Transcatheter aortic valve replacement (TAVR) has revolutionized the treatment of symptomatic severe aortic stenosis (AS). It is now the standard of care for patients who are not surgical candidates, and is comparable to surgical aortic valve replacement in high- and intermediate-risk patients (1–6). The prevalence of coronary artery disease (CAD) in patients with severe AS is high (7). Even in the most recent randomized trials comparing TAVR to surgery in intermediate-risk patients, >60% have coexisting CAD (5,6). The prognostic significance and optimal management of CAD in this population remain controversial (7,8). The recent appropriate use criteria guidelines suggest that it is reasonable to offer revascularization before TAVR, even if there is no evidence of ischemia and only low-risk, noninvasive findings (9). Furthermore, management of symptomatic CAD after TAVR has not been systematically examined. As TAVR indication expands to lower-risk patients who have better long-term prognoses, there will be an increasing need for repeat coronary angiography and percutaneous coronary intervention (PCI) due to progressive CAD and development of acute coronary syndrome.

This paper aims to: 1) provide an overview of the incidence and management of CAD in patients undergoing TAVR; 2) summarize the worldwide experience with coronary angiography and PCI in patients after TAVR; 3) analyze the 3-dimensional geometric interactions between currently approved transcatheter aortic valves and coronary ostia, while providing a practical guide on how to manage these potentially complex situations. (J Am Coll Cardiol 2018;71:1360–78) © 2018 by the American College of Cardiology Foundation.
MANAGEMENT OF CAD IN PATIENTS WITH SEVERE AS UNDERGOING TAVR

PREVALENCE AND PROGNOSTIC SIGNIFICANCE OF CAD IN PATIENTS WITH AS. The prevalence of CAD in patients with severe AS undergoing TAVR ranges from 40% to 75% (7). Given its high prevalence, it is paramount to first ascertain the prognostic significance of CAD and second define the optimal way to manage CAD in patients undergoing TAVR. To date, however, there is no clear consensus on either clinical question, despite several reviews on the topic (7,8,10,11).

The heterogeneity in the definition of CAD across randomized trials and observational studies in patients undergoing TAVR is a major limitation in determining its prognostic significance (12). In a meta-analysis of 2,472 patients from 7 observational studies, CAD was evident in 52% of patients and was defined as: a history of previous PCI or bypass surgery in 4 studies; presence of 50% stenosis in ≥1 epicardial vessel in 2 studies; or a combination of previous revascularization or 50% coronary stenosis in 1 study. With this limitation, the presence or absence of CAD was not associated with an increased risk of death (odds ratio [OR]: 1.0; 95% confidence interval [CI]: 0.67 to 1.50) at a median follow-up of 452 days.

SYNTAX SCORING IN PATIENTS UNDERGOING TAVR. Using the SYNTAX score (SS) to more accurately define CAD has provided further insight into the association between baseline CAD, post-PCI residual CAD, and clinical outcomes, but not all studies were uniformly consistent. Stefanini et al. (13) showed a linear relationship between SS and major adverse cardiovascular events (MACE) at 1 year in patients undergoing TAVR; this was predominantly driven by higher cardiovascular mortality (no CAD 12.5%, low SS 16.1%, high SS 29.6%; p = 0.016). Interestingly, patients with a higher SS (>22) received more incomplete revascularization, and those with a residual SS in the higher tertile (>14) had significantly higher MACE rates (13). In another retrospective analysis from the United Kingdom, the angiographic presence or absence of CAD (≥70% epicardial artery stenosis and/or ≥50% left main stenosis) was not associated with adverse outcomes after TAVR (14). However, when stratified by SS, patients with a score >33 experienced a higher risk of death at both 30 days and 12 months when compared with those with intermediate and low SS (14). Furthermore, after a receiver-operating curve analysis, patients with an SS >9 were identified as having a higher risk of death (14). In the largest (N = 1,270) and most recent study, Witberg et al. (15) added weight to the association between SS and clinical outcomes. Severe CAD, defined as SS >22, was associated with increased mortality at a median follow-up of 1.9 years, even after multivariate analysis (hazard ratio: 2.09; 95% CI: 1.14 to 3.84; p = 0.02). In agreement with the 2 previous studies, incomplete revascularization (residual SS >8) was an independent predictor of mortality (hazard ratio: 1.72; 95% CI: 1.05 to 2.81; p = 0.03). Contrary to these positive studies, Paradis et al. (16) showed that when SS was assessed by a core laboratory, there was no longer a positive association with higher rates of MACE (mortality, myocardial infarction [MI], or stroke) at either 30 days or 1 year. In the small number of patients who underwent PCI (54 of 377), complete revascularization, defined as a residual SS <8, was also not associated with improved outcomes (16).

APPROPRIATE USE CRITERIA IN PCI BEFORE TAVR. Despite the inconsistent findings on the prognostic significance of CAD and effect of revascularization before TAVR, even when using SS, the 2017 appropriate use criteria deemed revascularization before TAVR predominantly appropriate (9). Consequent to these recommendations, a systematic review and meta-analysis of revascularization before TAVR found that of 3,858 patients from 9 studies with CAD, defined as coronary stenosis ranging from 50% to 90%, only 983 (25.5%) received revascularization before TAVR (10). There was no significant clinical benefit derived from revascularization with respect to 30-day cardiovascular death (OR: 1.03; 95% CI: 0.35 to 2.99), MI (OR: 0.86; 95% CI: 0.14 to 5.28), or stroke (OR: 1.07; 95% CI: 0.38 to 2.97). There was, however, an increase in 30-day all-cause mortality (OR: 1.42; 95% CI: 1.08 to 1.87; p = 0.01) with PCI, but this was no longer evident at 1 year (OR: 1.05; 95% CI: 0.71 to 1.56). More importantly, there was also a significant increase in major vascular complications in patients who underwent PCI (OR: 1.86; 95% CI: 1.33 to 2.6; p < 0.001).

It is clear that there is clinical equipoise regarding management of CAD before TAVR. The ACTIVATION (Percutaneous Coronary Intervention Prior to Transcatheter Aortic Valve Implantation; ISRCTN75836930) trial is currently randomizing patients with CAD and severe AS to either pre-TAVR PCI or no
### Summary of the Largest Published Studies (N > 5 Patients) on Coronary Angiography and PCI After TAVR

<table>
<thead>
<tr>
<th>First Author (Ref. #), Year Published</th>
<th>No. of Patients (Valve Used)</th>
<th>Study Summary on Feasibility of Coronary Angiography and PCI</th>
<th>Catheters Used</th>
</tr>
</thead>
</table>
| Chetcuti et al. (18), 2016           | 169 (CoreValve [Medtronic, Galway, Ireland]) | 190 coronary angiography or PCI; PCI attempted in 113 cases 75 cases in 72 patients with both catheterization reports and angiography reviewed Successful coronary angiography: 97.9% (186 of 190) possible in overall group 96.0% (72 of 75) possible from catheterization reports and angiography reviewed Successful PCI: 91.2% (103 of 113) possible in overall group 81.6% (31 of 38) possible among the 75 cases reviewedangiography reviewed | LCA (N = 74):  
  * Judkins 59.5%  
  * FLA 4.1%  
  * EBU 4.1%  
  * Amplatz 1.4%  
  * Other 6.8%  
  * Unknown 24.3%  
  * RCA (N = 70):  
  * Judkins 42.9%  
  * Amplatz 5.7%  
  * Williams 1.4%  
  * FR4 1.4%  
  * EBU 1.4%  
  * Unknown 47.1% |
| Zivelonghi et al. (19), 2017         | 66 (Sapien 3 [Edwards Lifesciences, Irvine, California]) | Angiogram and FFR assessed pre- and post-TAVR Successful coronary angiography: 98.0% (65 of 66) successful diagnostic angiogram performed 6 semiselective angiograms requiring wiring 2 cases with Sapien 3 and 4 cases with Evolut R 1 nondiagnostic angiogram with Evolut R (presumed due to high valve implantation) Successful PCI: 100% (17 of 17 [5 Evolut R, 12 Sapien 3]) with 5 cases requiring rotational atherectomy (3 Evolut R, 2 Sapien 3) | Initial strategy was to use EBU and JR catheters Sapien 3:  
  * standard catheters used Evolut R:  
  * 6 of 25 cases needed a change of catheter (from EBU to JL) Generally, a smaller catheter was used (JL3.5 instead of JL4 and EBU3.0 instead of EBU3.5) For horizontal aorta: JL3.5 and 3DRC |
| Blumenstein et al. (20), 2015        | 35 (Sapien XT) 19 (CoreValve) 4 (Symetis Acurate [Boston Scientific, Marlborough Massachusetts]) 1 (Portico [Abbott, Lake Bluff, Illinois]) 1 (JenaValve [Irvine, California]) | 3.5% (35 of 1,000) patients required angiography and/or PCI post-TAVR 33.0% (10 of 35) had angiography during index hospitalization 76.0% (23 of 30) with delayed angiography had known CAD pre-TAVR. 80.0% femoral access Successful coronary angiography: 90.0% (9 of 10) selective angiograms 90.0% (9 of 10) selective angiograms | Sapien XT:  
  * Standard catheters used CoreValve:  
  * LCA: JL3.5  
  * RCA: AR1 Portico:  
  * LCA: JL3.5  
  * RCA: AR1 Symetis Acurate:  
  * LCA: AL2  
  * RCA: AR1 |
| Htun et al. (21), 2017               | 28 (CoreValve) | 43 coronary angiographies in 28 patients: Successful coronary angiography: 97.0% selective engagement of LCA 90.0% selective engagement of RCA Successful PCI: 29 of 29 (100%) lesions | LCA:  
  * JL (86.0%), EBU, AL2, GuideLiner RCA:  
  * JR4 (93.0%), 3DRC, IM |
| Allali et al. (22), 2016             | 17 (CoreValve) | 24 PCI procedures to 29 lesions Indication: STEMI 8.3%; NSTEMI 20.8%. Median time: TAVR to PCI = 17.7 months (range: 1–72 months) Successful PCI: Procedural success 95.8% (1 periprocedural death) 9 of 15 cases required different guides to pre-TAVR PCI 4 cases: suboptimal support 1 case: rotational atherectomy | LCA:  
  * JL (95.0%)  
  * EBU (5.0%)  
  * JR4.0/JR4.5 (67.0%)  
  * AR2 (33.0%) |
| Boukantar et al. (23), 2017          | 16 (CoreValve) | Indications: Angina: 3 NSTEMI: 7 Silent ischemia: 3 Worsening left ventricular function: 3 Successful coronary angiography: 9 of 16 successful angiograms (no patient had selective engagement of both coronary arteries; only 2 had selective RCA engagement) Successful PCI: 6 of 7, one failed PCI due to poor backup support related to nonselective LM cannulation | LCA:  
  * EBU3.5/3.75 for all RCA:  
  * No RCA PCI performed |

Continued on the next page
pre-TAVR PCI (17). Until the results of this trial are available, patients with CAD undergoing TAVR will need to be evaluated by a multidisciplinary heart team and receive individualized management based on their clinical and angiographic findings.

**MANAGEMENT OF CAD IN PATIENTS AFTER TAVR**

TAVR indications are expanding. In the past year in the United States, both balloon-expandable and self-expanding valves have been approved in patients at intermediate surgical risk (5,6). Furthermore, there are ongoing trials assessing TAVR in low-risk patients (PARTNER 3 [Placement of Aortic Transcatheter Valves (P3); NCT02675114] and the Medtronic Transcatheter Aortic Valve Replacement in Low Risk Patients trials [NCT02701283]), whereas the EARLY TAVR (Evaluation of Transcatheter Aortic Valve Replacement Compared to Surveillance for Patients With Asymptomatic Severe Aortic Stenosis; NCT03042104) trial compares TAVR to routine surveillance in patients with asymptomatic severe AS.

As previously discussed, the incidence of CAD in patients undergoing TAVR is high, even in those who are at intermediate risk (5,6). Given the progressive nature of CAD, a significant proportion of these patients will require coronary angiography and possibly PCI. However, there is a paucity of data documenting the feasibility of either coronary angiography and/or PCI after TAVR (Table 1) (18-24). Success rates have varied with challenges reported particularly with the self-expanding supra-annular valve.

**CORONARY REACCESS IN SELF-EXPANDING VERSUS BALLOON-EXPANDABLE VALVES.** In the largest observational study, Zivelonghi et al. (19) reported the feasibility of angiography in 66 patients immediately after TAVR (25 CoreValve Evolut R valves [Medtronic], 41 Sapien 3 [Edwards Lifesciences]). In 4% of vessels, selective angiography required positioning of a guidewire in the vessel and only 1 artery could not be engaged due to high implantation of the Evolut R. In this case, it was hypothesized that the leaflet base of the supra-annular valve landed at the level of origin of the coronary ostium. PCI was successful in all 17 patients, including in 6 with Evolut R. Encouragingly, rotational atherectomy was successfully performed in patients with both valves.

Blumenstein et al. (20), however, reported more difficulty with coronary angiography, particularly with self-expanding valves. Of 1,000 consecutive patients, only 35 (3.5%) required coronary angiography after TAVR at their center. This was feasible in all patients who received a balloon-expandable valve (n = 19) with only 1 patient requiring a different catheter for engagement. PCI was successfully performed in 5 patients. In the 10 patients with a self-expanding valve, only 3 patients had selective intubation of both coronary ostia, and 6 had semi-selective, but diagnostic angiograms with different catheters or an aortogram. In 1 patient, the coronary arteries could not be visualized due to the implantation of 2 self-expanding valves during the index case. None of these patients required PCI.

Boukantar et al. (23) also reported difficulty with the self-expanding valve, as only 9 of 16 patients had successful selective engagement of both coronary ostia. Furthermore, only 2 patients had selective engagement of the right coronary artery (RCA). PCI was consequently indicated in 7 patients, but was only successful in 6. The predominant issue with failed reaccess was a lack of guide catheter support. Given the difficulties encountered, it was not surprising that the investigators reported significantly higher fluoroscopic times, radiation dosage, and contrast medium use when compared with coronary angiography performed before TAVR.

Allali et al. (22) found 5.7% (n = 17) of patients post-TAVR with a self-expanding valve required PCI at a median follow-up of 17.7 months, the indication being acute coronary syndrome in 37.5% of cases. Of the 15

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**TABLE 1 Continued**

<table>
<thead>
<tr>
<th>First Author (Ref. #), Year Published</th>
<th>No. of Patients (Valve Used)</th>
<th>Study Summary on Feasibility of Coronary Angiography and PCI</th>
<th>Catheters Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chakravarty et al. (24), 2016</td>
<td>9 4 (CoreValve) 5 (Sapien)</td>
<td>Left main PCI post-TAVR</td>
<td>No details</td>
</tr>
</tbody>
</table>

**Note:** 3DRC = 3-dimensional right coronary, AL = Amplatz left, AR = Amplatz right, CAD = coronary artery disease, EBU = extra backup, FFR = fractional flow reserve, FL = femoral left, FR = femoral right, IM = internal mammary, JL = Judkins left, LCA = left coronary artery, LM = left main; NSTEMI = non-ST-segment elevation myocardial infarction; PCI = percutaneous coronary intervention; RCA = right coronary artery; STEMI = ST-segment elevation myocardial infarction; TAVR = transcatheter aortic valve replacement.
patients who also had interventions before TAVR, 9 required a different guiding catheter after TAVR. Of note, in almost all (18 of 19) left coronary lesions, a Judkins left (JL) catheter was used. In 1 case, a patient with known low right coronary ostia (9 mm) had an inferior ST-segment elevation MI complicated by ventricular fibrillation 2 days post-TAVR. The aortogram showed ostial RCA occlusion, but the artery could not be opened. It is plausible that the valve prosthesis was responsible for the occlusion, and the interplay with the ostium, which usually makes engagement challenging, was impossible in the context of hemodynamic instability and cardiopulmonary resuscitation. Less dramatic, but equally noteworthy, was the recurring issue of inadequate guide support reported in 4 cases. Although not universally used, a guide extension catheter (e.g., GuideLiner, Vascular Solutions, Minneapolis, Minnesota), has proven to be a helpful adjunct to PCI after TAVR (25).

Htun et al. (21) more recently showed that coronary angiography through a self-expanding valve was feasible with the selective engagement of the left coronary artery (LCA) and RCA in 97% and 90% of cases, respectively. Furthermore, PCI was successful in 29 lesions, and there were no issues reported with the use of intravascular ultrasound or instantaneous wave-free ratio. Notably, in 2 cases, a guide extension catheter was used to facilitate engagement and subsequent PCI.

Chetcuti et al. (18) previously presented results of 169 (4.5%) patients from the CoreValve US Trial program who required angiography plus PCI post-TAVR (18). Coronary access was achieved in 97.9% of cases, and PCI was only successful in 103 of 113 (91.2%). Of the 75 cases where coronary angiography and reports were reviewed independently, coronary reaccess was possible in 96.0% and PCI was successful in 31 of 38 (81.6%) cases.

Data from the TAVR-LM (Transcatheter Aortic Valve Replacement and Left Main Stenting) registry showed the feasibility of performing left main PCI in 9 cases at a median of 368 days after TAVR. Although full technical details were not described, it was worth noting that procedural success was achieved in patients with both balloon-expandable and self-expanding valves (24).

Since the first case report highlighting successful coronary angiography and PCI post-TAVR with a balloon-expandable valve in 2007, there have been numerous case reports and small case series published (Online Table 1) (25-40). The major themes of these case reports are the difficulties with a self-expanding valve regarding coronary engagement, guide support, and the need to use different catheters and/or guide extensions to optimize guide support. Despite these challenges, PCI appears feasible, even in complex disease such as chronic total occlusions (34). However, it should be noted that an extra backup catheter has caught on the stent frame in 2 cases, 1 directly contributing to a patient’s death (34,35).

In patients with balloon-expandable valves, there have been recent case reports highlighting difficulties with selective coronary engagement (39,40). As the Sapien 3 valve becomes more widely used, it is possible that more coronary access issues will be encountered due to its higher frame height. Even in cases where the top of the valve frame was partly or completely positioned above the ostium, PCI was feasible (41). In 1 case where selective engagement was not possible, a coronary wire was used to enter the coronary artery, but neither the guide catheter nor a guide extension catheter could be advanced through the struts (40). Engagement was finally possible using balloon-assisted tracking of a guide extension catheter.

With limited published studies regarding coronary access and interventions in patients with prior TAVR, it is nearly impossible to estimate the incidence, feasibility, and success rates of coronary angiography and PCI in this patient population. However, it is evident that valve design matters in terms of ease of reaccess, because the self-expanding valve is associated with greater challenges in coronary angiography and PCI post-TAVR. Given the possibility of coronary reaccess in patients with established or intermediate CAD lesions, especially in younger and lower-risk patients, a heart team discussion on the management of CAD in patients with severe AS would be valuable. An individualized approach on: 1) the treatment of both diseases (e.g., PCI then TAVR vs. surgery); 2) which coronary lesions to intervene before TAVR; and 3) valve selection, which may affect coronary reaccess, is recommended.

Post-TAVR multidetector computed tomography (CT) can be helpful to determine the anatomy and approach to coronary reaccess. However, several practical limitations in using this imaging modality as common practice exist: 1) CT cannot be performed in urgent situations, such as acute coronary syndrome, when urgent cardiac catheterization or PCI is necessary; 2) it can be a logistical challenge to schedule a CT before an elective catheterization, especially in terms of the intravenous contrast medium load in patients with renal insufficiency; and 3) motion artifact and image quality may limit the ability to visualize leaflet orientation of the transcatheter valve
relative to the coronary ostia, making it difficult to
determine whether the commissural post may
impede the ability to reaccess coronaries. Nonethe-
less, it remains essential to understand the 3-
dimensional geometric interaction among the valve
prosthesis, the aortic root, and coronary ostia to help
predict and prepare for potential challenges of coro-
nary reaccess in these patients (Central Illustration).

### GEOMETRIC INTERACTION BETWEEN
SELF-EXPANDING AND
BALLOON-EXPANDABLE VALVES
AND CORONARY OSTIA

Pre-procedural planning predominantly focuses on
predicting the likelihood of acute coronary obstruction
because of the life-threatening nature of this rare
complication (42). However, to date, there has not
been any emphasis on factors that will affect future
coronary reaccess, such as valve design and selection,
positioning during deployment, as well as potential
interactions between the transcatheter valve and the
native aortic valve leaflets, coronary ostia height, and
sinus of Valsalva diameter and height.

**SELF-EXPANDING VALVE.** The CoreValve self-
expanding valve is composed of 2 parts; the self-
expanding nitinol support frame with diamond cell
configuration and the trileaflet porcine pericardial
tissue valve. The frame has 3 levels:

1. The inflow exerts a high radial expansive force that
   secures the frame across the annulus.
2. The concave central portion allows the frame to avoid contact with the coronary ostia.

3. The outflow is the largest part of the frame and rests in the ascending aorta.

The dimensions of Evolut-R and Evolut-PRO (Medtronic) repositionable self-expanding valves are shown in Figure 1. There are several important considerations regarding coronary reaccess. First, it is important to consider the depth of implantation, particularly in patients with low coronary ostia. Due to their design, these self-expanding valves extend beyond the coronary ostia, but the narrow waist in appropriately large sinuses ensures that the risk of acute coronary obstruction is low (42). To optimize future coronary reaccess, implantation depth is critical, especially if the ostia is <10 mm, as shown in Figure 2. Because the skirt height of the Evolut-PRO is

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**Figure 1** Repositionable Self-Expanding Valves With and Without an External Pericardial Wrap: Features and Dimensions

<table>
<thead>
<tr>
<th></th>
<th>23 mm Evolut R / PRO</th>
<th>26 mm Evolut R / PRO</th>
<th>29 mm Evolut R / PRO</th>
<th>34 mm Evolut R</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Inflow Diameter</td>
<td>23 mm</td>
<td>26 mm</td>
<td>29 mm</td>
<td>34 mm</td>
</tr>
<tr>
<td>B. Waist Diameter</td>
<td>20 mm</td>
<td>22 mm</td>
<td>23 mm</td>
<td>24 mm</td>
</tr>
<tr>
<td>C. Outflow Diameter</td>
<td>34 mm</td>
<td>32 mm</td>
<td>34 mm</td>
<td>38 mm</td>
</tr>
<tr>
<td>D. Frame height</td>
<td>45 mm</td>
<td>45 mm</td>
<td>45 mm</td>
<td>46 mm</td>
</tr>
<tr>
<td>E. Commissure Height</td>
<td>26 mm</td>
<td>26 mm</td>
<td>26 mm</td>
<td>26 mm</td>
</tr>
<tr>
<td>F. Skirt Height</td>
<td>13 mm</td>
<td>13 mm</td>
<td>13 mm</td>
<td>14 mm</td>
</tr>
</tbody>
</table>

Various dimensions of the Evolut-R and Evolut-PRO CoreValve (Medtronic, Galway, Ireland) are listed for comparison.

**Figure 2** Self-Expanding Valve and Coronary Access Depending on Level of Implantation Across the Annulus

Red dot represents the location of the coronary ostium in relation to the valve frame, and the red line represents the annular plane. The red x's depict the closest diamonds that can be used to access the coronary ostium. An optimally positioned Evolut-R (Medtronic, Galway, Ireland) (A) would make coronary access potentially easier than one with a higher implant (B).
13 mm, we need to implant at least 4 mm below the annular plane to ensure the skirt is not overlaying the coronary artery. Because the Evolut-R and Evolut-PRO are recapturable when partially deployed, it is possible to position the valve with such precision. In this optimal position, it is feasible to engage the coronary artery in a coaxial manner, assuming the native aortic valve leaflets will not interfere with the path to the coronary ostium (Figure 2A). If the valve is deployed high, as seen in Figure 2B, coronary obstruction would not occur due to the narrow waist of the valve and sufficient sinus of Valsalva width. However, selective coronary angiography would be difficult in this scenario and would have to occur from a diamond above the ostium, given that the supra-annular valve and its covered segment (e.g., sealing skirt) would be above the level of the ostium. A straighter catheter with a short tip, such as a Judkins right (JR) 4, could be used in this scenario, even for left main artery engagement.

Second, during TAVR, there is no reliable and consistent way to assess the position of the transcatheter valve commissures in relation to those of the native aortic valve. This is different from surgical aortic valve replacement, where surgeons usually align the commissural frame posts to the native commissures. With the repositionable Evolut-R self-expanding valve, the commissure with the paddle (with the letter C on the tab) is introduced facing the anterior part of the ascending aorta, but because the delivery system traverses the aorta and crosses the native valve, it is not possible to determine its final position until after the valve has been released. Theoretically, a commissure can end up positioned directly in front of the coronary ostium. As there are 3 commissures, and the valve has 15 rows of diamonds, there is a significant chance that this may occur. Although the circumferential sealing skirt is 13 mm in height (14 mm in the 34-mm Evolut-R), depending on the height of coronary ostia, a different catheter and approach is necessary for coronary reaccess, when the ostium faces the side of the commissural post.

**Figure 3** Self-Expanding Valve and Coronary Access If Ostia Lines Up With Commissural Post

Red line represents the annular plane. The 3 red dots depict coronary ostia heights of approximately 10, 14, and 18 mm above the annular plane, respectively. The red x’s depict the closest diamonds that can be used to access the coronaries. The commissural post of an Evolut-R (Medtronic, Galway, Ireland) is 26 mm in height (A). Depending on the height of coronary ostia, a different catheter and approach is necessary for coronary reaccess, when the ostium faces the side of the commissural post (B).
the coronary ostia; the wider the sinus the more room there is to manipulate a catheter toward the coronary ostia, particularly in the scenario shown in Figure 3. A narrow sinus would require a very acute angle for the catheter to be pointing toward the ostia for a nonselective coronary angiogram. If selective engagement is required, a coronary wire would have to be manipulated into the coronary artery, and the guide, or a guide extension catheter, would then have to be railed into the ostium. This represents the most difficult scenario: a valve commissure overlying a low coronary ostium in a patient with a narrow sinus of Valsalva. Of course, this description has not accounted for the native aortic leaflet height and severity of calcification facing the left and right sinuses. A tall and bulky leaflet may extend beyond the 13- or 14-mm sealing skirt of the repositionable Evolut-PRO self-expanding valve and would likely further add to the challenge of coronary reaccess based on these scenarios.

Third, the repositionable Evolut-R self-expanding valve has a concave central portion (“waist”) that measures 20 to 24 mm, depending on the valve size. Clearly, this is narrower than native aortic root dimensions; therefore, it is not surprising that smaller catheters, such as a JL3.5 or JL3, have frequently been used to engage the LCA. On the contrary, engagement of the RCA can usually be managed with a JR4 catheter. If the sinus width is large, there is a larger distance from the valve frame to the ostium, and thus a longer catheter tip would be required. In this circumstance, JR4.5, JR5, Amplatz right (AR) 2 catheters would be more suitable.

CT analysis post-TAVR with the self-expanding valve can aid in identifying potential issues of coronary reaccess, such as the relationship between skirt
height and the coronary ostia, as well as the position of the commissural posts. In Figure 4, we highlight a case of left main PCI post-TAVR with a 29-mm repositionable Evolut-R self-expanding valve. CT analysis clearly revealed that the commissural posts were away from the coronary ostia and the skirt (13 mm) was well below the left main coronary artery (23.4 mm from base of the valve). As the diamond narrowed towards the center of the left main artery, coronary engagement was achieved by coming from

**FIGURE 5** Balloon-Expandable Valves: Features and Dimensions

<table>
<thead>
<tr>
<th></th>
<th>23 mm Sapien XT</th>
<th>26 mm Sapien XT</th>
<th>29 mm Sapien XT</th>
<th>20 mm Sapien 3</th>
<th>23 mm Sapien 3</th>
<th>26 mm Sapien 3</th>
<th>29 mm Sapien 3</th>
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<tr>
<td>A. Frame Height</td>
<td>14 mm</td>
<td>17 mm</td>
<td>19 mm</td>
<td>15.5 mm</td>
<td>18 mm</td>
<td>20 mm</td>
<td>22.5 mm</td>
</tr>
<tr>
<td>B. Inner Skirt Height</td>
<td>6.7 mm</td>
<td>8.7 mm</td>
<td>11.6 mm</td>
<td>7.9 mm</td>
<td>9.3 mm</td>
<td>10.2 mm</td>
<td>11.6 mm</td>
</tr>
<tr>
<td>C. Outer Skirt Height</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>5.2 mm</td>
<td>6.6 mm</td>
<td>7.0 mm</td>
<td>8.1 mm</td>
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<td>D. Valve Diameter</td>
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<td>20 mm</td>
<td>23 mm</td>
<td>26 mm</td>
<td>29 mm</td>
</tr>
</tbody>
</table>

Various dimensions of the Sapien XT and Sapien 3 valves (Edwards Lifesciences, Irvine, California) are listed for comparison.

**FIGURE 6** Balloon-Expandable Valve and Coronary Ostia Based on Depth of Implant

Red dots represent the different locations of the coronary ostium in relation to the valve frame of a 29 mm Sapien 3 valve (Edwards Lifesciences, Irvine, California), and the red line represents the annular plane. An optimally positioned Sapien 3 valve (Edwards Lifesciences, Irvine, California) (**A**) would make coronary access potentially easier than one with a higher implant (**B**), where the coronary ostium will be located below the seal skirt. Tall native leaflet or bulky calcium at the leaflet tip may further increase difficulty of coronary access in a high valve implant.
**FIGURE 7** Coronary Reaccess in a Patient After TAVR With a Balloon-Expandable Valve

White arrows depict the commissural tabs visible on fluoroscopy, and the numbers 1 to 4 refer to the open cells separating the commissural tabs. Bulky calcium (orange arrow) and the height of the Sapien 3 valve frame (Edwards Lifesciences, Irvine, California) can make advancement of a guide catheter into the left main orifice challenging (A). A narrow sinotubular junction, and the presence of a commissural tab facing the left main orifice, can make coronary access difficult, requiring the guide to be placed on either side of the commissural tab to access the sinus of Valsalva for a semiselective injection (B and C). TAVR = transcatheter aortic valve replacement.

**FIGURE 8** CT Analysis of Coronary Anatomy After TAVR

CT shows the stent frame of a Sapien 3 balloon-expandable valve (Edwards Lifesciences, Irvine, California) extending above the left main coronary ostium (white arrow) in axial (A), coronal (B), and reconstructed views (C and D). Colored dots approximately depict the respective nadir of the non (yellow), right (green), and left (red) coronary cusp forming the annular plane. Abbreviations as in Figures 4 and 7.
above, rather than in a coaxial manner. Consequently, a guide extension catheter was used to optimize engagement. PCI was then successfully undertaken, and during post-dilation of the left main ostium, there was overhang of a 4-mm balloon through the valve frame, emphasizing the area of diamond, which can easily accommodate a 10-F guide, as per the manufacturer.

**BALLOON-EXPANDABLE VALVES.** The design of balloon-expandable valves differs significantly from that of self-expanding valves. It is well documented that acute coronary obstruction is more prevalent with balloon-expandable valves (42); however, significant issues with coronary access post-TAVR have not been documented. This is despite the balloon-expandable valve frames frequently ending up above the coronary ostia (41,43). In a CT analysis of patients post-TAVR with Sapien and Sapien XT valves (Edwards Lifesciences), partial (>1 mm) or complete coverage of the left coronary ostium was evident in 33.6% and 2.1% of cases, respectively (41). The right coronary ostium was partially or completely covered in 42.3% and 7.7% of cases, respectively, whereas in 2.1% of cases, both ostia were completely covered. There were no reported issues with patients who subsequently required coronary reaccess or PCI. Another CT study similarly showed a high proportion of patients with balloon-expandable valves having at least partial coverage of the left main (71%) or RCA (29%) (43).

**Figure 5** shows the dimensions of the Sapien XT and Sapien 3 valves (Edwards Lifesciences). The newer-generation Sapien 3 valve is taller, and thus more likely to extend above the coronary ostia and potentially interfere with coronary access. However, it is also important to note that the cells in the upper row of the Sapien 3 valve are 38% larger in area than those of the Sapien XT valve.

The Sapien 3 valve has 12 open cells on its frame, 3 of which contain the commissures and leaflet attachment, along with a 3-mm pledge in the middle of the upper row of cells (**Figure 5**). Thus, it is possible that the commissure may end up directly in front of a coronary ostium after valve deployment. Another important consideration more pertinent to the balloon-expandable valves is the sinotubular junction (STJ) diameter and height. Because it does not have a narrowed waist like the self-expanding valve, the balloon-expandable valve frame, especially Sapien 3, can extend beyond the STJ, making future coronary access from above the valve more challenging or impossible.

Similar to our theoretical model with the self-expanding valve, in **Figure 6**, we show a 29-mm balloon-expandable Sapien 3 valve with the commissural post over the coronary ostia at heights of approximately 10, 14, and 18 mm, respectively, with the valve deployed optimally at 80% aortic position.
In this position, only low coronary arteries (<10 mm) would cause any concern, as the skirt on the frame would be around this level. If the valve is deployed in a more aortic position, with the inflow near the level of the annulus, this would complicate engagement further, as the skirt is well above the ostia. Of course, this model has not taken the native aortic valve leaflets into account. A tall and bulky leaflet may create an even higher barrier for coronary access, given the bulky calcium would be in the way (Figure 7A). Coronary angiography and PCI may be undertaken in 2 ways. First, if the catheter is placed just above the skirt through the upper row of cells, only a nonselective angiogram is likely to be achieved, and PCI would require a coronary wire to engage the artery with a railing technique to engage the catheter. Second, if the STJ is high enough above the valve, a catheter can be used to engage the coronary artery from above the Sapien 3 valve. Coaxial engagement from this position would depend on the sinus of Valsalva width. If the sinuses are effaced, there will be a relative lack of room to manipulate the catheter and engagement of the artery would be more difficult. In cases where the commissural tab faces the coronary ostium and the top of the Sapien 3 valve frame is in contact with the STJ, it may be necessary to engage from the open cell on either side of the commissural tab to reaccess the coronary artery (Figures 7B and 7C).

CT analysis post-TAVR with the balloon-expandable valve is also useful in identifying whether the stent frame extends partially or completely over the coronary ostia (Figure 8). Three-dimensional reconstruction is able to depict the location of the ostia in relation to the stent frame. However, it is limited by the inability to visualize the commissural posts.

In a proof-of-concept study, Blumenstein et al. (44) used DynaCT-guided (Siemens, Erlangen, Germany) rotation of the Sapien XT valve to ensure the commissural posts were not positioned in front of the...
coronary ostia. Unfortunately, this was used during transapical TAVR, and does not appear to be feasible with transfemoral or subclavian approaches, due to the longer distance from the access site to the aortic valve and the inability of the delivery system to be adjusted during positioning and deployment (44).

**VALVE-IN-VALVE TAVR.** The risk of acute coronary obstruction is higher in valve-in-valve TAVR when compared with those with native aortic valves (45). In the VIVID (Valve-in-Valve International Data) registry, 3.5% experienced this catastrophic complication, which lead to death in >50% of the cases (45). The risk is similar across both valve designs, but is dependent on the characteristics of the surgical bioprosthesis and the relationship of its leaflets with the coronary ostia, STJ, and sinus of Valsalva (Figure 9). As surgical valve commissural posts are usually remote from the coronary ostia and do not usually interfere with coronary access unless the ostium is located closer to one of the commissural posts (e.g., bicuspid valve). However, in valve-in-valve TAVR, the commissural posts and bioprosthetic valve leaflets can be deflected outward by the transcatheter valve, especially with balloon-expandable valves, reducing the distance between the surgical bioprosthetic valve leaflets and coronary ostia, and potentially compromising coronary flow (45). Self-expanding valves may also risk coronary obstruction, but due to their conformation to the bioprosthetic leaflets and the surgical valve frame, the risk may potentially be lower (Figure 9). Stenotic bioprosthetic valves, due to thickening and calcification of the leaflets, may also increase the risk of coronary obstruction over regurgitant valves.

The feasibility of coronary angiography and PCI in patients after valve-in-valve TAVR who did not have...
acute coronary obstruction has not been described. Full description of each bioprosthetic aortic valve and the interaction with a transcatheter valve are beyond the scope of this paper. However, the same principles we describe in this review should apply to valve-in-valve TAVR as to TAVR in a native aortic valve.

### CORONARY ACCESS IN PATIENTS AFTER TAVR

Undoubtedly, there will be an increasing number of patients with TAVR valves presenting with progressive CAD or acute coronary syndrome in the coming years. This will occur at both major tertiary centers and at community hospitals with limited exposure to transcatheter valve interventions. It is therefore essential for diagnostic and interventional cardiologists to understand the potential challenges of coronary angiography and PCI in this patient population and to have an algorithm to aid with troubleshooting.

This would be particularly useful in time-critical scenarios, such as ST-segment elevation MI.

#### SELF-EXPANDING VALVE TROUBLESHOOTING.

**Catheter selection.** Given the design of CoreValve, particularly its narrow waist, engagement of the LCA typically requires a smaller catheter than usual. For LCA engagement, JL3.5 and JL3.0 catheters can be used for femoral and radial access, respectively. A JR4 can also be used to troubleshoot the narrow waist and engage the LCA (Figure 10A). An essential component to consider is the position of the commissural post, which usually necessitates entering through the valve from a diamond superior and/or lateral to the coronary ostia. Consequently, and due to its design, our recommended second-line catheter of choice for left coronary engagement is the Ikari right guide catheter. Furthermore, using a guide catheter as a second-line strategy allows the possibility of coronary wiring if more selective...
engagement is required to perform a diagnostic angiogram.

For RCA engagement, JR4 is the catheter of choice. When the sinus of Valsalva is wide, longer-tipped catheters, such as an AR2 (preferred), JR4.5, JR5, or an Ikari right guide provide more adequate engagement. If a commissural post is in front of the coronary ostium, a multipurpose catheter or an Ikari right guide is preferred.

A femoral left 3.5/3.0 guide catheter is the preferred guide for left coronary intervention. Extra backup catheters have been associated with kinking and should be used with extreme care (35). AJ R4 guide catheter is preferred for right coronary interventions, whereas an AR2 guide is the preferred choice when there is significant room between the valve frame and the ostia due to a wide sinus of Valsalva.

On occasions when the coronary ostia can only be accessed from above, a downward pointing catheter, such as a multipurpose guide, can also be used, especially for RCAs.

**Catheter engagement.** Selective catheter engagement can be difficult, depending on the position of the skirt and commissural posts relative to the coronary ostia. If possible, cannulation should be performed in a coaxial manner through the diamond directly in front of the ostia. Engaging from a diamond below the ostia has been associated with kinking of the guide and the inability to remove it (35). Operators have found it useful to cannulate at the fifth alternating diamond above the base of the frame, so as not to be hindered by the pericardial tissue that extends from the base or native valve leaflets. A J-wire is very useful in finding the diamond closest to the ostia, and the catheter can be railed over it for engagement and angiography (Figure 10B). If this fails, a stiff, angled glide wire (Terumo Cardiovascular Systems, Elkton, Maryland) can be used for the same purpose. As it is more lubricious, it can more easily enter the diamond of the valve frame close to the ostium, while its stiffness allows the catheter to be straightened as it is railed across the diamond. Although the angled tip provides a degree of safety, it should always be used with care, given the proximity of the left main coronary artery.

If selective engagement continues to be problematic, a coronary wire can be used to enter the coronary artery from the aorta, and then it can act as a rail for the guide (Figure 10C). If guide engagement and support is still suboptimal, a 2.0 mm × 12-mm balloon...
can be placed in the left main coronary artery for extra support while attempting to rail the guide over it. If this fails, a guide extension catheter can be used (Figure 10D), with balloon-assisted tracking in the most difficult cases (40).

**Catheter disengagement.** Care should be taken when disengaging the guide, as it can kink during the procedure (39). Thus, the guide should be disengaged from the ostium, preferably over a wire, before withdrawal through the diamond of the valve frame. If this becomes problematic, using excessive force should be avoided, as it can kink, or even break, the catheter over the valve frame. If necessary, the use of a balloon may further facilitate disengagement and withdrawal from the valve frame.

**BALLOON-EXPANDABLE VALVE TROUBLESHOOTING.** Coronary angiography technique does not have to be modified significantly in the presence of a balloon-expandable valve. Even in cases where the valve frame extends above the coronary ostia, as seen on CT, selective angiography is usually feasible. The occurrence of a balloon-expandable valve frame extending beyond the coronary ostia is likely to increase with the use of the newer and taller balloon-expandable valve.

If there is a problem with selective coronary engagement, the most likely cause is the position of the commissural tab in front of the coronary ostia. In this scenario, placement of the catheter across the adjacent frame is recommended and nonselective angiography is usually diagnostic. If PCI is indicated, a coronary wire can be used to enter the coronary artery from the aorta, and it can then act as a rail for the guide. Furthermore, a guide extension catheter can be used if guide engagement and support remain suboptimal. Balloon-assisted tracking of the guide catheter extension has been successfully reported with the Sapien 3 valve (40).

In the rare (and yet undescribed) clinical scenario where the deployment is high and the skirt is in front of the coronary ostia without causing acute coronary obstruction, direct ostial engagement would be difficult. Using a downward-pointing catheter, such as a multipurpose 1, would facilitate engagement from either a cell above the ostia or from the space between the valve frame and the STJ.

Practical algorithms for coronary angiography and PCI for both the self-expanding and balloon-expandable valves are shown in Figures 11 to 14.
FUTURE DIRECTIONS

It is essential to consider future coronary access in patients undergoing TAVR. At present, there is no reliable way to control the transcatheter valve commissural orientation in relation to the coronary ostia, nor is there an easy way to orient the valve to optimize future coronary access. Theoretically, when the self-expanding valve is 80% deployed, trans-esophageal echocardiographic views can determine the commissural position, but the constrained valve frame before release may cause acoustic shadowing and limit the ability to determine leaflet orientation. In addition, it is not practical to recapture the valve and move it to the descending aorta to reorient it before attempting deployment again.

In the future, it would be advantageous if the commissural tabs can be easily identified on fluoroscopy and there is a simple mechanism to align the prosthetic valve commissures with those of the native valve, thus optimizing its placement in relation to the coronary arteries. There may also be a role for specifically designed catheters to engage the coronary arteries through self-expanding valves.

CONCLUSIONS

Coronary angiography and PCI in patients after TAVR can be challenging. Intricate knowledge of the valve design and its relationship with the coronary ostia, sinus of Valsalva, and STJ anatomies can help predict the difficulty in coronary reaccess and identify a strategy to manage these patients. Proposed algorithms on cardiac catheterization and PCI may aid troubleshooting in the management of these complex clinical scenarios.

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REFERENCES


**KEY WORDS** aortic stenosis, aortic valve, cardiac catheterization, coronary artery disease

**APPENDIX** For a supplemental table, please see the online version of this paper.