The “Crush” Technique for Coronary Artery Bifurcation Stenting: Insights From Micro-Computed Tomographic Imaging of Bench Deployments

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Objectives This study provides insights into “crush” coronary bifurcation stenting through imaging of bench deployments.

Background Although the strategy of provisional side-branch stenting is widely accepted for suitable bifurcation lesions, there is no consensus on the best option for elective stenting with 2 stents. The crush technique has the potential to scaffold and apply the drug to the side-branch ostium where restenosis is most common.

Methods Sequential steps of crush stent deployment and post-dilation were undertaken in silicone phantoms and recorded on cine angiography and microcomputed tomography. We assessed the effect of deployment strategies, post-dilation strategies, and cell size on side-branch ostial area.

Results Side-branch ostial coverage by metal struts was 53% (95% confidence interval [CI]: 46 to 59) after 1-step kissing post-dilation and was reduced by 2-step kissing post-dilation to 33% (95% CI: 28 to 37; p < 0.0001). Although the residual stenosis after the classical crush strategy was 47% (95% CI: 39 to 53), it was 36% (95% CI: 31 to 40; p = 0.002) after mini-crush deployment. Stents with larger cell size (>3.5 mm diameter) had a residual stenosis of 37% (95% CI: 32 to 42) after crush deployment that was less than the residual stenosis for stents with smaller cell size (52%; 95% CI: 44 to 60; p < 0.0001).

Conclusions Side-branch ostial stenosis after crush stenting was minimized by mini-crush deployment, 2-step kissing post-dilation, and the use of stents with larger cell size. It is unknown if optimizing stent deployment at bifurcation lesions will reduce clinical stent thrombosis and restenosis.

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Percutaneous treatment of coronary bifurcations is a challenge for interventional cardiology. Drug-eluting stents (DES) reduce restenosis in coronary bifurcation lesions compared with historical bare metal stent controls (1). The treatment strategy of provisional side-branch (SB) stenting where the main branch (MB) is stented, and the SB is stented only if necessary, is widely employed because outcomes are better with 1 DES than 2 (1,2). However, if the SB is large and has disease extending beyond the vessel ostium, 2 stents are usually needed (3,4), but there is no consensus on the best technique. The “crush” procedure was introduced to optimize scaffolding and drug application to the SB ostium, a common site for restenosis (1,5,6).

This report describes the use of bench imaging to provide insights into the strengths and limitations of the crush technique (7–9) by comparing various deployment and post-dilation strategies.

**Methods and Materials**

For this bench study, silicone phantoms were constructed with angles between the MB and SB of 30°, 60°, or 90°. The MB diameter was 3.5 mm tapering to 3.0 mm, and the SB diameter was 3.0 mm. The stents evaluated were Cypher Select (Cordis, Miami Lakes, Florida), CoStar and Nevo stent (Conor Medical, Menlo Park, California), Driver/Endeavor (Medtronic, Santa Rosa, California), Liberté (Boston Scientific, Natick, Massachusetts), and Vision (Abbott Vascular, Santa Clara, California).

Following deployment, the stents were imaged using micro-computed tomography (CT) (SkyScan 1172, SkyScan, Belgium). The CT images obtained were manipulated electronically allowing image rotation, electronic dissection, and “fly through” so that stents could be examined from different perspectives and confusing overlying struts could be removed to demonstrate adequacy of stent deployment. In total, 58 deployment procedures (116 stents) were imaged.

**Figure 1** shows the radiographic images of stents deployed in silicone phantoms using the classical crush stenting strategy and 1-step kissing post-dilation. Mini-crush with 2-step kissing post-dilation is shown in **Figure 2**.

We used a planimeter (Fig. 3) to measure the area of the side branch ostium (A1) and the area free of struts (A2) and calculated the percentage area stenosis \((\frac{A1 - A2}{A1} \times 100\%)\) to assess aspects of crush stenting. Three aspects of crush stenting were evaluated. “Classical crush” (Fig. 1), where approximately one-third of the length of the SB stent is crushed, was compared with “mini-crush” (Fig. 2), where only the very proximal end of the SB stent is crushed. “One-step post-dilation,” where a single simultaneous kissing balloon post-dilation was performed, was compared with “2-step post-dilation,” where a high pressure balloon post-dilation was performed in the SB followed by simultaneous kissing inflation. Stents with a small cell size (<3.5 mm diameter) (10) had more coverage of the SB ostium by struts after post-dilation than stents with a larger cell size.

The null hypothesis that the SB stenoses for the different stenting strategies, post-dilation strategies, and stent cell size were the same was tested by analysis of variance. The post hoc Tukey honestly significant difference test was applied to correct for type I errors in the multiple comparisons. The Shapiro-Wilks test was used to check the normality of the residuals. Equal variance tests were applied.

Reproducibility was tested by having the same technician, who was blinded to the first measurement, repeat the reconstruction and ostial measurements. A Bland-Altman
plot was generated, and Pearson correlation was used to quantify reliability.

**Results**

To confirm reproducibility of measurements, a Bland-Altman plot showed high intra-operator agreement with a correlation coefficient for the 2 measurements of 0.90 (p = 0.001) and a difference between the 2 measurements that was not significantly apart from 0 (mean difference 0.3 ± 6.2, p = 0.9).

After crush stenting and before post-dilation, the SB is “jailed” by 2 layers of struts covering the SB ostium and separating the MB from the SB (Fig. 4). Conventional 1-step kissing balloon post-dilation partially cleared struts from the SB ostium but left some residual metallic stenosis. This was not apparent on angiography (Fig. 4), nor was it visible on the bench when magnified images of the stents were viewed from the side. Two-step kissing post-dilation significantly improved the SB lumen compared with 1-step (Table 1) reducing the residual area stenosis from 53% (95% confidence interval [CI]: 46 to 59) to 33% (95% CI: 28 to 37; p < 0.0001). This is depicted in Figure 5. The residual stenosis of 36% (95% CI: 31 to 40) after the mini-crush deployment strategy was less than the residual stenosis after the classical crush strategy (47%; 95% CI: 39 to 53; p = 0.002). Stents with larger cell size (>3.5 mm diameter) had less residual stenosis (37%; 95% CI: 32 to 42) after kissing post-dilation (Table 1) than those with smaller cell size where residual stenosis was 52% (95% CI: 44 to 60; p < 0.0001).

Following classical crush deployment, the 2 layers of crushed SB stent in addition to a layer of MB struts form 3 layers of struts (Fig. 6). The orientation of the layers of the crushed SB stent in relation to the MB stent is unpredictable so that by chance they may lie adjacent to the MB stent in line with the orientation of the SB stent or may be wrapped around either side of the MB stent. The length of multiple layering depends on how much of the SB stent protruded into the MB before crushing. There is potential for minimal overlapping of struts with mini-crush deployment (Fig. 6).

We have observed that gaps in stent coverage (and thus in scaffolding and drug application) sometimes occur with kissing balloon post-dilation after crush deployment (Fig. 7) and are found with all designs. They occur in the SB stent usually on the side of the stent opposite to the crushed portion. They are caused by the post-dilating balloon following a SB wire that has exited the MB stent and re-entered the SB stent after a course outside the stents (Fig. 7). Inflation of this balloon pushes struts aside. Gaps are most common with classical crush and less common with mini-crush.
Discussion

This study used conventional cineangiography and micro-CT to image 6 different stent designs deployed in silicone phantoms at 3 different SB angles, using 2 different crush stenting strategies (classical crush, mini-crush) and 2 post-dilation strategies (1- and 2-step kissing balloon post-dilation).

The major findings of this study are:

1. Before kissing balloon post-dilation, 2 layers of stent strut separated the MB from the SB.
2. After 1-step kissing balloon post-dilation, struts were partially cleared from the SB ostium but there was residual strut coverage causing narrowing that was not visible on angiography or when the stent was viewed from its side.
3. 2-step kissing post-dilation further reduced the ostial SB strut coverage.
4. Stents with potential cell sizes that are greater than 3.5 mm in diameter had less residual stenosis after crush stenting than stents with smaller cell sizes.
5. Gaps in strut scaffolding and drug application that are sometimes found at the SB ostium occur after post-dilation. They are most common following classical

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**Table 1. The Side-Branch Ostial Percentage Area Stenosis Following Different Deployment Strategies**

<table>
<thead>
<tr>
<th>Deployment strategy</th>
<th>Side-Branch Ostial % Area Stenosis</th>
<th>n</th>
<th>Mean (95% CI)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classical crush</td>
<td>32</td>
<td>47 (39–53)</td>
<td></td>
<td>0.002</td>
</tr>
<tr>
<td>Mini-crush</td>
<td>26</td>
<td>36 (31–40)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-dilation strategy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1-step kissing</td>
<td>26</td>
<td>53 (46–59)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2-step kissing</td>
<td>32</td>
<td>33 (28–37)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Stent cell size*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;3.5 × 3.5 mm</td>
<td>18</td>
<td>52 (44–60)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;3.5 × 3.5 mm</td>
<td>40</td>
<td>37 (32–42)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
</tbody>
</table>

*See Reference 10. Stent designs used for strategies (n pairs of stents): Classical crush: CoStar (3), Cypher (5), Cypher Select (1), Driver/Endeavor (10), Express (1), Liberté (7), Nevo (0), Vision (3); Mini-crush: CoStar (0), Cypher (0), Cypher Select (9), Driver/Endeavor (2), Express (0), Liberté (1), Nevo (3), Vision (13); 1-step kissing: CoStar (3), Cypher (2), Cypher Select (4), Driver/Endeavor (5), Express (0), Liberté (5), Nevo (0), Vision (7); 2-step kissing: CoStar (0), Cypher (3), Cypher Select (6), Driver/Endeavor (7), Express (1), Liberté (3), Nevo (3), Vision (9); CoStar and Nevo stents were manufactured by Conor Medsystems (Menlo Park, California); Cypher and Cypher Select stents by Cordis Corporation (Miami Lakes, Florida); Driver and Endeavor stents by Medtronic (Minneapolis, Minnesota); Express and Liberté stents by Boston Scientific (Natick, Massachusetts); and Vision stents by Abbott Vascular (Santa Clara, California).
crush and less common after mini-crush. They were found with all stent designs.

Limitations of our previous photographic technique (6,7) were that stents could not be imaged in an opaque phantom, and we deployed them in a trough in a rigid investigator designed Perspex block. Silicone phantoms better mimic a coronary bifurcation, but are insufficiently translucent for good quality conventional photographic imaging but are suitable for CT imaging as they are radiolucent.

Restenosis after classical crush stenting is most commonly focal and located at the SB ostium and still occurs after 1-step kissing post-dilation (11–13). An intravascular ultrasound study of classical crush and 1-step kissing post-dilation (11) found stent underexpansion, unsuspected on angiography, in >60% of cases. The Costa et al. (11) suggestion that stent underexpansion may be the dominant mechanism of restenosis with DES is consistent with our bench results. Although 2-step kissing post-dilation improves SB ostial stenosis on the bench, it is unknown whether this translates into improved clinical outcomes.

The gaps in strut scaffolding and drug application that may occur at the SB ostium after post-dilation are less common with mini-crush techniques. Gaps may be caused by the post-dilating balloon following a SB wire that has exited the MB stent and re-entered the SB stent after a course outside the stents (Fig. 7). Gaps potentially reduce scaffolding and drug application and therefore may contribute to restenosis. Paradoxically, even though the kissing post-dilation of a single MB stent produces the best scaffolding of the SB ostium if the wire crosses into the SB distally in the SB ostium (14), the reverse is true after crush stenting, where distal crossing is more likely to result in gaps. With current techniques, the operator has little control over where the wire crosses into the SB after crush stenting and therefore has minimal control over gap formation.

Stent thrombosis rates by 9-month follow-up are higher after classical crush stenting than after simple stenting, and the incidence was not reduced with 1-step kissing post-dilation, although reported patient numbers were small.
One-step kissing post-dilation leaves considerable residual metallic stenosis that may predispose to thrombosis because of eddy currents, stasis, altered shear stress, and foreign body presence. Whether 2-step kissing post-dilation will reduce stent thrombosis by improving SB ostial stenosis is unknown. Classical crush stenting may also be predisposed to stent thrombosis because of the multiple layering of stent struts. Overlapping of DES is associated with reduced endothelialization of struts in preclinical studies (15) and reduced tissue coverage in humans (16). Mini-crush variations of classical crush (Figs. 1 to 3), limit multiple layering of stent struts opposite the SB ostium have been removed electronically (A) to allow clear viewing of the SB ostium for these Driver stents. The double layer of stents before post-dilation (B) are partially cleared from the SB ostium by 1-step kissing post-dilation (C) and more fully cleared by 2-step kissing post-dilation (D). See Online Videos 1, 2, and 3. Abbreviations as in Figure 1.

When stents are crushed, especially with classical crush and before kissing post-dilation, there is a “V-shaped” trough between the MB and SB stents on the opposite side to the crushed portion (left panel, B). In this figure, by chance, a wire from the MB lumen (A) has passed outside the stents through the trough (B) before entering the SB stent (C). The post-dilating balloon following this wire will have a short course outside both stents. Upon balloon inflation, the stent strut or struts on the luminal side of the wire will be pushed out of position causing a gap in stent scaffolding (open arrow, lower right panel). Vision stents were used for this deployment. See Online Video 4. Abbreviations as in Figure 1.
struts (Fig. 5) and may be associated with more complete endothelialization.

Crush stenting is simple and quick. Recrossing the crushed stent for kissing post-dilation, the most difficult part of the procedure, is technically easier with mini-crush than with classical crush.

Other 2-stent bifurcation stenting techniques have strengths and weaknesses. Although “T” stenting can be performed through a 6-F guide, there are gaps in metal coverage and drug application at the SB ostium especially in shallow angles (1). At 90° angled bifurcations, “T” stenting and mini-crush stenting can be identical. Cutole stenting (10) is technically more difficult and is associated with double layering of stent struts, but it can be performed through a 6-F guide. The simultaneous kissing stent technique is simple and quick, requires an 8-F guide, and produces a metallic septum upstream from the bifurcation that may be predisposed to stent thrombosis (17). “V” stenting is a variation of simultaneous kissing stent technique but with minimal stent overlap. It is appropriate for a limited range of stenoses (Medina classification 0,1,1) (18), and if an upstream dissection occurs, this is difficult to manage. “Y” stenting (19) has the potential to cover the bifurcation and if an upstream dissection occurs, this is difficult to manage. We have not evaluated every visualization of stents in bifurcations, but are time-consuming and expensive. We have not evaluated every variation of crush bifurcation stenting, such as the “internal” (or reverse crush) technique (6).

Study limitations. Bench deployments can never exactly represent clinical situations although silicone phantoms are an improvement over rigid Perspex phantoms. Micro-CT imaging and reconstruction provide previously unobtainable visualization of stents in bifurcations, but are time-consuming and expensive. We have not evaluated every variation of crush bifurcation stenting, such as the “internal” or reverse crush technique (6).

Conclusions

In conclusion, bench deployments provide unique insights into crush bifurcation stenting and post-dilation strategies (6,10–12). Clinical studies with long-term outcomes are needed to determine if these in vitro observations are clinically important.

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REFERENCES


Key Words: coronary bifurcations ■ stents ■ crush stenting ■ bench testing ■ bifurcation stenting.