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Inflow mapping method for numerical flow simulations of OCT-based patient-specific vessels using CFD

Abstract: Alteration of the flow characteristics in coronary vessels is correlated with coronary heart disease (CHD). In particular, wall shear stress (WSS) appears to be a hemodynamic key factor in the genesis of CHD. Since computational fluid dynamics (CFD) is a well-known method for the investigation of WSS, it may be a valuable tool for the prediction of CHD. Latest imaging techniques, such as optical coherence tomography (OCT) in conjunction with angiography deliver precise 2D data sets of patient-specific vessel geometry, which can be used for CFD analysis. Current CFD studies utilize patient-specific geometries, but are lacking well defined physiologic inflow conditions.

In this study, we present an inflow mapping method for patient-specific arterial vessels, which is capable of considering the influence of bifurcations located proximal of the OCT-data set. At first, the patient-specific vessel was reconstructed. For this purpose the OCT-based vessel cross sections were arranged along an angiographic based vessel pathway. Secondly, we simulated the flow field in a generic bifurcation model by means of CFD. Thereafter the flow field of a side branch was extracted and transferred (mapped) to the inlet of the patient-specific vessel.

To evaluate the influence of the physiological inlet the WSS distribution of the same patient-specific vessel was calculated using an axial-symmetric inflow condition. Analysis of the simulation data yielded deviations of the WSS distribution in the proximal vessel segment. A bifurcation, located upstream of the relevant vessel segment strongly affects the flow in the OCT-based vessel reconstruction and has a strong influence on the results of the numerical analysis. Therefore, it is important to implement not only the patient-specific geometry, but also an inlet boundary condition adapted to the upstream velocity distribution reflecting the actual proximal flow situation of the vessel.

Keywords: 3D CFD, velocity profile, OCT, wall shear stress.

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1 Introduction

Alteration of the flow situation in coronary vessels is correlated with coronary heart disease (CHD). Bifurcations and curvatures induce an asymmetric flow situation characterized by low wall shear stress (WSS) regions. These regions are characterized by flow separations on the one hand and regions with high shear rates due to local flow acceleration on the other hand. Areas of low WSS are known to be linked with the formation of stenosis or thrombosis [1].

In the past decade CFD-simulations were used to determine WSS in various anatomical model structures [2]. Therefore, CFD seems to be a promising tool to predict pathological incidences in patient-pacific vessel segments.

As a result of today's improved imaging techniques, one focus of research is the reconstruction of 3D-vessel models based on patient-specific data. Optical coherence tomography (OCT) is an intraluminal imaging method, which is an efficient tool for the visualization of lumen and vessel wall. OCT in combination with angiography can be used for the localization and classification of stenosis and plaque as well as for the reconstruction of 3D-models for numerical flow simulations [3, 4].

The aim of this numerical study is to evaluate the influence of different inlet velocity profiles, such as velocity profiles found downstream of bifurcations, on the WSS distributions in patient-specific coronary vessels.

2 Materials and methods

2.1 Generation of patient-specific vessel models

For the reconstruction of patient-specific coronary vessel models, OCT and angiography data were merged in a two-step procedure. At first the OCT catheter pathway was reconstructed based on angiography data. Afterwards the lumen outlines detected from OCT files were assembled normal to the catheter path. Using computer aided design (CAD) software, CFD-compatible files of the vessel models were created. To generate a mesh and volume cells the open source software OpenFOAM (OpenCFD Ltd. (ESI Group), Bracknell, UK) with an implemented semi-automatic meshing tool *snappyHexMesh* was used.

For each volume cell, the Navier-Stokes-Equation has to be solved:

$$\boldsymbol{\rho}\frac{\boldsymbol{du}}{\boldsymbol{dt}} = -\mathrm{grad}\,\boldsymbol{p} + \mathrm{div}(\boldsymbol{2\eta}(\dot{\boldsymbol{\gamma}})\boldsymbol{D}) \qquad (\mathbf{1})$$

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.

2.2 Generation of a generic bifurcation model

Considering the angiographic data, both patients have a bifurcation of approximately 90° directly before OCT imaging starts (see **Figure 1**). Thus, a generic bifurcation model with a 90° angle between the side branches was constructed, according to previous studies [5]. Following the numerical simulation a velocity profile, located downstream of the bifurcation, was extracted. This velocity profile was used as inlet boundary condition for the reconstructed patient-specific vessels.

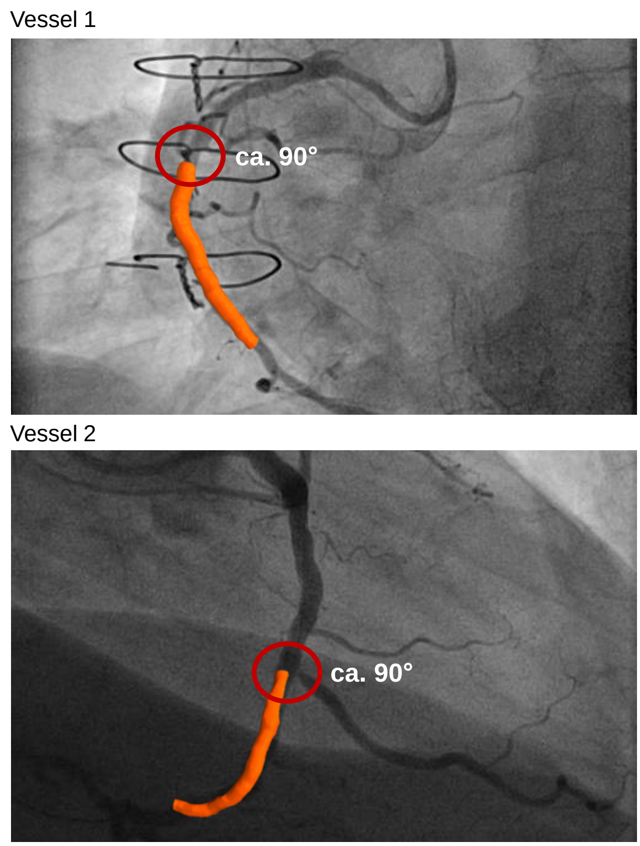

Figure 1: Coronary patient-specific vessel models with angiography image and bifurcation marked red.

2.3 Boundary conditions

The aim of the numerical simulation is to point out the dependencies between the inlet velocity condition and the flow condition. In this study we investigated uniform velocity profile, Hagen-Poiseuille profile and different bifurcation velocity profiles.

The uniform and Hagen-Poiseuille profile can be directly defined in the used CFD software package. The bifurcation velocity profiles are taken from the generic bifurcation model. Because of the elliptic inlet geometries of both reconstructed patient-specific vessels the velocity distribution was slightly distorted.

Furthermore, there is a need to examine the effect of the orientation of the upstream bifurcation on the numerical flow simulation results. Overall, six different inlet velocity profiles were analysed for each reconstructed vessel: a uniform inlet and a Hagen-Poiseuille profile and four bifurcation inlet profiles, rotated clockwise by 90° about the *x*-axis, respectively (see **Figure 2**). Both patient-specific reconstructions apparently have a velocity inlet profile similar to the inlet profile of Bifurcation 3.

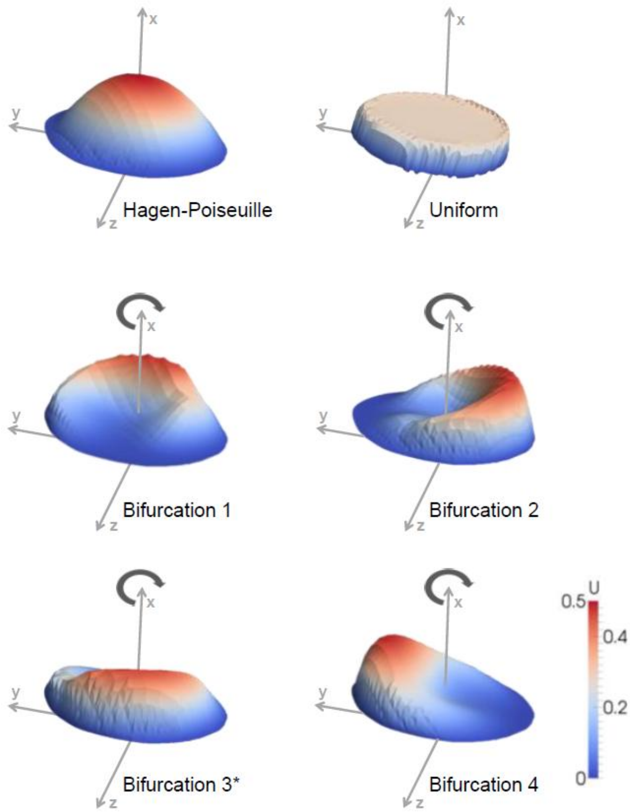

Figure 2: Inlet velocity profiles for both reconstructed vessels: uniform, Hagen-Poiseuille and four bifurcation inlet profiles, the applicable one is marked with an asterisk.

Steady-state blood flow was simulated in the bifurcation as well as in the reconstructed patient-specific coronary vessel models. Furthermore, stiff vessel walls and no slip conditions were assumed. At the inlet of the patient-specific models a mean velocity of u = 0.26 m/s was defined according to Ofili et al. [6]. This matches a Reynolds number of approximately Re = 200. Due to the small Reynolds number laminar flow is assumed and thus no turbulence model is needed. The shear thinning behaviour of blood is approximated by the non-Newtonian Carreau model:

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

The used parameters are adopted from Johnston et al. [7]. At the flow outlet a pressure of p = 0 Pa is defined.

3 Results and discussion

The influence of different inlet velocity profiles on the hemodynamic situation in the reconstructed vessels is examined by a hemodynamic quantity. Since stenosis is likely to occur in regions with a WSS below or equal 0.4 Pa [1], we calculated areas of the vessel surface (A_{WSS}) regarding this condition ($A_{WSS} \leq 0.4$ Pa).

Figure 3 shows an overview of the wall shear stress distribution of Vessel 1 for all inlet profiles. In particular major differences in WSS distribution occur at the proximal end of the vessel.

Figure 4 exemplarily depicts WSS distributions of the proximal end of Vessel 1 with an inlet condition based on Bifurcation inlet 2 and 3. For better illustration A_{WSS} is coloured in red. The orientation of the bifurcation located proximal of the reconstructed vessel section influences the WSS distribution particularly at the bulge, indicated by arrows (see **Figure 4**). To clarify, Bifurcation inlet 2 leads to high velocity values at the right edge and consequently high WSS values in the region of the bulge. As a result high velocities in this region minimize $A_{WSS} \leq 0.4$ Pa.

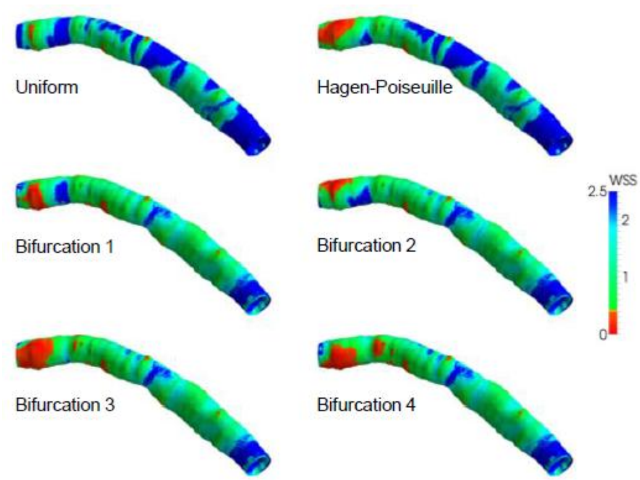

Figure 3: Global view of the wall shear stress distribution of Vessel 1.

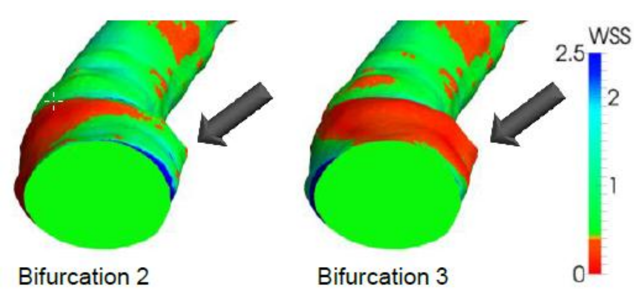

Figure 4: Bulge of Vessel 1 indicated by arrows, with Bifurcation 2 and 3 velocity inlet profiles.

Figure 5 summarizes $A_{WSS} \leq 0.4$ Pa calculated from different velocity inlet profile simulations. Regarding Vessel 1, smallest $A_{WSS} \leq 0.4$ Pa value of 6.0 mm² was calculated using the uniform velocity inlet, due to high velocities near the vessel wall, compared to the other inlet profiles. High velocities at the vessel wall cause high WSS, leading to smaller

$A_{WSS} \leq 0.4$ Pa. Bifurcation inlet 1, 3 and 4 feature the largest areas of low WSS, which are also approximately equal sized, 34.2 mm², 33.6 mm², 35.9 mm², respectively. $A_{WSS} \leq 0.4$ Pa calculated with inlet boundary condition Bifurcation 2 is considerably smaller with 23.1 mm². The simulation result determined with the Hagen-Poiseuille velocity inlet is comparable with Bifurcation 2, 22.1 mm². In general, the symmetric Hagen-Poiseuille inlet profile induces no regions of low WSS. In combination with the bulge, however, stagnation regions occur, resulting in areas of low WSS. On the contrary, the asymmetric rotational inlet profile of Bifurcation 2 leads to regions of low WSS on the left edge. On the right edge, where the bulge is located, high velocities lead to minimization of low WSS areas. The flow characteristics described for Bifurcation 2 inlet profile features a low WSS area ($A_{WSS} \leq 0.4$ Pa), which is comparable to the Hagen-Poiseuille simulation result.

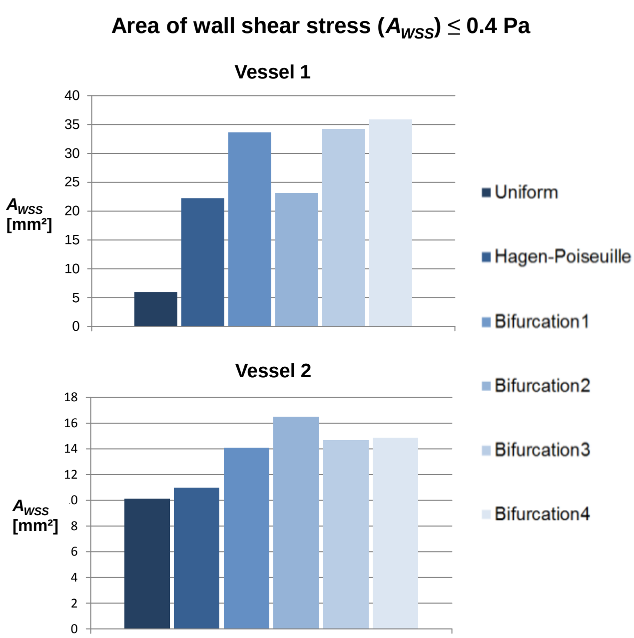

Figure 5: Extend of the areas with a wall shear stress beneath 0.4 Pa for Vessel 1 and Vessel 2.

Vessel 2 shows minor deviations in the outcome of an area of low wall shear stress between the uniform and Hagen-Poiseuille velocity inlet. All bifurcation velocity inlet profiles result in larger regions where stenosis can occur.

4 Conclusion

Based on the results, we conclude that patient-specific anatomy has a crucial effect on the WSS distribution in vessels. If there is any anatomical peculiarity proximal of the reconstructed segment of the vessel it is of importance to use an adjusted velocity inlet profile for numerical simulations. Moreover, we found that bifurcation inlet velocity profiles lead to an increase of low wall shear stress which potentially causes a higher risk of stenosis and thrombus formation. The bifurcation inlet velocity profile, used in this study, can be seen as a worst case scenario for numerical simulations. These conclusions are not limited to flow simulations of reconstructed vessels without any implants.

Author's Statement

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