Sylvia Saalfeld*, Masoud Mirzaie, Sheila Fatehpur, Jana Korte and Philipp Berg

Image-based Blood Flow Analysis of Popliteal Artery Aneurysms – an Interdisciplinary Pilot Study

Abstract: Although popliteal artery aneurysms (PAAs) are the most frequent aneurysms in the lower peripheral arteries, research has not covered the potential of blood flow analysis of these pathologies yet. We therefore present a pilot study for the image-based hemodynamic evaluation of patient-specific PAAs. To ensure a large vascular domain with similar boundary conditions, we combine a vascular tree from a healthy proband with six patient-specific vessel models and corresponding segmentations of thrombi. The patients exhibit different severities of the disease ranging from partly blocked to totally blocked lower arteries. Our pilot study demonstrates that the precise assessment of individual thrombus formation and associated local hemodynamics is feasible. In consequence, image-based blood flow analysis might reveal important insight in PAA interaction with thrombus growth and remaining blood supply of the lower limbs.

Keywords: Blood Flow, Hemodynamic Simulation, Popliteal Artery Aneurysm, Segmentation

<https://doi.org/10.1515/cdbme-2021-2227>

1 Introduction

Popliteal artery aneurysms (PAAs) are pathologic dilatations of the popliteal artery that may burst or cause blood clots, which might even result in leg amputation or fatal consequences. With 85%, they are one of the most frequently occurring peripheral aneurysms [1].

Treatment usually consists of open surgery where a bypass is created around the PAA to ensure the blood supply of the lower leg. Also, endovascular repair where a stent graft is put in the popliteal artery is feasible [2].

Due to increasing accuracy of medical imaging devices and rapid advances in the field of image processing, patient-specific morphological information can be obtained. Exemplarily, Spinella et al. evaluated morphological changes of the femoropopliteal arteries caused by limb flexion after PAA treatment [3].

Furthermore, with the existence of three-dimensional image data, modelling of pathological phenomena becomes feasible. Here, Shiwani et al. tracked the growth of 32 patients harbouring a PAA. They associated growth rates with the presence of an abdominal aortic aneurysm [4].

Although, the acquisition of precise hemodynamic information would be of great interest for the attending physician, corresponding analyses are not covered by previous approaches yet. Therefore, we aim to introduce an interdisciplinary approach combining image acquisition, image processing, segmentation and image-based blood flow simulation to provide patient-specific flow details in pathologic vessel sections. Hence, this workflow allows for a detailed and risk-free evaluation of the individual's hemodynamic state and a prediction of potential treatment outcomes.

2 Material and Methods

2.1 Material

Our study comprises six patient-specific data sets of patients suffering from PAAs at the left popliteal artery, the right popliteal artery or at both sides, as well as one healthy proband, see Table 1.

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Table 1: Medical image data sets used in the pilot study.

Patient/ Proband ID	Data size and resolution	Depiction of 3D models of vessels and thrombi
Patient 1	512 x 512 x 317 voxels 0.763 x 0.763 x 3 mm ³
Patient 2	512 x 512 x 255 voxels 0.699 x 0.699 x 5 mm ³
Patient 3	512 * 512 * 326 voxels 0.848 x 0.848 x 2.8 mm ³
Patient 4	512 x 512 x 286 voxels 0.977 x 0.977 x 5 mm ³
Patient 5	512 x 512 x 256 voxels 0.849 x 0.849 x 5 mm ³
Patient 6	512 x 512 x 334 voxels 0.761 x 0.761 x 3 mm ³
Proband 1	512 x 512 x 342 voxels 0.789 x 0.789 x 3 mm ³

2.2 Methods

The workflow of our interdisciplinary study is depicted in Figure 1 and will be described in the following.

2.2.1 Segmentation and Model Extraction

For each patient and each proband, a threshold-based segmentation of blood vessels was conducted in the contrast-enhanced image data with MeVisLab 2.8 (Fraunhofer MEVIS, Bremen, Germany, www.mevislab.de). Furthermore, a 3D surface mesh of the left and right popliteal artery was extracted within MeVisLab, see Figure 1A. Next, in presence of thrombi, manual segmentations were gathered from an experienced visceral surgeon. Based on MeVisLab's contour library, these manual segmentations were interpolated, transferred into volumes and converted into 3D surface meshes (recall Fig. 1B).

In order to prepare comparable vascular domains, we combined the surface models of the left and right arteries of the leg with the healthy proband's model. This is reasoned by the bad condition of the patient data, where especially for femoral arteries artefacts occur due to possible arteriosclerotic burden or pathologic vessels. By using the proband's model, we could always maintain the aorta and iliac arteries, see Fig. 1E.

2.2.2 Hemodynamic Simulation

The three-dimensional segmentation models were used to carry out highly-resolved blood flow simulations. First, the surface models were remeshed applying a sufficient base size of 0.1mm. Second, volume meshes were generated using STAR CCM+ 2020.1 (Siemens Product Lifecycle Management Software Inc., Plato, TX, USA) according to recommendations related to vascular flow simulations [5]. Third, time-dependent CFD simulations were performed using the commercial fluid dynamics solver STAR CCM+ 2020.1 as well. In this regard, representative flow rates were applied at the inlet cross section adjusted to the individual cross-sectional area [6]. Due to missing flow information in the outflows, constant relative pressure values were defined. Finally, rigid vessel walls were assumed and blood was treated as an incompressible ($\rho = 1055 \text{ kg/m}^3$), Newtonian ($\eta = 0.004 \text{ Pa} \cdot \text{s}$) fluid. In total, three cardiac cycles were simulated for each case, while only the last was included in the analysis.

Figure 1: Illustration of our workflow starting with segmentation of the right and left popliteal artery (A), the segmentation of possible thrombi (B) and the combination into a joint 3D model (C). For a larger vascular tree, this model is combined with the model from a healthy proband (D) into (E) for a subsequent hemodynamic simulation.

2.2.3 Analysis

Based on the highly resolved image-based blood flow simulations, hemodynamically relevant parameters can be extracted at arbitrary locations and time points during the cardiac cycle. Exemplarily, (time-averaged) wall shear stresses (AWSS) as well as the oscillatory shear index (OSI) – a nondimensional parameter measuring the directional change of wall shear stress during the cardiac cycle (T) – were calculated to assess local flow patterns and their potential effect on diseased vessel sections (see Eq. 1 and 2).

$$AWSS = \frac{1}{T} \int_0^T |wss| dt \quad (1)$$

$$OSI = \frac{1}{2} \left\{ 1 - \frac{\left| \frac{1}{T} \int_0^T wss dt \right|}{\frac{1}{T} \int_0^T |wss| dt} \right\} \quad (2)$$

Furthermore, local cycle-averaged velocity values were obtained to demonstrate the variability of the flow depending on the vessel section of interest.

3 Results

3.1 Thrombus Quantification

Based on the segmentations of the thrombi, automatic morphological parameters can be extracted for further analysis. In this pilot study, we included the thrombus volumes, see Table 2, and provided the information to the medical expert as further information.

Table 2: Automatic quantification of the thrombus volumes.

Patient ID	Size of left thrombus	Size of right thrombus
Patient 1	24306.1 mm ³	4533.5 mm ³
Patient 2	240124.9 mm ³	130870.4 mm ³
Patient 3	113685.1 mm ³	184086.9 mm ³
Patient 4	No thrombus	37355.7 mm ³
Patient 5	37355.3 mm ³	No thrombus
Patient 6	No thrombus	104768.5 mm ³

3.2 Hemodynamics

As presented in Fig. 2, highly-resolved hemodynamic results can be obtained. Specifically, the distribution of locally varying wall shear stresses can be assessed by the attending physician. Furthermore, directional changes of the shear become visible by illustrating oscillatory shear. These shear parameters occurring on the luminal side of the vessels can be colocalized with temporally changing flow patterns.

Overall, the prediction of four-dimensional hemodynamic parameters (3D+time) allows for the evaluation of endangered regions and helps to identify the appropriate patient-specific treatment strategy.

4 Summary

In this work, we present a pilot study for the analysis of patient-specific popliteal artery aneurysms. Our first results of this interdisciplinary approach demonstrate that the precise

assessment of individual thrombus formation and associated hemodynamics is feasible. Future work includes further automation of the technical workflow in order to decrease the processing time and reduce potential inaccuracies due to manual manipulations. Furthermore, improved simulation settings will be implemented, e.g., an adjustable flow-splitting approach allowing for the variation of different treatment scenarios [7].

Author Statement

Research funding: This study was funded by the Federal Ministry of Education and Research within the research campus *STIMULATE* (grant number 13GW0473A) and the German Research Foundation (grant number SA 3461/2-1, BE 6230/2-1). **Conflict of interest:** Authors state no conflict of interest. **Informed consent:** Informed consent has been obtained from all individuals included in this study. **Ethical approval:** The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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Figure 2: Representative illustration of the highly-resolved blood flow simulation results in both legs of two patients. Left: time-averaged wall shear stress (AWSS); Right: oscillatory shear index (OSI). Notice the three-dimensional segmentations of the thrombi (illustrated in purple) and option to calculate patient-specific mean velocities at arbitrary vessel sections.