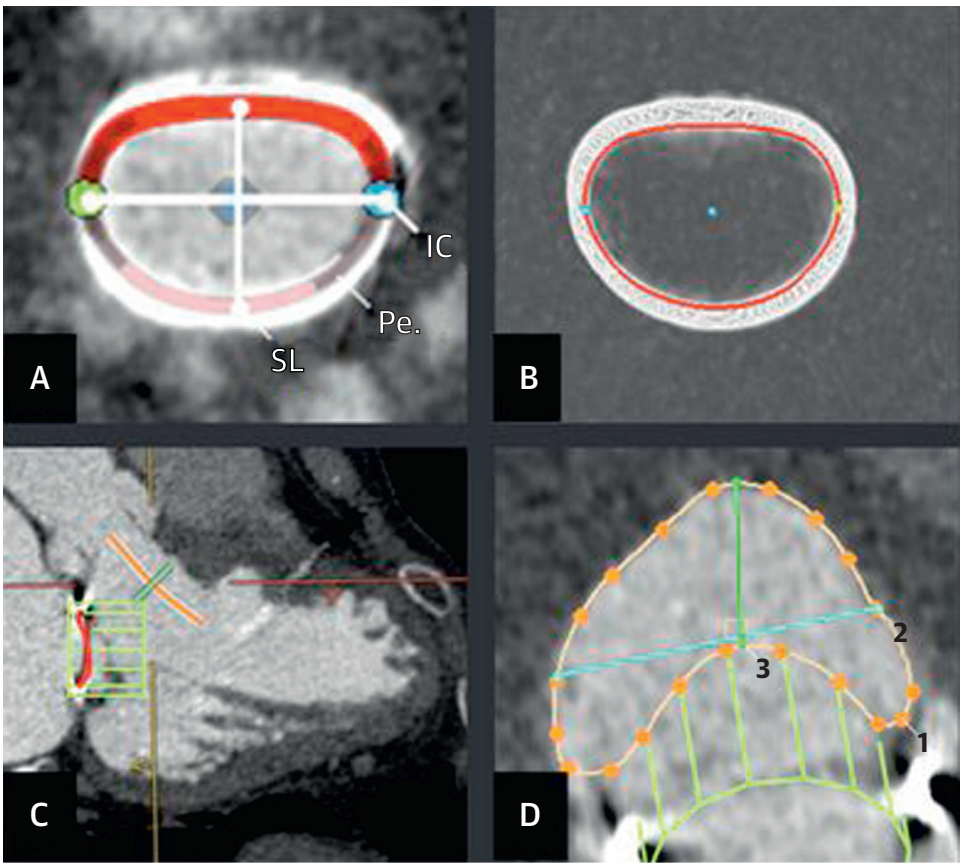
dimension of <48 mm, LV mass index >105 g/m^2, and relative wall thickness of >0.38 convey increased risk of neo-LVOTO (17). Validation of these thresholds in a larger cohort of patients is required.

Procedurally, transcatheter heart valves are generally oversized to reduce the risk of valve embolization and paravalvular leak. The resultant flaring should be taken into consideration during the pre-procedural imaging assessment; however, this is challenging to do quantitatively. Larger and longer transcatheter heart valves, with deep implantation into the LVOT, will likely decrease the neo-LVOT area (20). The field is in need for TMVR-specific devices for ViV and ViR, other than balloon-expandable TAVR devices.

VALVE-IN-MAC. LVOTO is the most important and independent predictor of 30-day and 1-year mortality (32) post-TMVR for TMVR ViMAC. Compared with ViV and ViR, procedural mortality after LVOTO has been reported to be as high as 45% in ViMAC (17).

The cause of LVOTO in this group is multifactorial. It has been described that intrinsically, severe posterior MAC can push the mitral valve coaptation point atrial and anteriorly, which along with AML then causes LVOTO (34). Other studies have reported that systolic anterior motion of the AML also causes LVOTO in these patients (35). Furthermore, MAC is highly heterogeneous, and prediction the final positioning of the TMVR device (in most cases, Edwards SAPIEN 3 TAVR device has been used) is difficult to predict, and the current method of prediction also does not account for the dynamic interaction of the prosthesis and MAC, as there is insufficient data to date with regard to the

FIGURE 6 Computed Tomography Angiographic Evaluation of the Risk of LVOT Obstruction in Mitral Valve in Ring



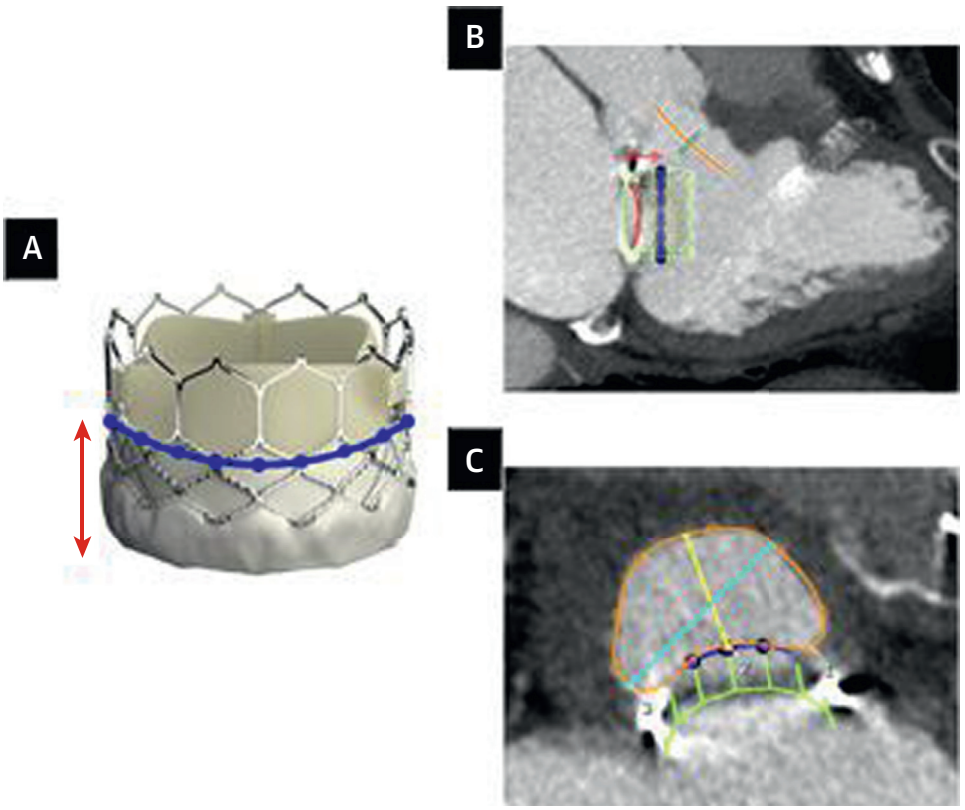
An 80-year-old patient presented with recurrent severe mitral regurgitation, 5 years after mitral valve repair with a 26-mm CE Physio mitral annuloplasty ring. **(A)** Annuloplasty ring segmentation was consistent with the manufacturer's sizing, the internal dimension was 24.6 mm, and septolateral (SL) dimension was 17 mm. **(B)** A 3-dimensional rendering of the annuloplasty ring demonstrating segmentation of the inner rim, which may be difficult to determine because of blooming artifact. Virtual implantation of a 23-mm circular valve with 15% atrial offset was **(C)** applied and **(D)** a neo-left ventricular outflow tract (LVOT) area of 4.1 cm^2 was measured, indicating low risk of neo-LVOT obstruction. IC = intercommissure; Pe = perimeter.

deformation of the MAC with radial stress (36). Patients with severe MAC are typically older, with concomitant cardiac diseases such as aortic stenosis, hypertension, and renal dysfunction, all of which predispose the unfavorable anatomic and functional characteristics such as small, hyperdynamic LVs with LV hypertrophy (37,38).

FUTURE DIRECTIONS

To reduce the risk of LVOTO, various surgical and transcatheter methods have been proposed. Given that basal septal hypertrophy is an important contributing risk factor in the development of LVOTO, pre-procedural alcohol septal ablation has also been proposed as a potential therapeutic strategy, similar to its use in patients with obstructive hypertrophic cardiomyopathy (39). The Achilles heel of this technology is an increased incidence of requirement for permanent pacemaker implantation after alcohol septal ablation, the obligatory 2-week wait time for the LV basal anteroseptum to remodel, and the risk that patients may have appropriate target vessels for Alcohol Septal Ablation. Historically, in this patient population, the LAMPOON technology was developed, with intention to lacerate the AML as an adjunct to decrease the risk of LVOTO in this patient population By lacerating the native AML using

FIGURE 7 Computed Tomography Assessment of the Skirt Neo-LVOT



The same patient from Figure 6 is presented to demonstrate the concept of the skirt neo-LVOT. **(A)** An Edwards SAPIEN 3 valve, with the fabric skirt identified by the **red arrows and blue dotted line**. **(B)** This valve is then modeled as per Figure 6. The **blue dotted line and red arrows** again represent the level of the skirt on the model. **(C)** If LAMPOON were performed, with laceration to the level of the skirt, the neo-left ventricular outflow tract (LVOT) area at this level would be 5.0 cm^2.

an electrified wire that traverses the leaflet, the cells of the "unskirted" portion of the TAVR are exposed, allowing blood to flow across, thereby increasing the size of the neo-LVOT. The anticipated "skirt neo-LVOT" can again be modelled pre-procedurally (**Figure 7**) (26). The limitations of this procedure include the understanding that it is technically challenging both from an interventional and imaging intraprocedural skillset, and is not feasible in calcific leaflets, and may not completely resolve neo-LVOTO caused by the fabric skirt. Teams will need to be ready for bail-out alcohol septal ablation if insufficient laceration of the AML occurs on the table. Given these limitations, newer technology is being evaluated looking at preemptive radiofrequency septal ablation to decrease the risk of LVOTO post-TMVR (40).

There is much to learn in the TMVR space. Three-dimensional printing of anatomic models for neo-LVOT evaluation have also been demonstrated, but these are limited, of course, by their fixed anatomy, high costs, and the lack of printing materials that mimic human tissue (41). Patient-specific computerized models of computational fluid dynamics are under investigation (39), with the anticipation that that they may overcome the limitation of a purely geometric analysis. Using 3-dimensional finite element models of the heart, both mechanical and geometric properties of the valve and the heart can be applied to predict LVOTO (39). Further study will be required to determine the role of these approaches across a wider spectrum of patients requiring TMVR. Improved valve design includes lower profiles, includes anterior leaflet capture, and allows for more

HIGHLIGHTS

- TMVR is increasingly becoming more common.
- Neo-LVOT is a concept that was introduced to describe the residual LVOT area created after the implanted transcatheter mitral valve prosthesis.
- Measurement of the neo-LVOT is explained and step-by-step process is proposed.
- Multiple factors affect the hemodynamic and sizing of the measured neo-LVOT.
- A summary of recommendations with regard to the risk of LVOTO and methods to reduce the risk of LVOTO are reviewed.

atrial positioning. Such concepts are in their infancy, and more data are required to determine their efficacy.

CONCLUSIONS AND FUTURE DIRECTION

Patient-specific risk stratification prior to transcatheter therapy is the goal of procedural planning with advanced imaging. CTA is integral to planning for TMVR, with careful measurement of the neo-LVOT area, which remains one of the most important predictors for iatrogenic LVOTO (**Central Illustration**). Further refinement of the methodology through the integration of post-TMVR CTA imaging in expanding patient populations, with longer-term outcome data, is essential to enhance patient selection and simulation methodology, and to improve procedural outcomes.

AUTHOR DISCLOSURES

Dr. Wang has served as a consultant for Edwards Lifesciences and Boston Scientific; has received research grant support from Boston Scientific; and had patents on left ventricular outflow tract prediction modeling software assigned to assigned to her employer (Henry Ford Health System). Dr. Piazza is a consultant for Medtronic, HighLife, MicroPort, and Circle CVI. Dr. Cavalcante has received institutional grants to provide core lab services and consultant services to Boston Scientific, Edwards LifeSciences, and Abbott Structural; and received research support from 3Mensio, Circle CVI, Medis, and Siemens Healthineers. Drs. Blanke and Leipsic have received institutional grants to provide core lab services from Edwards Lifesciences, Medtronic, and Abbott; and served as consultants to Circle CVI and MVRX. Dr. Blanke has served as a consultant to Edwards Lifesciences and Abbott. All other authors have reported that they have no relationships relevant to the contents of this paper to disclose.

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KEY WORDS LVOT, LVOT obstruction, neo-LVOT, transcatheter mitral valve replacement