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Location of side branch access critically affects results in bifurcation stenting: Insights from bench modeling and computational flow simulation ☆

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ABSTRACT

Background: The aim of this study was to evaluate the impact of stent design and side branch access on final strut apposition during bifurcation stenting.
Methods and results: A series of 6 different commercially available Drug Eluting Stents (DES) (n = 42) were deployed in an identical model of a coronary bifurcation. Kissing Balloon (KB) optimization was performed after either proximal or distal recrossing of the guidewire and results were analyzed by micro-Computed-Tomography.
Stent design only had a minor impact on side branch lumen area free of stent struts. Similar rate of strut malapposition was observed within the bifurcation when a consistent KB optimization protocol and an optimal distal recrossing of the wire to reaccess the side branch (SB) are followed.
Conversely, proximal instead of distal cell recrossing toward the side branch produced a significant lower area of the side branch lumen free of struts than an optimal distal recrossing (60.3 ± 7.1% versus 81.1 ± 8.0%, $p < 0.0001$), as well as a higher rate of strut malapposed toward the SB ostium (40.6 ± 6.0% versus 26.0 ± 5.7%, $p = 0.0005$).
Conclusions: Optimal cell recrossing of the guidewire may be critical to ensure successful stent optimization in bifurcation PCI.

1. Introduction

Higher rates of focal restenosis and stent thrombosis are still concerning after treatment of bifurcation lesions by Percutaneous Coronary Interventions (PCI) [1].

Kissing Balloon (KB) post-dilatation is generally been recommended as final step in the different bifurcation stenting strategies to optimize strut apposition and flair the stent strut left jailing the side branch (SB). Evidence from recent randomized bifurcation trials are challenging the systematic practice of KB optimization by showing no improvements on patients' outcome of routine KB post-dilatation over leaving a jailed SB for bifurcations treated with a single stent provisional approach [2,3].

Intravascular imaging studies with Optical Coherence Tomography (OCT) have shown previously that despite optimization and final KB, stent malapposition remains a frequent, if not systematic, issue in bifurcation [4,5].

A critical step in bifurcation stenting for both provisional and more complex two stent procedures involves rewiring of the side or main branch through the stent and dilatation of the strut jailing the branch access [1,6,7]. Stent design and the maximal side branch opening that can be obtained during side branch dilatation through the stent mesh have been generally considered as one of the most determinant parameters affecting final side branch access result after bifurcation optimization [8,9].

Previous in-vitro work [9–11] and in-vivo evidences by OCT [12,13] showed that the results of bifurcation optimization are however critically dependent on the location of guidewire cell recrossing before dilatation of the SB and final optimization.

2. Methods

2.1. Bench model

To evaluate the impact of SB access and stent design on final result after KB, a series of commercially available Drug Eluting Stents (DES) (n = 42) were deployed in a model bifurcation and optimized with KB after either proximal or an optimal distal recrossing of the guidewire.

The DES used were 16 mm to 28 mm in length and included the Everolimus eluting *Xience V* (n = 9, Abbott Vascular, Santa Clara, CA), *Promus Element* (n = 9, Boston Scientific, Natick, MA), the Paclitaxel eluting *Taxus Liberte* (n = 8, Boston Scientific, Natick, MA), the Biolimus eluting *Biomatrix Flex* (n = 7, Biosensors International,

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Morges, Switzerland), the Sirolimus eluting *Cypher Select* (n = 4, Cordis, Warren, NJ) and the Zotaroliums eluting *Resolute* stents (n = 5, Medtronic, Santa Rosa, CA) [Table 1].

The stents were deployed in a model representative of a coronary bifurcation anatomy (*Proximal Main Vessel = 3.5 mm*, *Distal Branch = 2.75 mm*, *SB = 2.75 mm*, *MV/SB angle = 45°*). All stents were deployed in the main branch at 3.0 mm following their indicated compliance chart. Guidewire was then advanced under visual control through the stent strut accessing the SB through either an optimal mid-distal cell, defined as the stent cell found toward the distal part of the side branch and centered on the ostium (n = 34) or through a proximal cell, defined as the most proximal cell available for recrossing immediately after the SB take-off (n = 8).

A non-compliant balloon (2.5 × 15 mm NC sprinter and Quantum Maverick) was then advanced through the strut into the SB and a semi-compliant 3.0 mm balloon was advanced in the MB. Dilatation of the SB ostium was performed by first a SB dilatation at 14 atm followed by a simultaneous KB inflation of both balloons at 10 atm. In case some struts were left not fully apposed in the proximal edge of the stents after KB, a final proximal post-dilatation was performed with a NC 3.75 mm balloon to complete strut apposition in the proximal vessel segment.

.2.1.1. Quantification and 3D reconstruction

To assess results, the model and stent were scanned using high resolution micro-Computed Tomography (HMX-ST, X-TEK Systems Ltd., Tring, UK). After reconstruction, data were analyzed (ImageJ, rsbweb.nih.gov) to quantify stent final geometry and apposition to the vessel. Measurements including Lumen Diameter, stent area, maximal strut–wall distance and percentage of strut malapposed (strut–wall distance >150 μm) was assessed in reference segments through the bifurcation.

Residual area malapposed at the ostium was evaluated from an average of two 3D views of the SB ostium. % residual ostial stenosis was defined as the % of area left malapposed after KB compared to the reference ostium area [14]. 3D rendering of representative cases was performed and the model was virtually cut-open to allow visualization of the stent strut apposition in the final result through different viewpoints.

.2.1.2. Computational flow simulation

Flow patterns were reconstructed using Computational Fluid Dynamics (CFD) to identify potential risk of flow disturbance and high shear rate induced by unapposed struts. Cases representative of the results were obtained with either proximal or distal recrossing after KB post-dilatation was performed. Bench results were segmented and surface meshes obtained were imported into a commercial CFD suite (CFX 12.1, ANSYS Inc., US) as described previously [7]. The inlet flow condition used was a flow waveform recorded in a human LAD by ultrasound Doppler (Combowire, Volcano Corp., US) [7]. The flow split between Main Branch (MB) and SB was assumed to be 70% to MB and 30% to SB. Blood was assumed to be a Newtonian fluid.

2.2. Statistical analysis

Results are expressed as mean ± SD. Comparison among the different strategies was tested by analysis of the variance and Tukey's multiple comparison tests. Welch's t-tests were used to compare results between samples with proximal and distal recrossing. Data were considered statistically significant for p values <0.05.

The authors of this manuscript have certified that they comply with the Principles of Ethical Publishing in the International Journal of Cardiology.

3. Results

3.1. Difference between stent platforms in terms of strut apposition and ostium opening after optimal KB remained moderate

The impact of stent design observed when performing the same optimization protocol with a distal recrossing was minimal. The range of difference observed between the average results of each platform tested was [15.9%–24.9%] for the percentage of ostium area obstructed and [15.4%–23.6%] for the cross-sectional rate of malapposed struts. Despite high pressure dilatation of the SB ostium and optimal distal recrossing, complete apposition of the stent at the SB ostium was never fully achieved after KB and residual unopposed struts were observed in almost all the cases performed [Figs. 1, 2].

3.2. Proximal crossing increase the rate of strut malapposition toward the ostium and in front of the carina

Comparing the average results observed on a series of identical stents optimized with proximal recrossing to the samples optimized after distal cell recrossing, we can see that proximal recrossing led to significantly higher residual ostial stenosis (SB area covered by struts) than distal recrossing (39.7 ± 7.1% versus 18.9 ± 8.0%, $p < 0.0001$), a higher rate of strut malapposed in the bifurcation on average (26.5 ± 10.5% versus 20.2 ± 6.4%, $p = 0.17$) as well as toward the SB ostium (40.6 ± 6.0% versus 26.0 ± 5.7%, $p = 0.0005$). Maximal strut–wall malapposition distance was also larger with proximal recrossing (1.2 ± 0.3 mm versus 0.7 ± 0.2 mm, $p = 0.001$) [Figs. 3 and 4].

3.3. Comparison of flow perturbations depending on recrossing location

In addition to a higher rate of malapposition, reconstruction of flow using CFD shows marked differences in flow profile in a stent optimized with distal recrossing as compared to stent optimized with proximal recrossing [Fig. 5].

Shear rate distribution show the impact of "jailing" struts disturbing blood flow to the side branch before optimization. Shear distribution reveals the danger of having struts left unopposed immediately in front of the carina (neo-carina). The area of blood affected by high shear components (2000–4000 s^{-1}) was the highest in the case where the ostium was still jailed and after proximal recrossing. Distal recrossing reduces the amount of malapposed struts disturbing flow and producing high shear components above 2000 s^{-1}. Proximal cell recrossing leaves on the opposite, a large amount of strut malapposition right in front of the carina. These struts, left in the path of the central highest velocity components, produce the highest impact on shear profile and may be more likely to cause shear induced platelet activation and a potential lethal stent thrombosis cascade.

4. Discussion

4.1. Impact of stent design on side branch access

Stent design determines the theoretical maximal side branch opening that can be obtained during side branch dilatation through the stent mesh [8,9].

Table 1
Design characteristics of the different drug eluting stent platforms evaluated in this study.

	Stent design evaluated (3.0 mm stents)						
	Alloy	Strut thickness	Drug	Polymer	Nb of crowns	Nb of connectors	Bare metal platform
Promus Element	PtCr	81	Everolimus (1.0 μg/mm^2)	Fluorinated polymer	8	2	Omega
Xience	CoCr (L-605)	81	Everolimus (1.0 μg/mm^2)	Fluorinated polymer	6	3	Vision
Taxus Liberte	316L SS	96	Paclitaxel (1.0 μg/mm^2)	Translute	9	3	Liberte
Resolute	CoCr (MP-35N)	91	Zotarolimus (1.6 μg/mm^2)	Biolinx (PC coating)	10	2	Driver
BioMatrix Flex	316L SS	120	Biolimus (15.6 μg/mm)	PLA degradable (abluminal)	6	2	Juno
Cypher Select	316L SS	140	Sirolimus (1.4 μg/mm^2)	PEVA/PBMA	6	6	BX Velocity