Flow Patterns at Stented Coronary Bifurcations
Computational Fluid Dynamics Analysis

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Background—The ideal bifurcation stenting technique is not established, and data on the hemodynamic characteristics at stented bifurcations are limited.

Methods and Results—We used computational fluid dynamics analysis to assess hemodynamic parameters known affect the risk of restenosis and thrombosis at coronary bifurcations after the use of various single- and double-stenting techniques. We assessed the distributions and surface integrals of the time averaged wall shear stress (TAWSS), oscillatory shear index (OSI), and relative residence time (t_r). Single main branch stenting without side branch balloon angioplasty or stenting provided the most favorable hemodynamic results (integrated values of TAWSS=4.13·10^{-4} N, OSI=7.52·10^{-6} m², t_r=5.57·10^{-4} m²/Pa) with bifurcational area subjected to OSI values >0.25, >0.35, and >0.45 calculated as 0.36 mm², 0.04 mm², and 0 mm², respectively. Extended bifurcation areas subjected to these OSI values were seen after T-stenting: 0.61 mm², 0.18 mm², and 0.02 mm², respectively. Among the considered double-stenting techniques, crush stenting (integrated values of TAWSS=1.18·10^{-4} N, OSI=7.75·10^{-6} m², t_r=6.16·10^{-4} m²/Pa) gave the most favorable results compared with T-stenting (TAWSS=0.78·10^{-4} N, OSI=10.40·10^{-6} m², t_r=6.87·10^{-4} m²/Pa) or the culotte technique (TAWSS=1.30·10^{-4} N, OSI=9.87·10^{-6} m², t_r=8.78·10^{-4} m²/Pa).

Conclusions—In the studied models of computer simulations, stenting of the main branch with our without balloon angioplasty of the side branch offers hemodynamic advantages over double stenting. When double stenting is considered, the crush technique with the use of a thin-strut stent may result in improved immediate hemodynamics compared with culotte or T-stenting. (Circ Cardiovasc Interv. 2012;5:530-539.)

Key Words: angioplasty ■ stents ■ hemodynamics ■ bifurcation ■ coronary circulation

Coronary bifurcations remain one of the most challenging lesion subsets, even in the era of drug-eluting stents. Single stent implantation in the main vessel with provisional stenting to the side branch vessel has been found superior to double stenting¹² and is considered the default approach in most coronary bifurcation lesions.³ However, in true bifurcation lesions, this provisional approach may leave significant residual stenosis of the side branch vessel after percutaneous coronary intervention (PCI), and in a recent randomized study, double stenting reduced target vessel revascularization without affecting major adverse coronary events compared with provisional side branch stenting.⁴ Thus, operators may opt for double stenting in the presence of a large side branch. Still, the ideal stenting technique is not established in this respect.

Several methods for deployment of 2 stents at bifurcations have been proposed, but their impact on clinical outcomes such as restenosis and, especially, stent thrombosis and iatrogenic myocardial infarction, still a reason for concern with drug-eluting stents,⁷ is not known. Stenting at the site of bifurcation inevitably affects coronary flow patterns that have been associated with restenosis rates and stent thrombosis.⁶ Indeed, altered geometry and associated blood flow disturbances induced by stenting can influence restenosis.⁷ Disturbed flow may also facilitate the accumulation of platelets and other blood thrombogenic factors close to the wall.⁸ Flow patterns in bifurcations are inherently complex, including vortex formation and creation of zones of low and oscillating wall shear stress that coincide with early intimal thickening.⁹ Luminal dimensions and flow patterns are theoretically restored after PCI, but bifurcation stenting is associated with geometric deformation of both the main and side branch and, most importantly, introduction of stents struts into the coronary artery with frequent protrusion into the lumen, which alter the original flow environment. Stent struts alter flow conditions both close to the vessel wall and inside the vessel lumen.¹⁰ Thus, each stenting technique has a distinct and possibly significant effect on the flow patterns at the bifurcation region. The disturbances that the various bifurcation
stenting techniques impose on post-PCI coronary flow have not been studied.

In the present study, we used computational fluid dynamics (CFD) analysis to assess hemodynamic conditions and flow patterns at stented coronary bifurcations by simulating single- and double-stenting techniques that are commonly used in clinical practice. Such an analysis may define the predisposition of each stenting technique to restenosis and thrombus formation and may guide clinical decisions for optimum therapy in this challenging setting.

**WHAT IS KNOWN**

- Altered geometry and associated blood flow disturbances induced by stenting can influence restenosis.
- The ideal technique for stenting of coronary bifurcations is not established.
- Data on the hemodynamic impact of various stenting techniques on stented bifurcations are limited.

**WHAT THE STUDY ADDS**

- Computational fluid dynamics analysis of bifurcation models indicated that stenting of the main branch with or without balloon angioplasty of the side branch offers hemodynamic advantages over a 2-stent technique.
- When the 2-stent technique for stenting of the main and side branch vessels is considered, the crush technique with the use of a thin-strut stent may result in improved immediate hemodynamics compared with culotte or T-stenting.

**Methods**

**Creation of an Idealized Coronary Bifurcation Model**

The model represents a typical left anterior descending [en] diagonal bifurcation, which are coronary bifurcations frequently affected by atherosclerosis (Figure 1A). The diameter of the proximal main branch (PMB) of the model is 3.5 mm and the diameter of the side branch (SB) is 2.5 mm, since usually only side branches with diameters >2.25 mm are considered for stenting.12 The diameter of the distal main branch (DMB) is calculated from the diameters of the PMB and SB by the scaling law of Finet: PMB=(DMB + SB)×0.678.13 The bifurcation angle, defined as the angle between the axis of the main vessel and the axis of the side-branch at its origin, is 50°, which is the median value of 538 coronary bifurcation lesions with a side branch >2 mm.14 The dimensions of simulated stents were 16 mm/3.5 mm at the MB and 7 mm/2.5 mm at the SB; thus stent implantation caused enlargement of the DMB. In the cases where there was residual stenosis at the SB, the lesion shape was considered cosine-shaped in the longitudinal view and circular-shaped in the cross-sectional view.

**Stent Simulation and Incorporation at the Bifurcation Model**

The simulated coronary stent closely resembles the strut design and linkage pattern of a third-generation, everolimus-eluting stent (PROMUS Element, Boston Scientific). The struts are particularly thin compared with other available stents (0.081–0.086 mm, depending on stent diameter) and widened at the crown to redirect the strain of expansion to the longitudinal portion.15 The cross section of the simulated stent struts was considered square with thickness of 0.081 mm, whereas the struts were slightly widened at the crowns to capture the design of the actual stent. Computer Aided Design (CAD) software was used to reproduce the stented geometry as accurate as possible (SolidWorks 2009, SolidWorks Corp, Concord, MA). The first step involved the creation of the solid model of the bifurcation geometry and the second step involved the creation of the actual expanded stent geometry. A hollow tube with outer diameter equal to the nominal expanded diameter of the actual stent and thickness equal with the thickness of the stent was created. A 2-dimensional sketch with the strut dimensions of the stent was propagated and wrapped around that tube. A cutout was then performed, thus obtaining 1 ring of the stent. That ring was propagated axially to create the full-length, expanded stent solid representation. The last step involves the modification and the “virtual implantation” of the solid stent model inside the bifurcation geometry. The solid stent model is placed in the proper position of the bifurcation model. At this point, depending on the case, material removal (ie, struts removal from the SB entrance) or flex deformation (ie, to simulate “culotte” or “crush” double-stenting techniques) was applied. Finally, by using Boolean operation, the modified solid stent model is subtracted from the solid bifurcation model to obtain the final geometry. It was assumed that after stent implantation of the main or side branch, there was no residual stenosis at the stented vessel, and, in all cases, optimal stent deployment and complete apposition of stent struts against the vessel walls were considered. Thus, studied models also fit well with the clinical scenario of kissing balloons after stent deployment.

**Considered Stenting Techniques**

Six bifurcation stenting techniques were considered: 3 single-stenting techniques and 3 double-stenting techniques as follows.

**1) Stenting of the MB Only**

In this case of provisional stenting, 1 stent is implanted at the MB without any intervention at the SB (Figure 2A). Stenting of the MB results in introduction of a stent inside the bifurcation lumen at the orifice of the SB. At the SB, we considered a symmetrical ostial diameter stenosis of 75% affecting both the outer vessel wall and the flow divider.

**2) Stenting of the MB Followed by Balloon Angioplasty of the SB**

In this case of provisional stenting, 1 stent is implanted at the MB and then a balloon is inflated at the SB through the struts of the MB stent (Figure 2B). Balloon inflation removes the stent struts from the orifice of the SB; thus, there are no struts inside the lumen at the bifurcation site. At the SB, we considered a residual diameter stenosis of 30% because angiographic success is frequently defined as achievement of <50% residual stenosis by any percutaneous method.16

**3) Balloon Angioplasty of the SB Followed by Stenting of the MB**

Balloon angioplasty of the SB precedes stenting of the MB (Figure 2C). After balloon inflation and stent implantation, there is usually a residual stenosis at the SB (considered 50%) due to the combined effect of plaque shifting from the proximal segment of the MB and displacement of the flow divider by the expanded stent struts. Because stenting of the MB follows balloon angioplasty of the SB, at the bifurcation site there are stent struts inside the lumen at the orifice of the SB.

**4) “Culotte” Stenting**

“Culotte” or “trousers” stenting consists of implanting a first stent from the proximal to the distal segment of the MB. A second stent is then placed from the proximal MB toward the SB through the struts of the first stent (Figure 2D). Culotte stenting results in a double layer of struts in the proximal part of the MB and presence of struts in the lumen of the MB at the bifurcation site.17
“Crush” Stenting

“Crush” stenting consists of advancing 2 stents simultaneously into both the MB and SB. The proximal segment of the SB stent is first deployed in the MB, and then it is crushed to the main vessel wall during deployment of the MB stent (Figure 2E). Crush stenting results in a triple layer of struts in the proximal MB wall toward the branching vessel and a double layer of struts (from the MB stent and the crushed SB stent) at the orifice of the SB.17

Ideal T-Stenting

This stenting technique simulates an “idealized” T-stenting method, in which 1 stent is implanted at the MB and 1 stent at the SB, while there is no strut overlap at any site of the bifurcation and additionally the struts at the orifice of the SB have been intentionally removed (Figure 2F). This model was included to consider it as the “gold standard” of bifurcation scaffolding.

CFD Methodology and Evaluation of Simulations Results

To study intracoronary flow, we used CFD simulations, which are computational techniques. The execution of CFD simulations require a theoretical vessel model (Figure 1A), which is then recreated as a 3-dimensional digital model (Figure 1B). On this model, inflow (Figure 1C) and outflow (Figure 1D) conditions are imposed and the Navier-Stokes equations that describe the laminar or turbulent motion of fluids are numerically solved using numeric grids. CFD simulations provide the spatially resolved velocity (Figure 1E), pressure, and shear stress distribution along the blood vessels for the prescribed in-flow and out-flow conditions. The simulations were conducted using the commercial software ANSYS FLUENT 12.1 (by Fluent Inc). The numeric grid for the simulation was created from the constructed geometries using ANSYS Meshing 12.1 (by Fluent Inc). The following assumptions were made.

Blood was considered a Newtonian fluid with viscosity 3.5 cP and density 1.06 g/mL.
The artery walls are assumed rigid and no deformation is taken into account.
At the inlet, a predescribed pulse of the blood flow rate and pressure has been assumed.18
Mass flow exit boundary conditions were used for the 2 branches. The flow was assumed to split proportionally to the (3/2) power of the bifurcation vessel’s normal diameters.
The hemodynamic parameters that were assessed at stented coronary bifurcations through CFD simulations were the time-averaged wall shear stress (TAWSS), the oscillatory shear index (OSI), and the relative residence time ($t_r$). TAWSS expresses the frictional force per unit area that is exerted by the flowing blood to the vascular wall due to the viscous properties of blood. OSI is a dimensionless parameter that accounts for the degree of deviation of WSS from the antegrade flow direction. Small OSI values (close to 0) indicate small variations of the WSS vector during the cardiac cycle. Conversely, OSI values close to 0.5 indicate that WSS vector is subject to large variations, and WSS can be very small or change direction at parts of the cardiac cycle, which means that at those time instances flow is stopped or reversed. Although OSI can identify regions of flow reversal, it is insensitive to shear magnitude thus it has been suggested that OSI should be used in combination with other shear measures. A relevant suitable index of flow is the relative residence time derived from TAWSS and OSI by the equation $t_r = (1 - 2 \times OSI) \times |\text{TAWSS}|$. Studies at stented coronary segments have shown that neointimal growth is located at regions of low WSS and high temporal oscillations in WSS quantified by high OSI. The atherosclerotic process is also enhanced at areas at which the solutes and formed elements of blood have high residence times in the neighborhood of the vascular endothelium. Hemodynamic parameters have also affect many processes involved in thrombus formation, including platelet recruitment to the vessel wall, platelet adhesion activation, and aggregation. Thrombus formation is enhanced at areas of slow and reversed flow characterized by high OSI and high residence times because these conditions enhance platelet aggregation. In this study, the bifurcation stenting techniques were comparatively evaluated in terms of the induced flow alterations at the region of the bifurcation. Although we cannot directly link hemodynamic disturbances and the risk of restenosis and thrombosis, it is plausible that the risk of restenosis and thrombosis would be higher if regions of the bifurcation are continuously exposed to low WSS or high OSI and $t_r$. Thus, high TAWSS, low OSI, and low $t_r$ values were considered hemodynamically favorable regarding the predisposition of each technique to restenosis and thrombosis. TAWSS, OSI, and $t_r$ were calculated as previously described.

**Results**

Figures 3, 4, and 5 give the TAWSS, OSI, and $t_r$ distributions for the 6 considered stenting techniques. These figures clearly demonstrate that each stenting technique has a distinct impact on the flow patterns that is reflected both at the distribution and the magnitude of the calculated flow indices to the bifurcation region.

**Single Stenting**

In the 3 single-stenting techniques (left panels of Figures 3 through 5), there is residual stenosis at the SB through which...
flow is accelerated resulting to high flow velocities and thus WSS values at this vessel. In the cases of tight residual stenosis (Figure 3A and 3C), high WSS values are seen at the whole stenotic region, whereas when the stenosis is less tight (Figure 3B), high WSS values are localized only close at the throat of the stenosis. OSI and $\ell_r$ are identical among cases at the SB close to the carina, indicating that due to the flow acceleration there is no stagnation or reversal of flow at this site. Flow conditions differentiate among cases at the SB distally to the carina and particularly at areas downstream the residual luminal constriction: in the case of SB balloon angioplasty followed by MB stenting, there is an area of low TAWSS, high OSI, and high $\ell_r$ values at the MB opposite the flow divider and distally a region of elevated WSS at the region of the edge between the stented and nonstented vessel due to the local vessel tapering that causes flow acceleration. We can thus assume that in single stenting, flow patterns are governed mainly by the degree of the residual stenosis, whereas the existence or absence of stent struts at the orifice of the SB do not impose any significant flow alterations.

**Double Stenting**

With double-stenting techniques (right panels of Figures 3 through 5), WSS, OSI, and $\ell_r$ distributions at the MB and SB exhibit pronounced differences among cases proximally to the carina, whereas distributions of flow indices are identical distally to the carina. Culotte stenting results in low WSS regions at both the proximal and the distal MB, whereas with the other 2 double-stenting techniques, low WSS regions are confined to the distal MB. Regarding the SB, culotte stenting results
at an extended region of low WSS opposite the flow divider. With T-stenting, the low WSS region is considerably smaller, whereas with crush stenting there are no low WSS regions at the SB. The distributions of OSI and $\tau$ also differ among stenting techniques; with culotte and T-stenting, “hot spots” of OSI are seen at the proximal SB, opposite the flow divider, whereas with crush stenting the OSI distribution at the SB is smooth. In all cases, small regions of high OSI are seen at the distal MB that coincide with the regions of low WSS. Regarding $\tau$, more distinct differences among cases are seen; in culotte stenting there are “hot spots” both at the SB opposite the flow divider and at the proximal MB. At T-stenting, there are “hot spots” at the both the SB and the distal MB, whereas at crush stenting “hot spots” are confined to the SB and occupy considerably less area. Similarly to single stenting, distally to the carina, there is a region of elevated WSS at the region of the edge between the stented and nonstented vessel due to the local vessel tapering that causes flow acceleration.

**Comparison of Techniques**

To compare findings, we calculated the surface integrals of TAWSS, OSI, and $\tau$ at a subregion of bifurcation site (Figure 1B). The integral of each index was normalized to that of the stenting technique that provided the most hemodynamically favorable results, that is, highest TAWSS and lowest OSI and $\tau$ (Table 1). The ranking of the stenting techniques in Table 1 follows a descending order, starting with the technique that gives the optimum results. From Table 1, we can derive that single-stenting techniques, and particularly stenting of the MB only and balloon angioplasty of the SB followed by stenting of the MB, give better overall results compared with the double-stenting techniques. Among the double-stenting techniques, crush stenting gives the most favorable results, whereas its overall ranging follows the 2 optimum single-stenting techniques.

Additionally, we calculated for each stenting technique the total area of the bifurcation region that is subjected to OSI values greater than specific predefined thresholds (Table 2).
As previously noted, OSI values close to 0.5 indicate arterial segments of flow stagnation or flow reversal. The results, shown in Table 2, indicate that single-stenting techniques result in smaller arterial segments at which flow is stopped or reversed. Crush stenting gives the optimum results among the double-stenting techniques, which are comparable to those of single-stenting techniques.

**Discussion**

Our results indicate that double stenting in bifurcations is associated with disturbed hemodynamics. They also indicate that double-stenting techniques do not produce similar hemodynamic disturbances at bifurcations. Plaque and neointimal hyperplasia tend to form in bifurcations within the coronary arteries where normal patterns of blood flow are disturbed. Even when proliferative responses to these altered hemodynamics are completely blocked by drug-eluting stents, abnormal flow patterns can be a possible cause of thrombosis. A number of computational studies have assessed hemodynamic alterations produced by stent implantation at nonbifurcated vessel segments: LaDisa et al studied WSS alterations after a slotted-tube coronary stent and found that flow stagnation zones are localized around the stent struts; minimum WSS decreased by 77% in stented compared with nonstented vessels. Faik et al validated the existence of secondary flow in the near wall region of the stented coronary segment and also demonstrated that secondary flow is more pronounced at the areas after the use of struts that are perpendicular to the main flow direction. Data regarding flow alterations caused by stent implantation at bifurcation lesion are limited. A computational study by Williams et al assessed hemodynamic changes after main branch stenting and side branch balloon angioplasty in a coronary bifurcation and indicated that this commonly used interventional strategy causes abnormal local hemodynamic conditions.

Our study is the first one to investigate flow patterns after different stenting techniques are used at bifurcation sites. Although the results and conclusions of the study are applicable only to the considered models and their relevance to

**Figure 5.** Relative residence time ($t_r$) distribution at the bifurcation for the considered bifurcation stenting techniques. Techniques (A) through (F) are described in detail in the text.
Table 1. Surface Integrals of Flow Indices for the 6 Considered Stenting Techniques and Normalized Integrals to the Technique That Provided Optimum Result

<table>
<thead>
<tr>
<th>Stenting Technique</th>
<th>TAWSS, ×10⁻⁶ m²</th>
<th>Normalized TAWSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stenting of the MB only</td>
<td>4.13</td>
<td>1.00</td>
</tr>
<tr>
<td>Balloon angioplasty of the SB followed by stenting of the MB</td>
<td>1.54</td>
<td>0.37</td>
</tr>
<tr>
<td>Culotte stenting</td>
<td>1.30</td>
<td>0.31</td>
</tr>
<tr>
<td>Crush stenting</td>
<td>1.18</td>
<td>0.29</td>
</tr>
<tr>
<td>Ideal T-stenting</td>
<td>0.78</td>
<td>0.19</td>
</tr>
<tr>
<td>Stenting of the MB followed by balloon angioplasty of the SB</td>
<td>0.15</td>
<td>0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>OSI, ×10⁻⁶ m²</th>
<th>Normalized OSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stenting of the MB only</td>
<td>7.52</td>
<td>1.00</td>
</tr>
<tr>
<td>Crush stenting</td>
<td>7.75</td>
<td>1.03</td>
</tr>
<tr>
<td>Stenting of the MB followed by balloon angioplasty of the SB</td>
<td>8.07</td>
<td>1.07</td>
</tr>
<tr>
<td>Balloon angioplasty of the SB followed by stenting of the MB</td>
<td>8.20</td>
<td>1.09</td>
</tr>
<tr>
<td>Culotte stenting</td>
<td>9.87</td>
<td>1.31</td>
</tr>
<tr>
<td>Ideal T-stenting</td>
<td>10.4</td>
<td>1.38</td>
</tr>
</tbody>
</table>

TAWSS indicates time-averaged wall shear stress; OSI, oscillatory shear index; t, relative residence time; MB, main branch; and SB, side branch.

Table 2. Bifurcation Total Area in Which OSI Exhibits Values Greater Than Specific Thresholds

<table>
<thead>
<tr>
<th>Stenting Technique</th>
<th>OSI &gt;0.25</th>
<th>OSI &gt;0.35</th>
<th>OSI &gt;0.45</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stenting of the MB only</td>
<td>0.29</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Balloon angioplasty of the MB followed by stenting of the MB</td>
<td>0.37</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>Stenting of the MB followed by balloon angioplasty of the SB</td>
<td>0.36</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>Crush stenting</td>
<td>0.34</td>
<td>0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>Culotte stenting</td>
<td>0.71</td>
<td>0.17</td>
<td>0.00</td>
</tr>
<tr>
<td>Ideal T-stenting</td>
<td>0.61</td>
<td>0.18</td>
<td>0.02</td>
</tr>
</tbody>
</table>

OSI indicates oscillatory shear index; MB, main branch; and SB, side branch.

clinical settings is unknown, it is plausible that the risk of restenosis and thrombosis would be higher at regions of the bifurcation that are continuously exposed to unfavorable hemodynamic conditions. In a recent study at specimens of stented bifurcations of patients dying of severe coronary artery disease, Nakazawa et al reported that neointimal formation is significantly less at the flow divider compared with the lateral wall and that late stent thrombosis has a higher prevalence at flow divider sites due to uncovered struts and disturbed flow at the carina region. Our computational findings are in part in keeping with these observations because in all simulated stenting techniques, regions of low WSS and high OSI, which are both associated to neointimal formation, are confined at the lateral arterial walls. Regarding stent thrombosis, our results indicate that the bifurcation regions at higher risk of thrombosis generally coincide with the regions of neointimal formation and are located opposite the flow divider. This difference is probably due to the fact that our study did not consider strut coverage by neointimal formation. Thus, considering the results of both studies, one might speculate that the risk of acute stent thrombosis is higher at sites opposite the flow divider, whereas the risk of late thrombosis is higher at the carina region. The flow disturbances induced by multiple strut layers is noticeable in various instances, for example, comparing OSI plots for culotte and crush techniques, where it is evident that in the latter case smaller values are observed at the entrance of the SB. That implies that the presence of 2 layers of struts before the entrance of the SB enhance small-scale vortices that significantly reduce the recirculation zone near the SB wall just after the bifurcation. Regarding the comparison of single- and double-stenting techniques, our findings are in keeping with the results of large clinical trials that documented that single stenting of the main vessel is preferable in the great majority of bifurcation lesions. A recent clinical trial comparing double-kissing (DK) crush with provisional stenting for the treatment of bifurcation lesions demonstrated that DK crush is associated with significant reduction of target lesion and target vessel revascularization, whereas there was no significant difference in major adverse cardiac events. Interestingly, in our study crush stenting was associated with the most favorable hemodynamic conditions among double-stenting techniques, which were in some cases comparable to those imposed by single stenting. It should be noted, however, that our study deals with immediate stenting results. The biological effect of multiple stent layers on the endothelium or the ostium of the side branch are not dealt with, although they may have important long-term consequences by means of neointimal growth stimulation and thrombus formation. With all single-stenting techniques, high values of TAWSS, OSI, and t are predicted at the SB that are associated with the residual stenosis. High WSS is considered favorable regarding the protection against neointimal growth, which is common at bifurcations; however, high WSS is also associated with plaque erosion and rupture and causes platelet activation. Additionally, areas of high OSI and t promote aggregation of the activated platelets and thus thrombosis. Regarding flow disturbances at vessel segments distal to the bifurcation, our computational findings indicate that differences among cases exist only among single-stenting techniques, which are confined at the SB, and are governed mainly by the degree of residual luminal stenosis of the SB. The most distinct feature appears in the case of 50% residual stenosis,
where an area of low TAWSS, high OSI, and high tr is evident at the circumference of the SB.

The flow parameters assessed in this study are not directly related to the functional significance of the bifurcation lesion. Functional significance of individual lesions is regularly evaluated by fractional flow reserve (FFR), and it has been recently shown that FFR-guided provisional side branch intervention is feasible and effective, whereas FFR can be calculated by computational techniques in simulated bifurcations. Computed tomography coronary angiography (CTCA) can be used to acquire patient specific coronary bifurcation anatologies noninvasively, whereas CFD simulations can be used to assess flow parameters at the bifurcation region and calculate the FFR of individual bifurcation lesions. Therefore, CTCA combined with CFD simulations can be theoretically used as a tool to guide both bifurcation stenting strategy and selection of the stenting technique with the optimal post-PCI flow conditions.

**Study Limitations**

The considered model represents an idealized coronary bifurcation. At the SB, we considered an ostial symmetrical stenosis, although the shape of an actual coronary lesion is seldom symmetrical. Although early atherosclerosis is localized at sites of low WSS, such as the outer walls of vessel bifurcations, at advanced to severe atherosclerosis, plaques grow circumferentially from the low WSS region into the high WSS flow divider; thus, severe ostial stenoses become circumferentially symmetrical. The vessels were considered straight, noncompliant, and stationary, because studies have shown that myocardial motion has only a minor effect on flow distribution within the arterial tree relative to the effect of the blood pressure pulse, and stent implantation causes straightening of the vessel and reduces its regional compliance. In all considered cases, optimal stent deployment and complete apposition of stent struts against the vessel walls were considered, although in real-life inadequate stent deployment is frequent and multiple overlapping stents increase the likelihood of strut malapposition. Thus, our model assumes perfect stent deployment that usually in clinical practice requires kissing-balloon after dilatation. In any case, it has been recently shown that thin-strutted, drug-eluting stents, such as the one simulated in our study, are less thrombogenic than thick-strutted, bare metal stents and that the lower thrombogenicity remains even with incomplete stent deployment. In the cases of single stenting, the residual stenosis at the SB causes high WSS distally to the bifurcation region; because such areas are partly within the integration region, this could have affected TAWSS calculation.

We acknowledge these limitations and believe that our data indicate that single stenting of the main branch with our without balloon angioplasty of the side branch ostium offers better hemodynamic patterns than double stenting. When double stenting is considered necessary, the crush technique with the use of a thin-strut stent is preferable to culotte or T-stenting. Whether these theoretical advantages translate into improved clinical outcomes cannot be deduced from our study.

**Disclosures**

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**References**


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