Open Access

Carolin Wüstenhagen*, Finja Borowski, Niels Grabow, Klaus-Peter Schmitz and Michael Stiehm

Comparison of stented bifurcation and straight vessel 3D-simulation with a prior simulated velocity profile inlet

DOI 10.1515/cdbme-2016-0065

Abstract: Coronary diseases are the main reason for death in the western world. Bio-fluid mechanical correlations with arterial diseases are in the focus of our research. To treat occluded vessels, stents are implanted. Stent implantations can be associated with blood flow disruptions leading to restenosis or thrombosis formation. Numerical flow simulation is a promising tool to evaluate the hemodynamic performance of cardiovascular implants, but is resource-intensive in time and computational power. Therefore, a reduction in grid size would be beneficial due to economic exploitation of computational cost. The purpose of this numerical investigation is to substitute the computational domain of a distal stented bifurcation with a stented straight vessel by using the right inlet condition. The deviation of the results of the two different methods to simulate the blood flow situation in a bifurcation is marginal. This inlet can be used for standardised simulations of bifurcations were lesions commonly occur.

Keywords: 3D CFD; bifurcation; stent; velocity profile; wall shear stress.

1 Introduction

Coronary diseases are the main reason for death in the western world. In Germany one seventh of these cases of death are resulting from a myocardial infarction, which is caused by an occlusion of a coronary artery [1]. The affected arteries are treated with a so-called stent, a scaffold that widens the vessel to ensure an unimpeded blood flow.

Since the introduction of bare metal stents, the development goes to decreasing stent struts, so the blood flow is decreasingly influenced due to the stent segments.

Bioresorbable stents made of materials like polymers, show, as a result of their inferior material properties, higher struts as bare metal stents to ensure strength properties. These larger cross profiles build an obstruction and change the blood flow situation in the vessels. It is common knowledge that disturbances in the blood flow are correlated with diseases like the peripheral artery disease. Stent implantations can be associated with those disruptions that lead to very high and very low shear rates, which can lead to restenosis or thrombosis formation [2, 3]. The regions of interest can be found especially in bifurcations [4].

2 Aim of the simulation

The aim of this simulation is to compare the blood flow situation in a bifurcation and a tube, where a velocity profile taken out of the simulation of a bifurcation is used as an inlet. Thus there would be an enormous saving in time for preparing bifurcation models, generating meshes and in simulation time, because of the lower number of cells.

For this numerical study there will be the following operating points:

- Modelling of three bifurcations with different angles between the side branches, the generic stent and a tube
- Definition of the boundary conditions and execution of the simulations
- Taking the velocity profile off the bifurcation simulation and using it as an inlet for the stented tube
- Evaluation and comparison of the blood flow fields.

***Corresponding author: Carolin Wüstenhagen,** Institute for Implant Technology and Biomaterials e.V. and Institute for Biomedical Engineering, Rostock University Medical Center, Friedrich-Barnewitz-Str. 4, 18119 Rostock-Warnemünde, Germany, E-mail: carolin.wuestenhagen@uni-rostock.de
Finja Borowski and Niels Grabow: Institute for Biomedical Engineering, Rostock University Medical Center, Friedrich-Barnewitz-Str. 4, 18119 Rostock-Warnemünde, Germany
Klaus-Peter Schmitz and Michael Stiehm: Institute for Implant Technology and Biomaterials e.V. and Institute for Biomedical Engineering, Rostock University Medical Center, Friedrich-Barnewitz-Str. 4, 18119 Rostock-Warnemünde, Germany

3 Material and methods

3.1 Construction of stented bifurcations and mesh generation

For the construction of the 3D bifurcation model CAD software is used. The inlet length until the junction of the two side branches is 17 mm. The diameter of the main branch is conical and goes from 4.71 mm to 3.5 mm and runs into the symmetrical side branches with a diameter of 3.5 mm and a length of 17 mm each [5]. Three bifurcations are constructed whereby they only differ in the constructed angle between the two side branches. The angles 70°, 90° and 110° are designed, since the average angle between LAD and LCx is about 82° $\pm$ 17° [6].

The generic stent is, as well as the bifurcation model, constructed with CAD software. The structure of the stent is helical, comparable to a spring, has a length of 8 mm and is located 12 mm ahead of the outlet in one of the two side branches. The cross section of the stent struts protruding into the lumen of the bifurcation is a semicircle with a height of 150 μm. The stent is cut out of the bifurcation.

The meshes of the three stented bifurcation models are made with open source software OpenFOAM and the tool *snappyHexMesh*. Each mesh contains 11–12 million volume cells.

To compare the blood flow conditions in the bifurcation model and in a tube with a velocity field taken out of the bifurcation model, a stented tube is needed. The tube is constructed and meshed in OpenFOAM and the stent is cut out with *snappyHexMesh*. It has about 3 million volume cells.

For each volume cell, the Navier-Stokes-Equation has to be solved (see eq. 1):

$$\rho \frac{Du}{Dt} = -\text{grad}\, p + \text{div}\, (2\eta(\dot{\gamma})D) \tag{1}$$

where ρ is density, p is pressure, u is velocity vector, t is time, η is absolute viscosity, $\dot{\gamma}$ is shear rate and D the tensor of deformation.

3.2 Boundary conditions

Steady-state blood flow is simulated in the bifurcation as well as in the tube model. Furthermore stiff vessel walls and no slip conditions are assumed. At the inlet of the bifurcation model there is a mean velocity of v $=$ 0.2 m/s in a block type profile. This matches a Reynolds number of 250, which is to be found in coronary vessels. The shear thinning behaviour of blood is approximated by the non-Newtonian Carreau model:

$$\mu_f = \mu_\infty + (\mu_0 - \mu_\infty)(1 + (\lambda\dot{\gamma})^2)^{(n-1)/2}$$

The used parameters are adopted from [7]. At the outlet a pressure of $p = 0$ is defined.

3.3 Velocity profile

For the inlet of the tube a velocity profile is taken out of the completely converged simulation of a bifurcation model which is not stented. The velocity profile is taken 2 mm ahead of the virtual beginning of the stent, as well as the inlet of the tube model is 2 mm ahead of the stent (see Figure 1).

To get the velocity profile all velocity vectors and their positions that lie on an imagined plain normal to the stented side branch are written out. A three dimensional illustration of the mapped velocity profile can be seen in Figure 2.

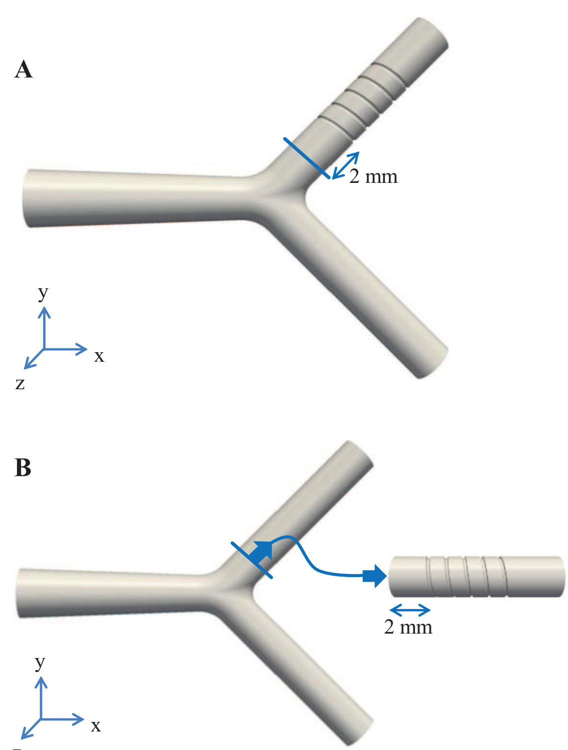

Figure 1: (A) Stented bifurcation model and (B) bifurcation model and stented tube model; blue arrows show the position of the obtained velocity profile which is used as an inlet in further simulations.

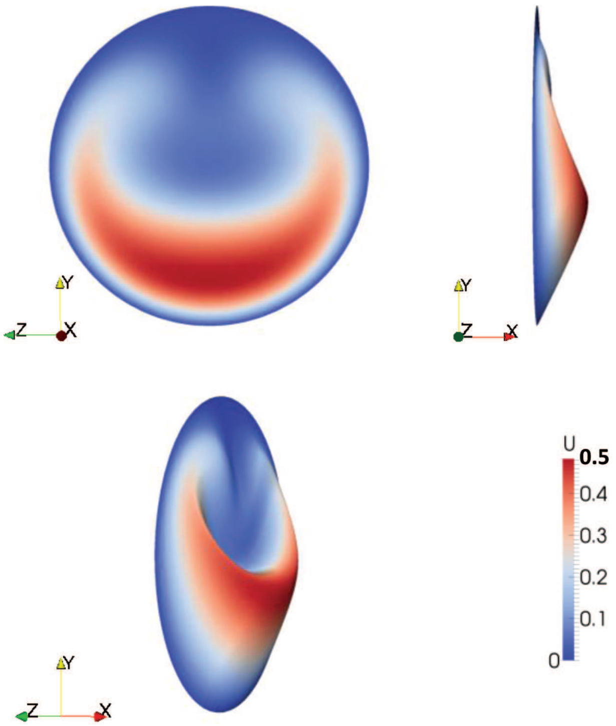

Figure 2: Mapped velocity profile of the bifurcation with 110 degree angle between the side branches.

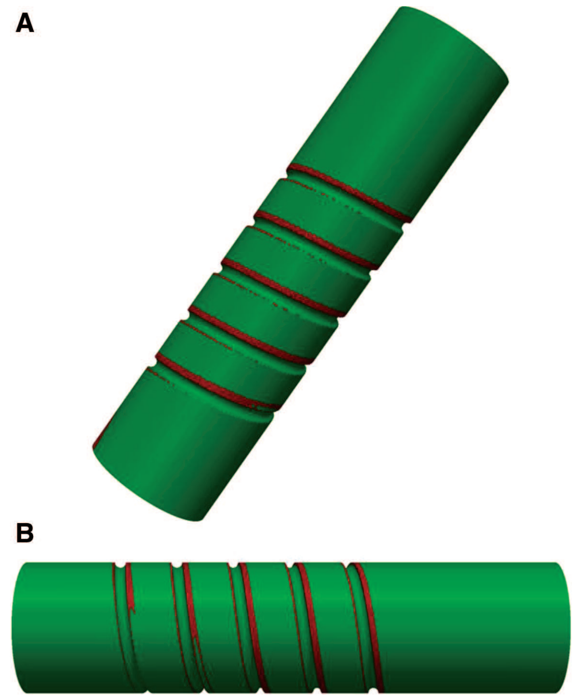

Figure 3: Wall shear stress distribution: red area has a wall shear stress <0.4 Pa. (A) bifurcation simulation, (B) tube simulation.

Table 1: Percentage deviation of the stented tube simulation compared to the stented bifurcation simulation.

	Area of wall shear stress <0.4 Pa mm^2	Max. velocity (m/s)	Max. shear stress (s^{-1})
Bifurcation 70 degree angle	1.67×10^{-5}	0.481	7370
Tube 70 degree angle	1.55×10^{-5}	0.486	6980
Bifurcation 90 degree angle	1.70×10^{-5}	0.484	6460
Tube 90 degree angle	1.47×10^{-5}	0.480	6470
Bifurcation 110 degree angle	1.09×10^{-5}	0.484	6480
Tube 110 degree angle	1.14×10^{-5}	0.492	7970

4 Results and discussion

4.1 Results and comparison of the blood flow situations

For comparison of the blood flow situation in the stented bifurcations with various angles and the stented tube models with a prior simulated inlet, there are severe criteria needed. Since restenosis is likely to occur at locations with a wall shear stress below 0.4 Pa, the area of the vessel walls with such shear stress is compared. Further on the maximal velocity and the maximal shear stress that are found in the stented vessel segments are compared.

The difference between the bifurcation and the tube having an area with a wall shear stress below 0.4 Pa is minor. The variation in percentage on all criteria is an average of 6.6%. A comparison of the wall shear stress distribution of the bifurcation with a 110 degree angle is shown in Figure 3.

4.2 Discussion

The analysis showed that the maximum deviation can be found at the comparison between the simulations of the bifurcation of 110 degree angle. This deviation occurs since the 110 degree bifurcation obtains the most complex flux with its vortex.

The deviation of the results of the two different methods to simulate the blood flow situation in a bifurcation is marginal. These slight differences can be the reason of having not completely similar meshes in the stented region due to the automatic meshing tool *snappyHexMesh*.

In addition, only the mapped velocity profile is used as inlet condition for the simulations of the straight vessels. It could be beneficial to transfer the pressure field or the pressure gradient field as well. Here the described method has its limits. Numerical simulations admit only the velocity or the pressure field as an inlet.

5 Conclusion

This method is successful due to its possibility of saving time and computational resources. Using this inlet in standardised simulations can be a benefit of it. A lot of simulations are made with a block type profile, a Hagen-Poiseuille-profile or symmetric profiles in general. This asymmetric inlet simulates a bifurcation right before the stented vessel segment, were lesions commonly occur and can expose possible stent design optimizations. Further simulations could include the mapping of the gradient pressure field.

Acknowledgment: Financial support by the Federal Ministry of Education and Research (BMBF) within RESPONSE "Partnership for Innovation in Implant Technology" is gratefully acknowledged.

Author's Statement
Research funding: The author state no funding involved. Conflict of interest: Authors state no conflict of interest. Material and Methods: Informed consent: Informed consent is not applicable. Ethical approval: The conducted research is not related to either human or animal use.

References

[1] Destatis Statistisches Bundesamt, Wiesbaden. Die 10 häufigsten Todesfälle durch Herz-Kreislauf-Erkrankungen. https://www.destatis.de/DE/ZahlenFakten/GesellschaftStaat/Gesundheit/Todesursachen/Tabellen/Sterbefaelle_HerzKreislaufErkrankungenInsgesamt.html. Accessed on April 18, 2016.
[2] Holme PA, Ørvim U, Hamers M, Solum NO, Brosstad FR, Barstad RM, et al. Shear-induced platelet activation and platelet microparticle formation at blood flow conditions as in arteries with a severe stenosis. Arterioscler Thromb Vasc Biol. 1997;17:646–53.
[3] Malek AM, Alper SL, Izumo S. Hemodynamic shear stress and its role in atherosclerosis. J Am Med Assoc. 1999;21:2035–42.
[4] Asakura T, Karino T. Flow patterns and spatial distribution of atherosclerotic lesions in human coronary arteries. Circ Res. 1990;66:1045–66.
[5] Lassen JF, Holm NR, Stankovic G, Lefèvre T, Chieffo A, Hildick-Smith D, et al. Percutaneous coronary intervention for coronary bifurcation disease: consensus from the first 10 years of the European Bifurcation Club meetings. EuroIntervention. 2014;10:545–60.
[6] Malvè M, Gharib AM, Yazdani SK, Finet G, Martínez MA, Pettigrew R, et al. Tortuosity of Coronary bifurcation as a potential local risk factor for atherosclerosis: CFD steady state study based on in vivo dynamic CT measurements. Ann Biomed Eng. 2015;43:82–93.
[7] Zhao W, Wang X, Jiang Y, Zhang J. Non-newtonian behavior of blood and arterial curvature influence variations of wall shear stress in stented artery. V European Conference on Computational Fluid Dynamics. Lisbon, Portugal, 14–17 June 2010.