Modeling the stent deployment in coronary arteries and coronary bifurcations

Accepted chapter available at https://doi.org/10.1016/C2017-0-03308-6

Modeling the Stent Deployment in Coronary Arteries and Coronary Bifurcations

Claudio Chiastra[1], Gabriele Dubini[1], Francesco Migliavacca[1]

[1.] Laboratory of Biological Structure Mechanics (LaBS), Department of Chemistry, Materials and Chemical Engineering "Giulio Natta", Politecnico di Milano, Italy

Address for correspondance:
Francesco Migliavacca
Laboratory of Biological Structure Mechanics
Department of Chemistry, Materials and Chemical Engineering "Giulio Natta"
Politecnico di Milano
Piazza L. da Vinci, 32
20133 Milano, Italy

Phone: +39.02.2399.4316
Fax: +30.02.2399.4286
E-mail: francesco.migliavacca@polimi.it

Abstract

Mathematical models are well-recognized and widely adopted tools to study stenting procedures. Nowadays, the increased computational power allows satisfying clinical needs more easily. The simulations of complex patient-specific cases including the implantation of multiple stents in coronary bifurcations or curved vessels has become a reality. Thanks to image-based methods, the peculiar anatomical features prior and after a stent insertion are detectable. The stress state exerted within the arterial wall of a coronary artery can be estimated by means of structural simulations. This review chapter aims to describe the most recent advances in this area with particular focus on stent deployment simulations in coronary bifurcations.

Keywords

Mathematical models, finite element analysis, coronary artery bifurcation, stent, virtual deployment, wall stress, patient-specific reconstruction.

1. Introduction

The treatment of coronary bifurcation lesions is characterized by a higher rate of procedural complications and adverse events as compared to non-bifurcation interventions [1]. Because of the anatomical variability of bifurcations (e.g. angle between branches, diameter of branches, location and severity of the plaques, etc.) and the anatomical modifications caused by stenting implantation (e.g. carina and/or plaque shift and dissection), it is difficult to define a gold-standard strategy for the treatment of atherosclerotic lesions in coronary bifurcations [1]. Indeed, the stenting techniques for the treatment of coronary bifurcations are still numerous and each of them is associated with limitations and drawbacks [2].

Structural simulations of stent deployment allow the quantification of quantities that are hardly detectable *in vitro*, using the bench test experimental approach, or *in vivo* [3,4]. By using idealized models of coronary arteries with or without bifurcations, the performance of different stent platforms or stenting techniques can be compared by analyzing a number of geometrical and mechanical quantities. Examples of geometrical quantities include malapposition, stent ellipticity, stent cell size, minimum lumen area, side branch ostial area, and side branch compromise. As regards the mechanical quantities, in addition to stress and strain within the stent, stress and strain inside the arterial tissue, and the vessel wall damage provoked by the stent struts pushing the wall can be quantified. The analysis of the stress field within the arterial tissue is of particular interest as animal studies have highlighted that the increased arterial wall stress due to stent expansion is related to in-stent restenosis [5]. Thus, when applied to patient-specific anatomies, structural simulations can be used to guide the choice of the best stent platform or stenting technique for that specific anatomy in terms of mechanical quantities relevant to the progression of in-stent restenosis.

The former part of this Chapter presents the models of stent deployment in idealized coronary bifurcated geometries while the latter outlines the usage of patient-specific models.

2. Structural models of stent deployment in idealized geometries

There is plenty of studies on stent modeling in the literature. The pioneering studies are dated nearly 20 years ago (e.g. [6–10]). Those works seldom considered the presence of the balloon or the vessel wall. We refer the reader to two recent reviews, which describe most of these studies [11,12].

Figure 1 schematically shows the necessary elements to carry out a standard acceptable structural simulation of stent deployment in a coronary vessel either idealized or patient-specific: the artery, the plaque(s), the balloon(s) and the stent(s). Indeed, nowadays, the presence of a balloon when simulating the stent expansion is considered mandatory as it highly affects the arterial wall stress patterns [13,14]. Similarly, the modeling of the arterial vessel with realistic mechanical properties [15] should be always included when studying the expansion of a stent. The modeling of the atherosclerotic plaque strongly influences the response of arterial wall when a stent is implanted [16–18]; for this reason, the majority of the modeling works takes this feature into account. The difficulty here lies in knowing the mechanical properties, as the plaque is heterogeneous and multi-component. An overview on plaque mechanics is offered in a recent special issue of the Journal of Biomechanics [19]. Phenomena like plaque shift, rupture, and delamination are still open issues for modelers.

<Figure 1 near here>

The most recent structural studies for coronary artery diseases are focused on the bifurcation area. A list as comprehensive as possible of those studies is reported in Table 1. In the majority of these studies [16,20–28], the provisional stenting technique is simulated as it is considered the standard strategy of treatment for most coronary bifurcations [2]. The first step of this technique consists in the deployment of a stent in the main branch of the bifurcation (i.e. cross-over stenting) [23]. Subsequently, the current consensus document by the European Bifurcation Club [2] suggests to post-dilate the proximal main branch using a short balloon (i.e. proximal optimization technique, POT) to ensure adequate stent apposition, and, depending on the specific case, to simultaneously expand two short balloons in both bifurcation branches (i.e. kissing balloon inflation, KBI) to improve side branch access, and to conclude the technique with another POT (i.e. rePOT). In case of poor angiographic results in a side branch supplying a vast myocardial territory, stenting of the side branch is still possible [2], thus leading to a double-stenting technique.

Some modeling studies [16,22,25] investigated the impact of the different procedural steps of provisional stenting from the biomechanical viewpoint to support the cardiologists' decision on performing some of those steps (or alternative steps). In particular, Gastaldi et al. [16] studied the impact of stent positioning on the access to the side branch and compared the KBI against the dilatation of the main branch only as the last procedural step of provisional stenting. The other two studies [22,25] compared different post-dilation strategies for concluding the provisional stenting technique (i.e. KBI against sequential dilatation of side and main branches). Foin et al. [22] computed the deformation induced within the arterial wall by the two different post-dilation strategies as additional analysis to *in vitro* bench tests and computational fluid dynamics simulations. Mortier et al. [25] performed exclusively a virtual bench test by carrying out finite element analyses in three bifurcation anatomies with three stent platforms. The simulated cases (n=54) were compared in terms of geometrical quantities, namely side branch ostial area stenosis, strut malapposition, and ellipticity of the proximal stent segment. In both studies, the sequential dilation resulted in better outcomes.

To improve the KBI step within provisional stenting, Morlacchi et al. [21] proposed a tapered balloon able to reduce the proximal main branch ellipticity and to mitigate the effects of high arterial wall stress in the proximal main branch provoked by the simultaneous inflation of two balloons in the bifurcation. Other studies [20,23] compared the biomechanical behavior of different stent platforms when deployed using the provisional stenting technique. Iannaccone et al. [28] investigated the impact of bifurcation angle, plaque composition, and post-dilatation strategies of provisional stenting on side branch ostium compromise. A parametric population-based bifurcation model was created with 60% diameter stenosis in all branches (Medina class 1,1,1). Two bifurcation angles and four different plaque types were analyzed. The simulations highlighted that provisional stenting causes an ovalisation of the side branch ostium, which can appear as significant stenosis in two-dimensional angiography, without causing any significant reduction of the side branch ostium area in the majority of cases. Furthermore, they showed that provisional stenting results in more severe outcomes for the side branch ostium in case of calcified plaques and that short balloons should be preferred when performing the post-dilatation step.

The number of finite element studies investigating double-stenting techniques for the treatment of coronary bifurcation is limited. Raben et al. [26] compared Provisional stenting, Crush, Culotte, and T-stenting with high protrusion from the biomechanical viewpoint. However, finite element analyses of stent deployment were used only to generate the fluid domain for subsequent computational fluid dynamics simulations. Morris and colleagues [29] performed detailed stent insertion simulations with the simultaneous kissing stents (SKS) technique (Fig. 2). Structural simulations were useful to demonstrate that the stents were not distorted and that this technique produced favorable outcome in selected patients. This study is a good example of how modeling studies, although with idealized geometries, can provide general guidelines to improve coronary bifurcation stenting treatments.

<Figure 2 near here>

The usage of new dedicated devices for the treatment of coronary bifurcations is increasingly reported in the recent literature. Arokiaraj et al. [30] proposed a double stenting technique consisting in the deployment in the main branch of a novel stent with an interface of three nitinol-based connection links followed by the stenting of the side branch with a conventional stent. The work by Morlacchi et al. [24] was focused on the Tryton stent (Tryton Medical, Inc., Durham, NC, USA), which is one of the few dedicated devices that underwent large clinical trials [31]. In particular, finite element structural simulations were used to compare the Tryton-based culotte technique against provisional stenting and culotte technique performed with conventional stents. Results showed that substantially different patterns of mechanical deformation were obtained with the different stenting techniques. The Tryton-based technique was proposed as the procedure able to facilitate the intervention by improving the access to the main branch and to lower mechanical stress in the vessel wall. Recently, the same group of authors continued to evaluate the performance of the Tryton stent [31,32]. Specifically, Grundeken et al. [31] evaluated the effect of rewiring through one of the panels of the Tryton device (instead of the suggested re-wiring in-between the panels) on stent geometry and mechanics. Chiastra et al. [32] investigated the impact of wrong positioning of the Tryton stent in coronary bifurcations on geometrical and mechanical quantities. Indeed, the device manufacturer provides specific recommendations to position the Tryton stent in the side branch. However, in daily practice, wrong positioning of the stent can occur. In both studies, the structural simulations were used to explain and support in vivo 3D optical coherence tomography (OCT) analyses. The two studies are an example of how simulations performed in idealized bifurcation models can help understand phenomena observed during stent deployment in the clinical practice.

<Table 1 near here>

3. Structural models of stent deployment in patient-specific geometries

One of the main aims behind the construction of patient-specific models is to use the simulation results to give indication in the interventional planning process. Furthermore, patient-specific models can be used to better interpret the procedural outcomes including adverse biological process after stent implantation, like the in-stent restenosis.

The first proof-of-concept study of patient-specific approach was proposed in 2008 by Gijsen et al. [33], who built a 3D model of a mildly stenosed coronary artery without bifurcation with a combination of biplane angiography and intravascular ultrasound. Such a model was used to predict stresses in the stent struts and the vessel wall. Since 2008, a limited number of patient-specific structural studies of coronary stenting have been published. Table 2 provides a list as comprehensive as possible of those works, limited to coronary bifurcations.

Mortier et al. [34] compared the biomechanical behavior of different stent platforms in an image-based coronary bifurcation model reconstructed from rotational angiography data. A detailed bifurcation model was created by accounting for the anisotropic mechanical behavior of its main three constitutive layers (i.e. intima, media, and adventitia) but discarding the presence of the plaque. The different stents were compared in terms of arterial wall stresses provoked at the end of the implanting procedure. To show the potentiality of the virtual stent design, two modified stent designs were also proposed, which allowed reducing the predicted maximum wall stress values.

Ragkousis et al. [35] compared the mechanical performance of different balloon delivery systems for the treatment of coronary arteries. In particular, a tapered and a stepped multi-folded balloon models were developed to maximize the minimum lumen area and minimize the stent malapposition. These balloon models were applied to both a non-bifurcated and bifurcated patient-specific coronary vessel.

Differently from the previous two works, other studies [36–38] proved the feasibility of performing patient-specific structural analyses that replicate the complete stenting procedure followed by the clinicians to treat a patient. Specifically, in Morlacchi et al. [36] image-based 3D vessel reconstructions were created combining data from conventional coronary angiography and computed tomography angiography and the clinical procedure was virtually replicated (Fig. 3). Although the imaging data did not provide precise information on plaque location and composition, the plaque location was estimated by computing the distance between each node of the mesh of the vessel and the centerline of the external wall. This study showed the biomechanical impact of stent deployment in patient-specific coronary bifurcations and pointed out how two overlapping stents have great influence on the stent and arterial wall stress state (Fig. 3). Mortier et al. [37] virtually replicated all the steps of the provisional stenting technique, including proximal optimization technique and kissing balloon inflation, in a patient-specific left main coronary bifurcation model. The bifurcation model was reconstructed from computed tomography and intravascular ultrasound images, thus allowing a more accurate anatomical description as compared to the previous study [36]. In fact, the high resolution (axial resolution of 100-200 µm and lateral resolution of 200-300 µm) and tissue penetration (10 mm) of intravascular ultrasound [39] enabled the 3D reconstruction of the arterial wall with patient-specific variable thickness. To demonstrate that alternative treatment approaches can be compared using the virtual bifurcation stenting, the stent sizing strategy performed in vivo was compared to a different one (i.e. 3.0 mm versus 3.5 mm Abbott Xience Prime stent) in terms of geometrical and mechanical quantities. Finally, Chiastra et al. [38] performed structural simulations of stent deployment in two patient-specific anatomies reconstructed from computed tomography and OCT. The plaque location was estimated using a previously developed method [36]. A different composition (i.e. soft or stiff plaque) was associated to different plaque regions, which were manually delineated from OCT. In addition to the in vivo clinical procedure, different stent platforms and positions were simulated and compared from the biomechanical viewpoint to show the use of these analyses as tools for pre-interventional planning.

It is worth mentioning that most of the recent studies on patient-specific models of coronary bifurcations are related to the investigation of the altered hemodynamics caused by the stent placement. This interest has gained attention thanks to the more and more common use of OCT in the clinical centers. We refer the reader to the chapter of this book on the hemodynamics in coronary bifurcations (Chapter 12) for detailed information about those studies.

<Table 2 near here>

<Figure 3 near here>

4. Model validation

Validation of the structural models described in this Chapter is a key process for determining whether these models are an accurate representation of *in vitro* or *in vivo* stent deployment [40]. Several studies validated the free-expansion behavior of both conventional coronary stents [8,13,41,42] and devices dedicated to bifurcations [43] by visually comparing the stent-balloon expansion patterns and/or by quantitatively comparing computed pressure–diameter relationships to experimental data or to the device compliance chart provided by the manufacturer. Figure 4 shows an example of qualitative comparison between a free-expansion simulation and the corresponding experiment for the Resolute Integrity stent (Medtronic, Minneapolis, MN, USA). The finite element simulation was able to predict the transient expansion behavior including the dog-boning effect.

<Figure 4 near here>

A good match between finite element analysis and reality was also observed by Gastaldi et al. [16] who qualitatively compared the geometric outcome obtained after provisional stenting simulated in a coronary bifurcation model against the results of an experimental test conducted in a bifurcation phantom with similar geometry [44].

To the best of the authors' knowledge, until now the work by Chiastra and colleagues [38] is the only study that evaluated the reliability of structural simulations to predict the post-operative geometric outcomes in patient-specific coronary bifurcation models. In particular, the lumen geometries obtained after virtual stent deployment were compared against those reconstructed from post-operative OCT images. The geometries showed a qualitative good agreement. Quantitatively, the maximum difference in lumen area with a relative distance lower than 0.25 mm (i.e. twice the stent strut thickness) between the two geometries was ~20%. The analysis was performed in two cases and was limited to the lumen surface without the comparison of the stent geometry.

5. Conclusions and future directions

In the present Chapter, several computational studies on the structural mechanics of stented coronary bifurcations have been reviewed, considering both idealized and image-based models. The vascular injury caused by device implantation is an important aspect that needs to be linked to the outcome of the stent procedure. Modeling can provide insight on the changes of the mechanical environment due to the stent expansion. More patient-specific data, like the plaque mechanical properties, need further investigation.

As proposed in the work by Ribeiro et al. [45], one direction to future developments in the stent arena is the design of specific stent design responding to precise performances. Their methodology is based on the accurate reconstruction of surrogate stent models designed to perform a sensitivity analysis to evince the geometrical struts characteristics having an impact on output variables. This method not only might be applied to an idealized coronary artery without any bifurcations, but it might be extended to patient-specific scenarios. So far, patient-specific structural simulations of stent deployment are sophisticated and time-consuming. To be useful and capable of predicting the best stent platform and technique for the specific patient, these simulations should be made in real time, while the cardiologist is planning the procedure. This means that the simulations should provide the surgeon results on the effects of different parameters (i.e. stent platform, positioning, bifurcation technique choice, etc.), and receive warnings in terms of abnormalities related to the geometrical and mechanical variables of interest.

6. Acknowledgments

We acknowledge Dario Ardemani and Francesco Bellavia (Politecnico di Milano, Milan, Italy) for their contribution to the computational analyses.

7. References

[1] Lassen JF, Holm NR, Banning A, Burzotta F, Lefèvre T, Chieffo A, et al. Percutaneous coronary intervention for coronary bifurcation disease: 11th consensus document from the European Bifurcation Club. EuroIntervention 2016;12:38–46. doi:10.4244/EIJV12I1A7.

[2] Lassen JF, Burzotta F, Banning A, Lefèvre T, Darremont O, Hildick-Smith D, et al. Percutaneous coronary intervention for the left main stem and other bifurcation lesions: 12th consensus document from the European Bifurcation Club. EuroIntervention 2018;13:1540–53. doi:10.4244/EIJ-D-17-00622.

[3] Migliavacca F, Chiastra C, Chatzizisis YS, Dubini G. Virtual bench testing to study coronary bifurcation stenting. EuroIntervention 2015;11 Suppl V:V31–4. doi:10.4244/EIJV11SVA7.

[4] Antoniadis AP, Mortier P, Kassab G, Dubini G, Foin N, Murasato Y, et al. Biomechanical Modeling to Improve Coronary Artery Bifurcation Stenting: Expert Review Document on Techniques and Clinical Implementation. JACC Cardiovasc Interv 2015;8:1281–96. doi:10.1016/j.jcin.2015.06.015.

[5] Timmins LH, Miller MW, Clubb FJ, Moore JE. Increased artery wall stress post-stenting leads to greater intimal thickening. Lab Invest 2011;91:955–67. doi:10.1038/labinvest.2011.57.

[6] Etave F, Finet G, Boivin M, Boyer JC, Rioufol G, Thollet G. Mechanical properties of coronary stents determined by using finite element analysis. J Biomech 2001;34:1065–75.

[7] Migliavacca F, Petrini L, Colombo M, Auricchio F, Pietrabissa R. Mechanical behavior of coronary stents investigated through the finite element method. J Biomech 2002;35:803–11.

[8] Migliavacca F, Petrini L, Montanari V, Quagliana I, Auricchio F, Dubini G. A predictive study of the mechanical behaviour of coronary stents by computer modelling. Med Eng Phys 2005;27:13–8. doi:10.1016/j.medengphy.2004.08.012.

[9] Tan LB, Webb DC, Kormi K, Al-Hassani ST. A method for investigating the mechanical properties of intracoronary stents using finite element numerical simulation. Int J Cardiol

2001;78:51–67.

[10] Petrini L, Migliavacca F, Auricchio F, Dubini G. Numerical investigation of the intravascular coronary stent flexibility. J Biomech 2004;37:495–501. doi:10.1016/j.jbiomech.2003.09.002.

[11] Morlacchi S, Migliavacca F. Modeling stented coronary arteries: Where we are, where to go. Ann Biomed Eng 2013;41:1428–44. doi:10.1007/s10439-012-0681-6.

[12] Martin D, Boyle FJ. Computational structural modelling of coronary stent deployment: a review. Comput Methods Biomech Biomed Engin 2011;14:331–48. doi:10.1080/10255841003766845.

[13] De Beule M, Mortier P, Carlier SG, Verhegghe B, Van Impe R, Verdonck P. Realistic finite element-based stent design: The impact of balloon folding. J Biomech 2008;41:383–9. doi:10.1016/j.jbiomech.2007.08.014.

[14] Gervaso F, Capelli C, Petrini L, Lattanzio S, Di Virgilio L, Migliavacca F. On the effects of different strategies in modelling balloon-expandable stenting by means of finite element method. J Biomech 2008;41:1206–12. doi:10.1016/j.jbiomech.2008.01.027.

[15] Holzapfel G, Sommer G, Gasser CT, Regitnig P. Determination of layer-specific mechanical properties of human coronary arteries with nonatherosclerotic intimal thickening and related constitutive modeling. Am J Physiol Heart Circ Physiol 2005;289:H2048–58. doi:10.1152/ajpheart.00934.2004.

[16] Gastaldi D, Morlacchi S, Nichetti R, Capelli C, Dubini G, Petrini L, et al. Modelling of the provisional side-branch stenting approach for the treatment of atherosclerotic coronary bifurcations: Effects of stent positioning. Biomech Model Mechanobiol 2010;9:551–61. doi:10.1007/s10237-010-0196-8.

[17] Pericevic I, Lally C, Toner D, Kelly DJ. The influence of plaque composition on underlying arterial wall stress during stent expansion: The case for lesion-specific stents. Med Eng Phys 2009;31:428–33. doi:10.1016/j.medengphy.2008.11.005.

[18] Zhao S, Gu L, Froemming SR. Finite Element Analysis of the Implantation of a Self-

Expanding Stent: Impact of Lesion Calcification. J Med Device 2012;6:021001. doi:10.1115/1.4006357.

[19] Gijsen FJH, Migliavacca F. Plaque mechanics. J Biomech 2014;47:763–4. doi:10.1016/j.jbiomech.2014.01.031.

[20] Mortier P, De Beule M, Van Loo D, Verhegghe B, Verdonck P. Finite element analysis of side branch access during bifurcation stenting. Med Eng Phys 2009;31:434–40. doi:10.1016/j.medengphy.2008.11.013.

[21] Morlacchi S, Chiastra C, Gastaldi D, Pennati G, Dubini G, Migliavacca F. Sequential structural and fluid dynamic numerical simulations of a stented bifurcated coronary artery. J Biomech Eng 2011;133:121010. doi:10.1115/1.4005476.

[22] Foin N, Torii R, Mortier P, De Beule M, Viceconte N, Chan PH, et al. Kissing balloon or sequential dilation of the side branch and main vessel for provisional stenting of bifurcations: Lessons from micro-computed tomography and computational simulations. JACC Cardiovasc Interv 2012;5:47–56. doi:10.1016/j.jcin.2011.08.019.

[23] Burzotta F, Mortier P, Trani C. Characteristics of drug-eluting stent platforms potentially influencing bifurcated lesion provisional stenting procedure. EuroIntervention 2014;10:124–32. doi:10.4244/EIJV10I1A19.

[24] Morlacchi S, Chiastra C, Cutrì E, Zunino P, Burzotta F, Formaggia L, et al. Stent deformation, physical stress, and drug elution obtained with provisional stenting, conventional culotte and Tryton-based culotte to treat bifurcations: A virtual simulation study. EuroIntervention 2014;9:1441–53. doi:10.4244/EIJV9I12A242.

[25] Mortier P, Hikichi Y, Foin N, De Santis G, Segers P, Verhegghe B, et al. Provisional stenting of coronary bifurcations: Insights into final kissing balloon post-dilation and stent design by computational modeling. JACC Cardiovasc Interv 2014;7:325–33. doi:10.1016/j.jcin.2013.09.012.

[26] Raben JS, Morlacchi S, Burzotta F, Migliavacca F, Vlachos PP. Local blood flow patterns in

stented coronary bifurcations: an experimental and numerical study. J Appl Biomater Funct Mater 2014;0:0–0. doi:10.5301/jabfm.5000217.

[27] Chen HY, Al-Saadon K, Louvard Y, Kassab GS. Biomechanical impact of provisional stenting and balloon dilatation on coronary bifurcation: clinical implications. J Appl Physiol 2017;123:221–6. doi:10.1152/japplphysiol.00245.2017.

[28] Iannaccone F, Chiastra C, Karanasos A, Migliavacca F, Gijsen FJH, Segers P, et al. Impact of plaque type and side branch geometry on side branch compromise after provisional stent implantation: a simulation study. EuroIntervention 2017;13:e236–45. doi:10.4244/EIJ-D-16-00498.

[29] Morris PD, Iqbal J, Chiastra C, Wu W, Migliavacca F, Gunn JP. Simultaneous kissing stents to treat unprotected left main stem coronary artery bifurcation disease; stent expansion, vessel injury, hemodynamics, tissue healing, restenosis, and repeat revascularization. Catheter Cardiovasc Interv 2018. doi:10.1002/ccd.27640.

[30] Arokiaraj MC, De Santis G, De Beule M, Palacios IF. A Novel Tram Stent Method in the Treatment of Coronary Bifurcation Lesions – Finite Element Study. PLoS One 2016;11:e0149838. doi:10.1371/journal.pone.0149838.

[31] Grundeken MJ, Chiastra C, Wu W, Wykrzykowska JJ, De Winter RJ, Dubini G, et al. Differences in rotational positioning and subsequent distal main branch rewiring of the Tryton stent: An optical coherence tomography and computational study. Catheter Cardiovasc Interv 2018;92:897–906. doi:10.1002/ccd.27567.

[32] Chiastra C, Grundeken MJ, Collet C, Wu W, Wykrzykowska JJ, Pennati G, et al. Biomechanical Impact of Wrong Positioning of a Dedicated Stent for Coronary Bifurcations: A Virtual Bench Testing Study. Cardiovasc Eng Technol 2018;9:415–26. doi:10.1007/s13239-018-0359-9.

[33] Gijsen FJH, Migliavacca F, Schievano S, Socci L, Petrini L, Thury A, et al. Simulation of stent deployment in a realistic human coronary artery. Biomed Eng Online 2008;7:23.

doi:10.1186/1475-925X-7-23.

[34] Mortier P, Holzapfel GA, De Beule M, Van Loo D, Taeymans Y, Segers P, et al. A novel simulation strategy for stent insertion and deployment in curved coronary bifurcations: Comparison of three drug-eluting stents. Ann Biomed Eng 2010;38:88–99. doi:10.1007/s10439-009-9836-5.

[35] Ragkousis GE, Curzen N, Bressloff NW. Computational Modelling of Multi-folded Balloon Delivery Systems for Coronary Artery Stenting: Insights into Patient-Specific Stent Malapposition. Ann Biomed Eng 2015;43:1786–802. doi:10.1007/s10439-014-1237-8.

[36] Morlacchi S, Colleoni SG, Cárdenes R, Chiastra C, Diez JL, Larrabide I, et al. Patient-specific simulations of stenting procedures in coronary bifurcations: Two clinical cases. Med Eng Phys 2013;35. doi:10.1016/j.medengphy.2013.01.007.

[37] Mortier P, Wentzel JJ, De Santis G, Chiastra C, Migliavacca F, De Beule M, et al. Patient-specific computer modelling of coronary bifurcation stenting: the John Doe programme. EuroIntervention 2015;11 Suppl V:V35–9. doi:10.4244/EIJV11SVA8.

[38] Chiastra C, Wu W, Dickerhoff B, Aleiou A, Dubini G, Otake H, et al. Computational replication of the patient-specific stenting procedure for coronary artery bifurcations: From OCT and CT imaging to structural and hemodynamics analyses. J Biomech 2016;49:2102–11. doi:10.1016/j.jbiomech.2015.11.024.

[39] Ferrante G, Presbitero P, Whitbourn R, Barlis P. Current applications of optical coherence tomography for coronary intervention. Int J Cardiol 2013;165:7–16. doi:10.1016/j.ijcard.2012.02.013.

[40] Steinman DA, Migliavacca F. Editorial: Special Issue on Verification, Validation, and Uncertainty Quantification of Cardiovascular Models: Towards Effective VVUQ for Translating Cardiovascular Modelling to Clinical Utility. Cardiovasc Eng Technol 2018:In press. doi:10.1007/s13239-018-00393-z.

[41] Wang W-Q, Liang D-K, Yang D-Z, Qi M. Analysis of the transient expansion behavior and

design optimization of coronary stents by finite element method. J Biomech 2006;39:21–32. doi:10.1016/j.jbiomech.2004.11.003.

[42] Mortier P, De Beule M, Segers P, Verdonck P, Verhegghe B. Virtual bench testing of new generation coronary stents. EuroIntervention 2011;7:369–76. doi:10.4244/EIJV7I3A62EIJV7I3A62 [pii].

[43] Chiastra C, Grundeken MJ, Wu W, Serruys PW, de Winter RJ, Dubini G, et al. First report on free expansion simulations of a dedicated bifurcation stent mounted on a stepped balloon. EuroIntervention 2015;10:e1-3. doi:10.4244/EIJV10I11A226.

[44] Ormiston J a., Webster MWI, El Jack S, Ruygrok PN, Stewart JT, Scott D, et al. Drug-eluting stents for coronary bifurcations: Bench testing of provisional side-branch strategies. Catheter Cardiovasc Interv 2006;67:49–55. doi:10.1002/ccd.20453.

[45] Ribeiro NS, Folgado J, Rodrigues HC. Surrogate-based visualization and sensitivity analysis of coronary stent performance: A study on the influence of geometric design. Int j Numer Method Biomed Eng 2018;34:e3125. doi:10.1002/cnm.3125.

Figures

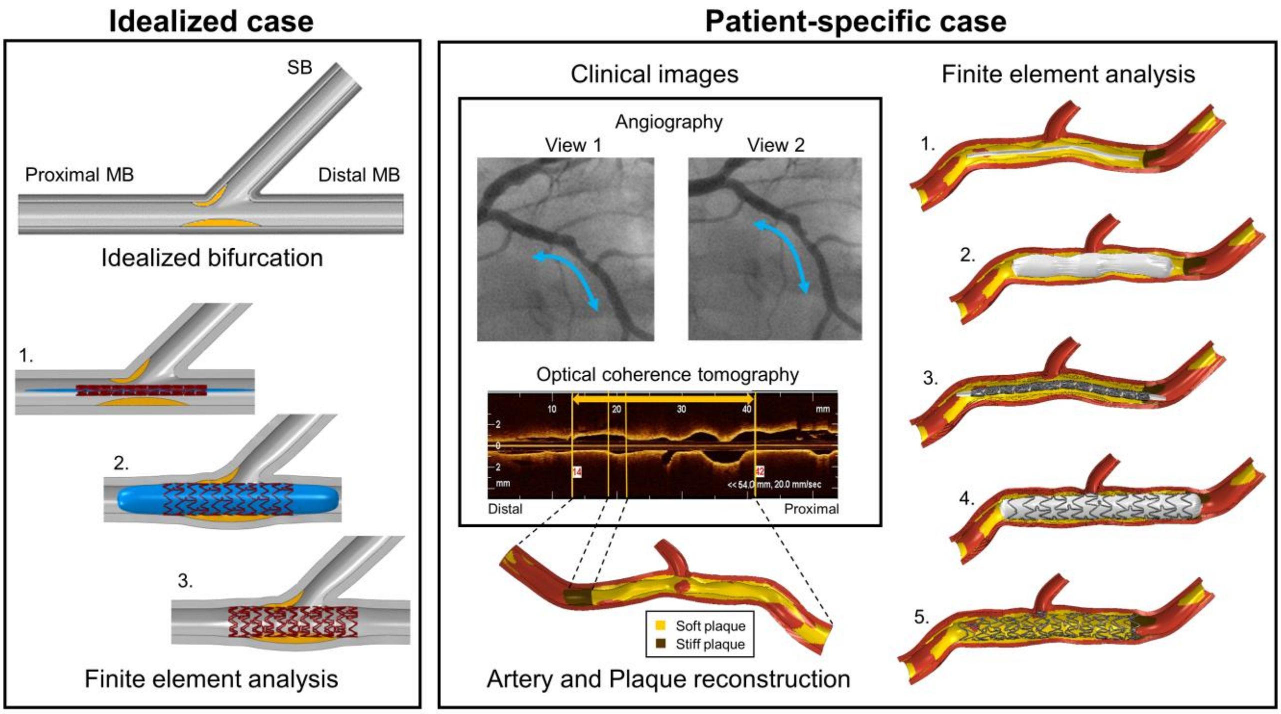

Figure 1. The elements to perform a structural simulation in an idealized (left) or patient-specific (right) case: the artery, the plaque, the balloon and the stent. Images inspired to [21,38].

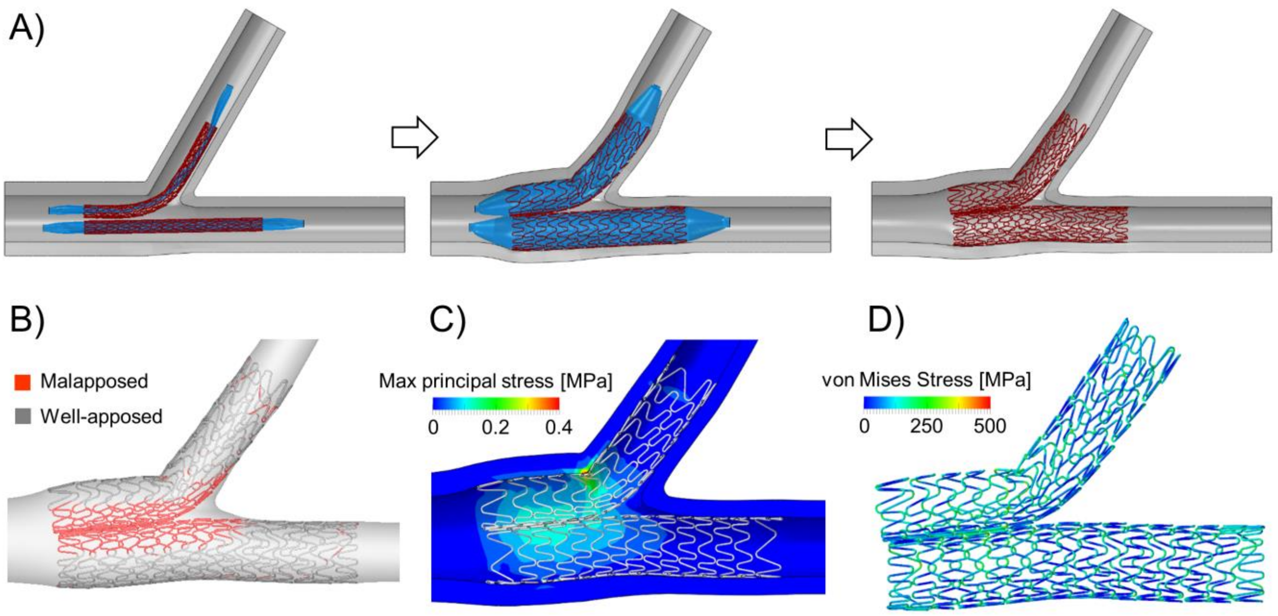

Figure 2. Finite element analysis of the simultaneous kissing stenting (SKS) technique. A) Virtual SKS deployment sequence of two stents in an idealized coronary bifurcation without disease. B) Stent strut malapposition. C) Maximum principal stress within the arterial wall. D) von Mises stress in the stents. Images inspired to [29].

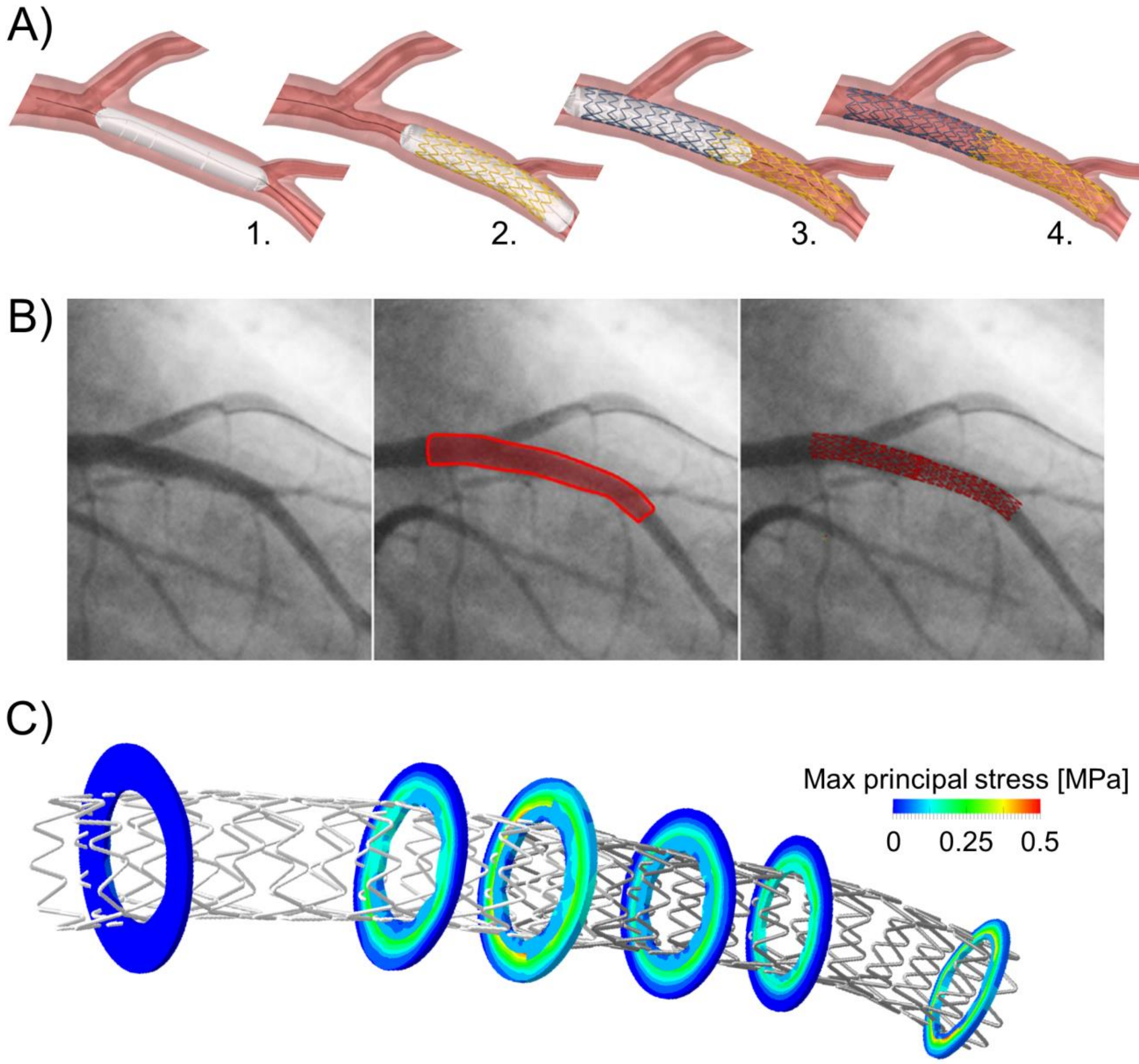

Figure 3. Example of patient-specific finite element analysis of stent deployment. The arterial bifurcated model is reconstructed from clinical images and the virtual implantation of multiple stents is simulated (A) and then compared with the angiography exam (B). The stress state in the arterial wall calculated from the structural simulations is shown in selected cross sections (C). Image inspired to [36].

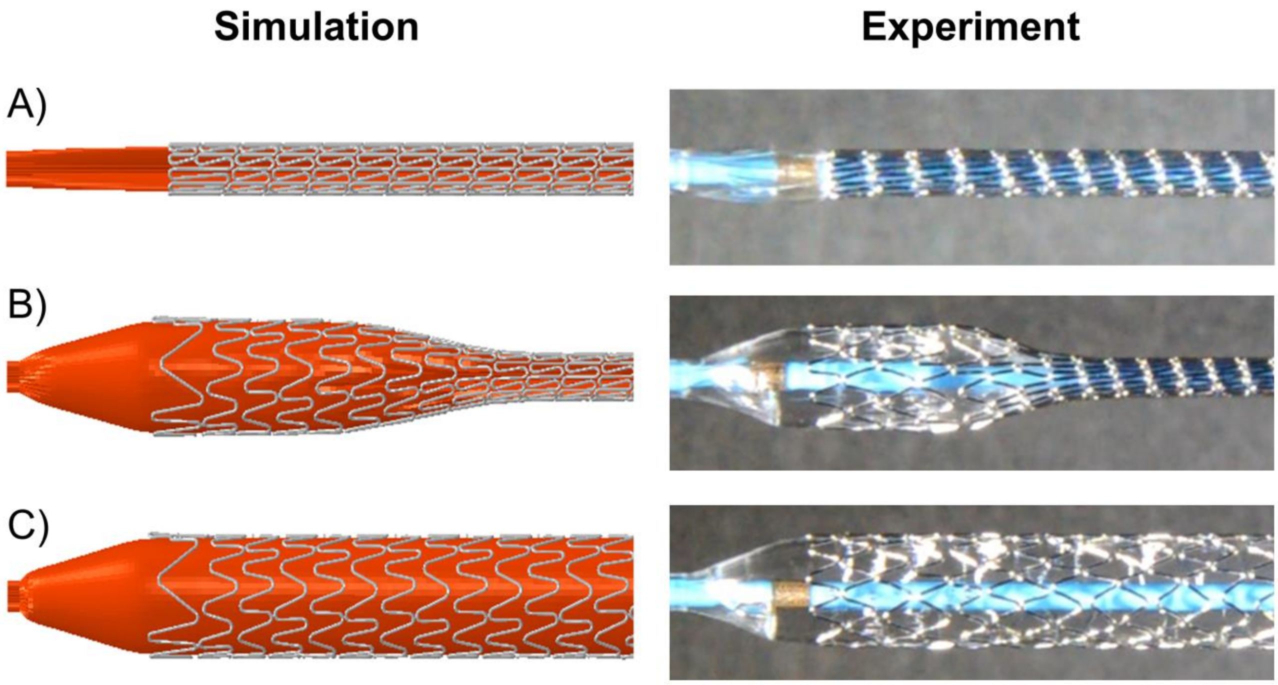

Figure 4. Qualitative comparison between a finite element analysis of free-expansion of a Resolute Integrity (Medtronic, Minneapolis, MN, USA) stent (left) and corresponding *in vitro* experiment (right): A) initial crimped configuration; B) intermediate configuration with evident dog-boning effect; C) final expanded configuration.

Table 1. List of published studies on structural simulations of stent deployment in idealized coronary bifurcation models.

First author, year [reference]	Aim	Bifurcation model			Stent platform(s) (Manufacturer)	Stenting techniques(s)	Solver (analysis type)
		Geometry (α – D_{PMB}, D_{DMB}, D_{SB}, thickness)	Arterial wall (thickness, material)	Plaque			
Mortier et al. 2009 [20]	To investigate the impact of different stent platforms and SB balloon sizes on the stent cell deformation and global stent distortion	1 geometry (45°, 3 mm, 2.5 mm, 2.5 mm)	Single layer (constant thickness, homogeneous isotropic hyperelastic material)	No	Cypher (Cordis) Multi-Link Vision (Abbott Vascular)	Provisional stenting (crossover stenting + SB balloon dilatation)	Abaqus/Explicit (quasi-static analysis)
Gastaldi et al. 2010 [16]	To analyze the provisional technique by comparing (i) different accesses to the SB and (ii) the KBI with the dilatation of the MB only	1 geometry (70°, 2.78 mm, 2.44 mm, 2.44 mm)	3 layers (constant thickness, homogeneous isotropic hyperelastic material)	Yes, isotropic hyperelastic model coupled with a perfect plasticity model	BX Velocity (Cordis)	Provisional stenting (crossover stenting + MB dilation) Provisional stenting (crossover stenting + MB dilation + KBI)	Abaqus/Explicit (quasi-static analysis)
Morlacchi et al. 2011 [21]	To investigate the biomechanical impact of different balloon designs on the FKB	1 geometry (45°, 2.78 mm, 2.78 mm, 2.44 mm)	3 layers (constant thickness, homogeneous isotropic hyperelastic material)	Yes, isotropic hyperelastic model coupled with a perfect plasticity model	Multi-Link Vision (Abbott Vascular)	Provisional stenting (crossover stenting + KBI)	Abaqus/Explicit (quasi-static analysis)
Foin et al. 2012 [22]	To compare different post-dilation strategies	1 geometry (ND)	ND (ND, hyperelastic material)	No	Taxus Liberté (Boston	Provisional stenting (crossover stenting	Abaqus/Explicit (quasi-static

Accepted chapter available at https://doi.org/10.1016/C2017-0-03308-6

	for concluding provisional stenting				Scientific)	+ KBI) Provisional stenting (crossover stenting + sequential SB-MB dilatation)	analysis)
Burzotta et al. 2014 [23]	To compare the performance of different stent platforms deployed with provisional stenting	1 geometry (ND, 4 mm proximal MV, 3.5 mm, 2.5 mm)	Silicon bifurcated phantom (ND, ND)	No	Cypher (Cordis) Taxus Liberté (Boston Scientific) Endeavor Resolute (Medtronic) Xience V (Abbott Vascular)	Provisional stenting (crossover stenting + POT) Provisional stenting (crossover stenting + POT) Provisional stenting (crossover stenting + POT + KBI)	ND
Morlacchi et al. 2014 [24]	To assess the biomechanical influence provoked by different stenting procedures	1 geometry (45°, 3.28 mm, 2.78 mm, 2.44 mm)	3 layers (constant thickness, homogeneous isotropic hyperelastic material)	No	Tryton (Tryton Medical) Xience V (Abbott Vascular)	Provisional stenting Culotte Tryton-based Culotte	Abaqus/Explicit (quasi-static analysis)
Mortier et al. 2014 [25]	Two compare two FKI strategies for concluding provisional stenting technique	Geometry 1 (80°, 3.8 mm, 2.9 mm, 2.75 mm) Geometry 2 (80°, 4.2 mm, 3.3 mm, 2.9 mm)	3 layers (constant thickness, homogeneous isotropic hyperelastic material)	Yes	Resolute Integrity (Medtronic) Omega (Boston Scientific) Multi-Link 8	Provisional stenting (crossover stenting + POT + conventional KBI) Provisional stenting (crossover stenting + POT + modified	Abaqus/Explicit (quasi-static analysis)

		Geometry 3 (40°, 3.8 mm, 2.9 mm, 2.75 mm)			(Abbott Vascular)	KBI)	
Raben et al. 2014 [26]	To compare different stenting procedures from the biomechanical viewpoint. FEA of stent deployment is used to generate the fluid domains for subsequent CFD simulations	1 geometry (60°, 3.96 mm, 3.96 mm, 2.77 mm)	1 layers (constant thickness, homogeneous isotropic linear elastic material)	No	Endeavor Resolute (Medtronic)	Provisional stenting Crush Culotte T-stenting with high protrusion	Abaqus/Explicit (quasi-static analysis)
Arokiaraj et al. 2016 [30]	To investigate a novel stent platform for the treatment of coronary bifurcations	1 geometry (60°, 3.2 mm, 2.7 mm, 2.3 mm)	3 layers (constant thickness, homogeneous isotropic hyperelastic material)	Yes, isotropic hyperelastic model	Novel stent with an interface of 3 nitinol-based connection links interposed in the stent	Novel 'tram' technique (MB stenting + SB stenting)	Abaqus/Explicit (quasi-static analysis)
Chen et al. 2017 [27]	To investigate the biomechanical impact of provisional stenting and balloon dilatation on coronary bifurcation	1 geometry (ND)	ND	No	ND	Provisional stenting (crossover stenting + KBI)	Abaqus/Standard
Iannaccone et al. 2017 [28]	To investigate the impact of bifurcation angle, plaque composition, and procedural strategy on SB compromise	Geometry 1 (45°, 3.3 mm, 2.8 mm, 2.1 mm, non-planar) Geometry 2 (70°, 3.3 mm, 2.8 mm, 2.1 mm, non-planar)	3 layers (constant thickness, homogeneous isotropic hyperelastic material coupled with a perfect	Yes, 4 scenarios: (i) fully lipid, (ii) fully fibrous, (iii) lipid with a half-calcified ring in the distal MB, (iv) lipid	Multi-Link 8 (Abbott Vascular)	Provisional stenting (crossover stenting + post-dilatation)	Abaqus/Explicit (quasi-static analysis)

			plasticity model)	with a full-calcified ring in the distal MB Isotropic hyperelastic material coupled with a perfect plasticity model			
Chiastra et al. 2018 [32]	To investigate the impact of wrong positioning of the Tryton stent in coronary bifurcations	1 geometry (45°, 3.5 mm, 2.76 mm, 2.4 mm)	3 layers (constant thickness, homogeneous isotropic hyperelastic material)	No	Tryton (Tryton Medical) Xience V (Abbott Vascular)	Tryton-based Culotte	Abaqus/Explicit (quasi-static analysis)
Grundeken et al. 2018 [31]	To evaluate the influence of rewiring through one of the panels of the Tryton device on stent geometry and mechanics	1 geometry (45°, 3.5 mm, 2.76 mm, 2.4 mm)	3 layers (constant thickness, homogeneous isotropic hyperelastic material)	No	Tryton (Tryton Medical) Xience V (Abbott Vascular)	Tryton-based Culotte	Abaqus/Explicit (quasi-static analysis)
Morris et al 2018 [29]	To analyze the simultaneous kissing stenting technique for the treatment of the left main bifurcation	1 geometry (60°, 4 mm, 3 mm, 2.5 mm)	3 layers (constant thickness, homogeneous isotropic hyperelastic material)	No	Resolute Integrity (Medtronic)	Simultaneous kissing stenting	Abaqus/Explicit (quasi-static analysis)

Table legend: MB – main branch; SB – side branch; KBI – kissing balloon inflation; POT – proximal optimization technique; FEA – finite element analysis; CFD – computational fluid dynamics; ND – not declared.

Accepted chapter available at https://doi.org/10.1016/C2017-0-03308-6

Table 2. List of published studies on structural simulations of stent deployment in patient-specific coronary bifurcation models.

First author, year [reference]	Aim	Bifurcation model			Stent platform(s) (Manufacturer)	Stenting techniques(s)	Solver (analysis type)
		Number of cases (imaging data)	Arterial wall (material)	Plaque			
Mortier et al. 2010 [34]	To compare the biomechanical behavior of different stent designs in an image-based coronary bifurcation model	1 LM bifurcation (Rotational angiography)	3 layers (anisotropic fiber-reinforced hyperelastic material)	No	Cypher (Cordis) Endeavor Resolute (Medtronic) Taxus Liberté (Boston Scientific).	Direct stenting (LM-LAD stenting)	Abaqus/Explicit (quasi-static analysis)
Morlacchi et al. 2013 [36]	To prove the feasibility of performing patient-specific structural analyses of stent deployment in image-based atherosclerotic coronary artery models	2 LAD with bifurcations (CT + conventional angiography)	Single layer (homogeneous isotropic hyperelastic material)	Yes, isotropic hyperelastic model coupled with a perfect plasticity model	Xience Prime (Abbott Vascular) Endeavor Resolute (Medtronic)	Case 1: pre-dilatation + provisional stenting with post-dilatation Case 2: pre-dilatation + deployment of 2 stents in the MB	Abaqus/Explicit (quasi-static analysis)
Mortier et al. 2015 [37]	To prove the feasibility of virtually replicating a coronary stenting procedure in a patient-specific bifurcation model	1 LM bifurcation (CT + IVUS)	ND	ND	Xience Prime (Abbott Vascular)	Provisional stenting (crossover stenting + POT + KBI)	Abaqus/Explicit (quasi-static analysis)

Accepted chapter available at https://doi.org/10.1016/C2017-0-03308-6

Ragkousis et al. 2015 [35]	To compare different balloon delivery systems for the treatment of coronary arteries	1 LM bifurcation (conventional angiography + IVUS)	2 layers (homogeneous isotropic hyperelastic material)	No	Xience (Abbott Vascular)	Direct stenting	Abaqus/Explicit (quasi-static analysis)
Chiastra et al. 2016 [38]	To replicate the complete procedure followed by clinicians to treat coronary bifurcations using FEA of stent deployment. To evaluate the reliability of FEA in predicting post-operative geometric outcomes	1 LAD with bifurcation and 1 LCx with bifurcation (CT + OCT)	Single layer (homogeneous isotropic hyperelastic material)	Yes, soft and stiff plaque, isotropic hyperelastic model coupled with a perfect plasticity model	Xience Prime (Abbott Vascular) Nobori (Terumo)	Pre-dilatation + MB stenting	Abaqus/Explicit (quasi-static analysis)

Table legend: LM – left main coronary artery; LAD – left anterior descending coronary artery; LCx – left circumflex coronary artery; CT – computed tomography; MB – main branch; IVUS – intravascular ultrasound; OCT – optical coherence tomography; KBI – kissing balloon inflation; POT – proximal optimization technique; FEA – finite element analysis; ND – not declared.