Effective Visual Exploration of Hemodynamics in Cerebral Aneurysms

Mathias Neugebauer†, Rocco Gasteiger[1], Gábor Janiga[2], Oliver Beuing[3], and Bernhard Preim[1]

[1]Department of Simulation and Graphics, University of Magdeburg, Germany
[2]Department of Fluid Dynamics and Thermodynamics, University of Magdeburg, Germany
[3]Department of Neuroradiology, University Hospital Magdeburg, Germany

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Abstract

Cerebral aneurysms are a pathological vessel dilatation that bear a high risk of rupture. For the understanding of this risk, the analysis of hemodynamic information plays an important role in clinical research. These information are obtained by computational fluid dynamics (CFD) simulations. Thus, an effective visual exploration of patient-specific blood flow behavior in cerebral aneurysms was developed to support the domain experts in their investigation process. We present advanced visualization and interaction techniques, which provide an overview, focus-and-context views as well as multi-level explorations. Moreover, an automatic extraction process of qualitative flow characteristics, which are correlated with the risk of rupture is introduced. Although not established in clinical routine yet, interviews and informal user studies confirm the usefulness of these methods.

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1. Motivation

Cerebral aneurysms represent a threatening vascular disease which bears a high risk of rupture with an annual rupture rate of 1% to 2%, a mortality rate in case of rupture of 40% to 50% [BSH*10]. The aneurysm's size is correlated with the risk of rupture: larger aneurysms are more likely to rupture. The majority of all ruptured aneurysms, however, are small (5-10 mm). The hemodynamics within the aneurysm plays also an important role in aneurysm progression and rupture. Complex and instable flow is correlated with an increased risk [CCAea05]. Thus, biomedical engineers and neuroradiologists who are involved in clinical research, are interested in the analysis of hemodynamic characteristics obtained by patient-specific CFD simulation. They focus on assessing the correlations between flow characteristics (e.g., flow velocity, WSS, and inflow jet) and the risk of rupture in order to support treatment decisions. Neuroradiologists want to alter the flow in a defined manner with an appropriate stent or coiling to induce thrombosis. The choice of a stent and the exact placement belong to the treatment decisions.

Since treatment carries a significant risk of complication, the decision to treat an aneurysm has to be balanced against the risk of rupture. A significant portion of patients exhibits multiple cerebral aneurysms. For a better evaluation, which of the aneurysms should be treated first the neuroradiologist investigates the individual hemodynamic characteristics.

However, neuroradiologists are not familiar with complex hemodynamic information but have a strong affiliation to the aneurysm morphology. Hence, they need methods for an effective visual exploration of the hemodynamics combined with the aneurysm morphology. We present a visual exploration pipeline for both kind of information. It allows for successive anatomy-driven exploration, from the general aneurysm wall towards specific features of the internal flow. In detail, the pipeline consists of the following visual exploration approaches: **(1)** A 2D map display which combines an overview of the aneurysm surface with derived surface flow data (e.g. WSS), **(2)** an adapted aneurysm surface visualization that depicts the morphology of vasculature, whilst simultaneously gaining maximum visibility of the embedded flow, **(3)** a multi-level exploration approach, which provides anatomy-guided seeding strategy and widgets that enable interactive investigations of local flow, **(4)** the FlowLens, which is a focus-and-context visualization technique to provide a flexible visual filtering of relevant hemodynamic pair attributes, and **(5)** methods to extract and display the inflow

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† mathias.neugebauer@ovgu.de

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jet. We also provide an approach for the automatic extraction of advanced anatomical landmarks that are necessary for some of the pipeline steps.

2. Data Acquisition and Preprocessing

The polygonal representation of the aneurysm surface and certain anatomical landmarks as well as the acquired hemodynamic information are used as input data. We briefly describe the acquisition steps and refer to [GNBP11] for more details. Overall, 18 clinical image data sets (MRA, CTA, or 3DRA) of one or multiple aneurysms as well aneurysms with a recent rupture are employed. Because of the high vessel-to-tissue contrast a simple thresholding segmentation followed by a connected component analysis is used to separate the aneurysm and its parent vessel from the surrounding tissue. Based on the segmented mask, the surface morphology of the aneurysm is reconstructed with Marching Cubes and optimized with respect to smoothness and mesh quality. The vessel structures are clipped to restrict the simulation to the relevant portion. While in cardiac vessel analysis 4D PC-MRI flow data is obtained, in the smaller cerebral vessels this is usually not possible. Thus we focus on hemodynamic data that is obtained by a CFD simulation. The simulation is performed on a hybrid volume mesh consisting of tetrahedra and three layers of prisms in the near wall region leading to a higher resolution in this particularly interesting region. This volume mesh is derived from the surface mesh. In addition to the geometric boundary of the vascular structure, the pressure, and the velocity at the inlet and the outlets are defined based on a typical heart rate, i.e., the velocities and pressure rates that are typically found in a living organ are used. We focus on a static scenario.

With all boundary conditions defined, the flow is computed based on the Navier Stokes equations using ANSYS Fluent. The resulting velocity and pressure of the blood flow can subsequently be used for further analysis. Also, the wall-shear stress can be computed based on the velocity field and the geometry.

3. Visual Exploration Pipeline

The proposed exploration pipeline [NGP11] follows the *"‘overview first, details on demand"’* strategy. It starts with data given on the surface, followed by the exploration of surface and flow, the exploration of flow at certain anatomical landmarks, the side-by-side exploration of hemodynamic attributes and finally the extraction of a relevant flow feature, the inflow jet. Thus, the medical researcher can start at familiar ground, the surface anatomy, and successively explore towards specific flow features. To encourage acceptance of the elaborated visualizations employed for each step of the pipeline, we aim for their automatic generation and provide template-based parameterizations. Additionally, interaction is supported by widgets with meaningful designed degrees of freedom. The automatic generation of visualizations and the guided interaction rely on advanced landmarks that need to be extracted from the surface representation.

3.1. Landmark Extraction

To understand, which landmarks are actually important to characterize the local vessel anatomy, Neugebauer et al. [NDSP10] questioned a couple of neuroradiologists to draw cerebral aneurysms and extracted characteristic points commonly used by them. The following points were found to be essential (see Fig. 1):

- the dome point of an aneurysm,
- the (curved) ostium plane, where the blood enters the aneurysm, and
- the central aneurysm axis (the closest connection between the parent vessel's centerline and the dome point)

For guiding the exploration, we also determine the vessel centerline. This enables the user to move a cross-sectional plane that is aligned perpendicular to the centerline, displaying scalar flow features, such as the speed.

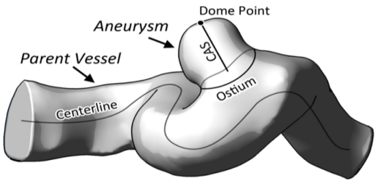

Figure 1: *Geometric descriptors for characterizing cerebral aneurysms (From: [NDSP10])*

The robust and precise detection is challenging due to the large variety of pathologic situations and is successful in about 90 percent of the cases (see [NDSP10] for a description of landmark extraction in saccular cerebral aneurysms).

3.2. Overview Map Display

A simple solution to display scalar flow features is to show the surface of the relevant vascular region with a scalar flow feature color-coded. The disadvantage of this simple solution is that only a small portion of the surface is visible at the same time. Map projections which fold an anatomic structure in a plane enable to display the whole scalar information simultaneously. However, a map exhibits distortions and, map displays are hard to relate to the complex 3D anatomy of pathologic vessels. A combination of a faithful 3D anatomy representation and a map view, where interaction in both views are synchronized is promising. Our design is inspired by map views in other areas of medical diagnosis, such as the Bull's eye plot in cardiology.

Neugebauer et al. [NGBea09] introduced a map display for scalar flow features where the 3D anatomy model is shown in a central part and flow features of the left, right, bottom, up and back side are presented as flat regions of a map surrounding the anatomic view. When the user selects a point in one of the map views and drags it towards the center, the 3D anatomy model is rotated such that this point becomes visible (see Fig. 2). Also, a rotation of the 3D view of the anatomic model is possible and results in an update of the map views. Neuroradiologists emphasized that this technique enables a better exploration of scalar flow features at opposite sites. There are many details to consider, such as map layout, interaction techniques, color selection and display of additional hints [NGBea09]. While it is applicable to instationary flows in principle, it is likely that modifications are necessary if the flow features change over time and lead to frequent changes of the map view and the 3D model view.

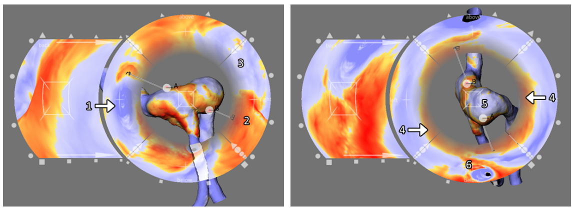

Figure 2: *A 3D model of the vascular anatomy is surrounded by map views that display the WSS of five sides (features at the left, right, bottom, and up side are shown at the corresponding ring portions). Scalar features of the backside are shown at the right (From: [NGBea09]).*

3.3. Adaptive Surface Visualization

Blood flow strongly depends on local variations of the enclosing vascular structures. Large changes in flow speed occur at stenotic regions, and turbulent flow occurs primarily at bifurcations or strongly curved areas. Thus, it is important to investigate the morphology of anatomical structures and the internal flow simultaneously.

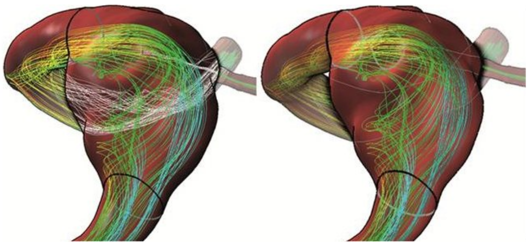

Figure 3: *Simultaneous visualization of the morphology and the embedded flow with ghosted views. In the right view, hidden flow lines are eliminated (From: [GNKP10]).*

In case of simulated flow, such an integrated analysis may reveal that a significant flow feature is due to a small variation of the surface, which may result from an inaccuracy in the segmentation. The simplest idea to display flow and vascular anatomy at the same time is to render the vascular surface transparently. However, depending on the transparency level, either the vascular anatomy is hardly recognizable, or the internal flow is strongly obscured by the vessel wall. As a remedy, smart visibility techniques, such as ghosted views, may be employed. The flow is considered as important and the vessel walls transparency is modified to reveal flow lines. This idea has been realized by Gasteiger et al. [GNKP10]. The specific solution to provide ghosted view visualizations is based on a Fresnel reflection model, where the reflection term is replaced by opacity. In Fig. 3 a comparison of that technique with conventional semitransparent rendering is presented. The landmarks discussed in Sect. 3.1 are used to draw lines at the ostium plane. All hidden flow lines may be removed to reduce visual clutter (see Fig. 3).

3.4. Anatomy-Guided Multi-Level Exploration

Neugebauer et al. [NGP11] presented techniques to support the flow exploration at different scopes: a global scope that consists of the aneurysm along with the inflow and outflow region, a local scope that is focussed on the aneurysm and even more detailed exploration of the inflow in the ostium plane. Based on the extracted landmarks and thus the patient-specific anatomy, 3D widgets may be moved along the vessel centerline and the central aneurysm axis. Streamlines are seeded almost regularly at the ostium plane. Transfer functions operating on flow features, such as speed, allow for parameterization of the visualization (see Fig. 4).

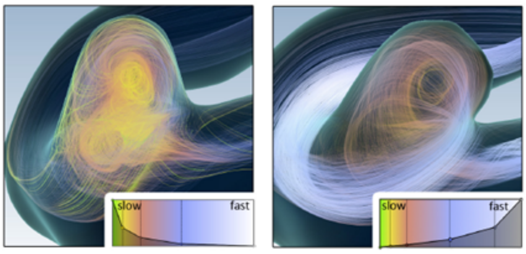

Figure 4: *Regions with particular slow flow and thus long residence time are crucial for thrombus formations and emphasized with an appropriate transfer function in the left image. The right image emphasizes particular fast flow since the region where such flow strikes the vessel wall is also at a higher risk of rupture (From: [NGP11]).*

3.5. FlowLens as Focus-and-Context Visualization

Often, it is desirable to explore one flow parameter in the context of another one. Based on a comprehensive literature review of flow parameters, [GNBP11] proposed the FlowLens which combines flow attributes by showing a different attribute within and outside the lens. Additionally, they incorporate a 2.5D lens to enable probing and slicing through the flow. To simplify the interface, they provide task-based scopes. Each scope consists of pairs of focus vs. context attributes. For each pair templates summarizing default parameters were developed and evaluated (Fig. 5).

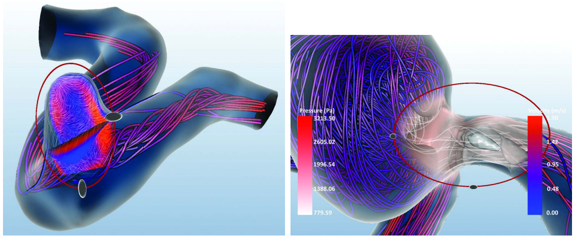

Figure 5: *Two examples of the FlowLens (red line with two handles). A view-aligned LIC probe plane for the investigation of the degree of vorticity is shown inside the lens (left) as well as different flow pressure isosurfaces (right). Outside the lens the flow is visualized with illustrative and color-coded streamlines. (From: [GNBP11]).*

3.6. Extraction of Qualitative Flow Characteristics

Qualitative flow characteristics, e.g., the *inflow jet* and the *impingement zone* are correlated with the risk of rupture. However, the assessment of these two characteristics is currently based on an interactive visual investigation of the flow field. We developed an automatic and robust detection as well as an expressive visualization of these characteristics. The inflow jet is characterized as a region with relatively fast and almost parallel flow.

The detection can be used to support a comparison, e.g., of simulation results reflecting different treatment options. Our approach utilizes local streamline properties to formalize the inflow jet and impingement zone. We extract a characteristic seeding curve on the ostium, on which an inflow jet boundary contour is constructed. Based on this boundary contour we identify the impingement zone.

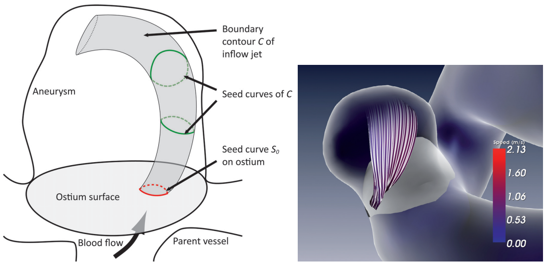

Figure 6: *Left: An analysis of the flow in the ostium may result in an inflow jet region. The inflow jet is displayed with different illustrative and abstracted styles, e.g., with a stripe pattern or an arrow glyph (From: [GLvP* 12]).*

4. Conclusions and Future Work

The methods described in this paper were developed in a close cooperation between neuroradiologists, flow simulation and visualization experts. They focus on clinically relevant questions, such as necessity and urgency of treatment and consider specific problems, e.g., in case of multiple aneurysms. Moreover, research questions are supported, e.g., the validation of simulation parameters and the understanding of the risk of rupture. However, there is still a gap between the insights provided by this medical research and the actual clinical application. The hypotheses derived from the detailed exploration of flow data need to be clinically evaluated. Then, they can be transformed into binary indicators necessary to support clinical treatment. The proposed exploration pipeline is flexible enough, to incorporate new parameters that result from ongoing research. However, the pipeline is also designed for efficiency by means of automatic parameterization and guided interaction.

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