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Anatomy-Guided Multi-Level Exploration of Blood Flow in Cerebral Aneurysms

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Abstract

For cerebral aneurysms, the ostium, the area of inflow, is an important anatomic landmark, since it separates the pathological vessel deformation from the healthy parent vessel. A better understanding of the inflow characteristics, the flow inside the aneurysm and the overall change of pre- and post-aneurysm flow in the parent vessel provide insights for medical research and the development of new risk-reduced treatment options. We present an approach for a qualitative, visual flow exploration that incorporates the ostium and derived anatomical landmarks. It is divided into three scopes: a global scope for exploration of the in- and outflow, an ostium scope that provides characteristics of the flow profile close to the ostium and a local scope for a detailed exploration of the flow in the parent vessel and the aneurysm. The approach was applied to five representative datasets, including measured and simulated blood flow. Informal interviews with two board-certified radiologists confirmed the usefulness of the provided exploration tools and delivered input for the integration of the ostium-based flow analysis into the overall exploration workflow.

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1. Introduction

The diagnosis of vascular diseases benefits from the visualization of the vascular morphology and the internal blood flow. As an example, the formation of cerebral aneurysms is significantly influenced by the hemodynamic of the internal blood flow. Cerebral aneurysms represent a threatening vascular disease that bears a high risk of rupture with often fatal consequences for the patient (fatality up to 52%). Based on the patient-specific aneurysm anatomy, researchers employ computational fluid dynamic (CFD) simulations and 4D PC-MRI flow measurement, to investigate the correlation between aneurysm morphology and blood flow patterns. This research aims at gaining a deeper understanding of the aneurysm growth, to evaluate the risk of rupture and develop new treatment options by means of virtual stenting.

The exploration of 3D medical visualizations strongly benefits from guidance based on anatomic features. The visualization can be focused on anatomically relevant information and a goal-directed interaction can be supported. We present a multi-level exploration scheme where each level takes advantage of anatomical features, extracted from the vessel geometry (see Fig. 1). Thus, we are able to represent only the subset of the flow data that is potentially rele-

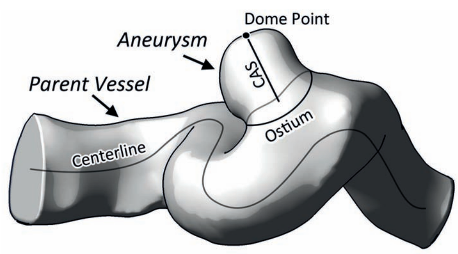

Figure 1: *Anatomic features of parent vessel and ostium.*

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vant with respect to the aneurysm and provide constraints for widget-based interaction. Due to the multi-level design, the medical expert is able to gain an overview of the overall flow characteristic before exploring details at anatomically meaningful regions. The main contributions of this paper are:

- Flow exploration at three scopes that integrates into an workflow for the visual exploration of flow in aneurysms.
- An anatomy-guided seeding strategy and color schemes for the streamline-based visualization of relevant flow, including slow-, fast-, in- and outflow characterization.
- A multi-parameter representation of the flow profile at the ostium of the aneurysm.
- Anatomy-guided widgets that enable interactive exploration of local flow in the parent vessel and the aneurysm.

2. Related Work

The number of medical research applications that benefit from a qualitative exploration of flow fields is rising, due to the increased availability of measured flow data and hardware-driven cost and time reduction of computational fluid dynamics (CFD) simulations. However, the primary field of application is still the analysis of vascular diseases by means of intravascular hemodynamics.

MRIView [Buo98] was one of the first applications towards the visual exploration of measured flow along cross sections through a vessel, utilizing 4D PC-MRI. Improved measurement and pre-processing techniques, presented by Isoda et al. [IOKea10], allow to explore measured flow even in the fine cerebral vasculature. Cebral et al. [CCA*05] employ CFD studies on a broad range of patient-specific vessel reconstructions to investigate aneurysm formation and to identify parameters for risk assessment. Among others they employed visual side-by-side comparison of scalar data mapped on the surface while Isoda et al. applied stream- and particle tracing to visually explore the measured data. Visualization techniques for blood flow exploration can be categorized into dense approaches, that aim at representing a complete flow field on a given subdomain, and tracing- or feature-based approaches [PVH*03]. Except for the separation into surface-near scalars and inner flow, the aforementioned visual exploration approaches do not define flow subdomains according to the anatomy. A definition of such subdomains requires some kind of anatomic reference system.

Piccinelli et al. [PVS*09] present a framework for the geometric description of patient specific vessel surface models. It was applied to cerebral aneurysms to quantify the angle between the aneurysm neck plane and the parent artery bifurcation. Instead of a planar neck Neugebauer et al. [NDSP10] extract anatomic landmarks to to reconstruct the ostium, which separates the aneurysm from its parent vessel. Chatziprodromou et al. [CBM*03] utilize aneurysm specific axis by employing cut planes that are orthogonal to the central aneurysm axis and provide qualitative color- and particle-based flow visualizations on those planes. In [vPBB*10] probing planes are positioned on the centerline of the aortic artery. Streamlines seeded from these planes and illustrative arrows are used to represent flow rates while the surrounding vessel context is rendered in a toon-shading style. Our anatomy-guided approach not only utilizes the centerline and the intra-aneurysm axis but also the reconstruction of the ostium.

3. Data Pipeline

The anatomy-guided exploration of the aneurysm flow is based on data such as the reconstructed vessel morphology and the flow data. The flow data can be derived from CFD simulations or direct measurement. The vessel morphology is input for the CFD simulation and also used to derive the needed anatomical features. How the anatomy-guided exploration is integrated into the overall workflow and what requirements need to be considered is described at the end of this section.

3.1. Input Data

All data that is directly derived from scans, measurements and simulations, is referred to as *input data*.

Vessel Morphology. As primary input data we have image slices either from Computed Tomography Angiography (CTA) or Magnetic Resonance Angiography (MRA). Through the use of contrast agent or special sequences (e.g. MRA: the Time-of-Flight sequence) the vessels bear high contrast in both modalities. Thus, in cases with low noise and artefact level, we employ thresholding for segmentation and Marching Cubes to generate a polygonal vessel surface. When the data quality is low, a deformable model is used [LABFL09]. To ensure anatomical plausibility, the resulting surfaces where evaluated by our medical partners.

Simulated Flow Data. A CFD-compliant mesh is needed as geometric input for the simulation. A high element quality is obtained by remeshing the surface that results from Marching Cubes. We utilize an advancing front approach to rebuild the mesh and optimize the quality by a combination of metric and topological changes (for details see [Sch97]). Concerning the tradeoff between accuracy and computation time, we model the blood as Newtonian fluid with steady flow and rigid walls. Cebral et al. [CCA*05] have shown that a qualitative flow characterization is still possible. The border conditions (in-/outflow rate) are derived from medical literature and validated by our medical partners. If measured blood flow data is available, we derive the border conditions from them.

Measured Flow Data. We obtain measured flow data from time-resolved phase-contrast MRI (4D PC-MRI) that encodes the flow direction and magnitude for each voxel [MHBea07]. Measurement errors introduced by eddy

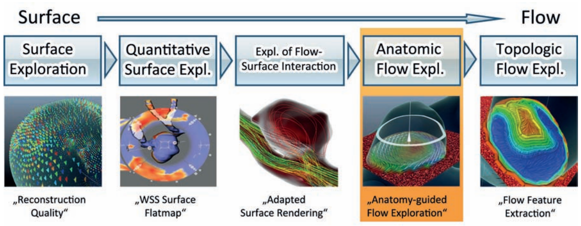


Figure 2: *Overall exploration workflow with application examples. The step our approach belongs to is highlighted in orange.*

currents, noise, and velocity phase wraps are corrected in an additional postprocessing step, for details see [HFSea11]. The measured data is sampled on a regular image grid while the simulation results are represented on a hybrid tetrahedron- prism grid. These grids form the input for the visual flow representation.

3.2. Anatomic Features

The relevant anatomic features are derived from the surface representation of the aneurysm and its parent vessel (Fig. 1).

Parent Vessel Centerline. Rather than deriving the centerline from image-based skeletonization it is directly calculated from the polygonal surface mesh. Thus, it does not include shape artifacts induced by the uniform sampling of the underlying image data. With their vessel modeling toolkit (VMTK), Piccinelli et al. [PVS*09] introduced a robust implementation of the Voronoi diagram-based calculation of the centerline. When passing below the aneurysm, the centerline tends to deviate into the aneurysm. Thus, the unreliable part below the aneurysm was identified and replaced by a cubic Lagrange polynomial that has the four points at the end pieces of the original centerline as control points [NP11].

Ostium Plane. The ostium, the area of inflow into the aneurysm, is an important anatomical feature, since it separates the aneurysm from the parent vessel. Additional anatomic descriptors like the central aneurysm axis can be derived from it. From expert interviews we learned that the ostium plane can be described by four control points on the aneurysm surface. Thus, to reconstruct the ostium, these four control points need to be identified. First, the distance between centerline and surface is used to estimate the dome point of the aneurysm. To restrict the search space for the first two control points, the centerline is projected on the surface towards the estimated dome point. A distance analysis between projected and original centerline is applied to identify the location of the first two control points (P_1, P_2). Incorporating these locations, an initial, planar ostium contour is created and the remaining two control points (P_3, P_4) are placed on this contour, in between P_1 and P_2. Finally, the contour is bent by shifting P_3 and P_4 towards the parent vessel, for details see [NDSP10]. The bent contour and a projection of the centerline into the ostium domain are the input contours for an adapted bilinear interpolation approach to generate a smooth surface [NP11] (see Fig. 3(a)).

Central Aneurysm Axis. This axis linearly connects the center of the ostium and the dome point (see Fig. 1) and does not resemble the medial axis of the aneurysm. The center of the ostium is defined by the middle of the centerline, after it is projected on the ostium plane (see Fig. 3(a)). The central aneurysm axis (CAS) can be used to align widgets, compute suitable camera positions or scale widgets and glyphs according to the aneurysm size. We use it mainly for widget alignment and scaling.

3.3. Workflow Integration and Requirements

We conducted a series of interviews with three radiologists from two hospitals to discuss a workflow for analysing blood flow in the context of vascular anatomy. First, we tried to characterize the current workflow and later to envision how this workflow has to be extended to integrate the exploration of flow, which is beyond the current practice. From these interviews, we derived a set of scenario descriptions which capture a sequence of individual steps relevant for medical research on certain kinds of aneurysms. After validating these scenario descriptions in another set of interviews, we came up with the following workflow. To describe it, we chose a spatially driven surface-to-flow layout (see Fig. 2), which consists of several sub-tasks:

- **Topologic Surface Exploration.** The geometric description of the reconstructed surface is of interest. This is relevant for therapy (e.g. indication of previous bleeding) and helps to estimate the quality of the reconstruction in comparison with underlying image data.
- **Quantitative Surface Exploration.** Near-wall flow parameters are assumed to indicate the risk of rupture. Special mapping approaches help to gain an overview of the spatial parameter distribution on the surface [NGB*09].
- **Exploration of Flow-Surface-Interaction.** To gain insight into the interaction between flow and vessel wall, both must be visually represented. Since the vessel wall embeds the flow, occlusion is a major problem. Specialized rendering techniques can reduce the occlusion while conveying visual hints about the shape and features of the surface [GNK*10].
- **Anatomy-guided Exploration of Flow.** The approach presented in this work belongs to this step. Instead of providing the complete vessel or flow or any combination, we concentrate on local, anatomically relevant sections of the flow.
- **Topologic Flow Exploration.** While most of the previous steps incorporate flow partially or as context, this step is focussing on the flow field. This includes the analysis of

topologic features like sources, sinks, saddle points and vortex cores [LHZP07].

Requirement Analysis. In the current state, the workflow aims primarily at the field of medical research and biomedical engineering. Questions answered by this workflow might involve the evaluation of reconstruction- and simulation-pipelines, insights into the biomechanical and hemodynamic influence on aneurysm evolution or the simulation of various stent designs and patient specific geometries in order to optimize the treatment process. Nevertheless, based on the approaches used in this workflow, diagnostic tools for clinical use will be developed. They will offer a condensed set of features to aid binary decisions instead of broad exploration as it is necessary for research. Thus, the requirements for supporting anatomy-driven flow exploration in the scope of this workflow are mainly derived from the application in medical research, yet influenced by the perspective of a later usage in diagnosis and treatment planning.

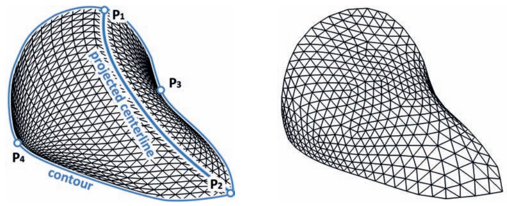
The requirements are derived from the challenge of transferring highly complex information from one expert domain (hemodynamic analysis) to another (biomedical research). Thus, the basic goal is to simplify the process as much as possible, yet provide all necessary information. This can be realized by satisfying three requirements:

- **Automatic Visualization Setup:** The effort of choosing and parameterizing various visualization techniques should be as low as possible. An automatic process or parameter templates support interpersonal compatibility of analysis results and prevents misjudgements due to an inappropriate parameter setup.
- **Incorporate Anatomic Descriptions:** According to the above described workflow, our approach aims at supporting anatomy-guided exploration of flow. Thus, it is not only important to choose the right parameter setup, but to also apply it to the spatially relevant section of the dataset. If possible, this task should be supported in an automatic manner or, in case of interaction, by the restriction of the degrees of freedom (DoF).
- **Guided Interaction:** As implied above, a meaningful restriction of DoF can ease interactive exploration and avoid unfavourable states [SSS01]. Neuroradiologists are used to 2D interaction (e.g. placing a measurement widget) on image planes. Even if one is used to 3D interaction, the control of an 6-DoF camera in conjunction with at least 6 DoF given by an 3D widget, is a tedious interaction task.

To summarize the requirements: in order to support medical researchers exploring complex hemodynamics with respect to anatomy, an approach must provide easy to use visualization setups and guide the user during interaction and selection of spatially relevant flow sections.

4. Exploration at Different Scopes

Our exploration approach is inspired by the visual information-seeking mantra: "overview first, details on demand" [Shn96]. It separates into three different scopes: a *global scope* that gives an overview about the blood flow into and out of the aneurysm, an *ostium scope* that concentrates on certain flow characteristics close to the area of in- and outflow and a *local scope* that enables the user to investigate the flow parameters in the parent vessel and the aneurysm in detail.



(a) Initial (b) Remeshed

Figure 3: *The ostium plane before and after remeshing.*

4.1. Global Scope

In order to understand how the flow in the aneurysm is connected to the blood flow in the parent vessel, one needs to know which portion the flow actually enters the aneurysm, how it evolves and how it has changed when it leaves the aneurysm. Streamlines are suitable representations to visually convey these flow characteristics. They encode direction and, through an appropriate color scheme, additional characteristic scalar values. Due to their non-dense nature, the geometric context given by the vessel surface is still visible. This is further supported by a hybrid rendering of the vessel surface. The Fresnel-term is used to define the opacity of front side. Thus, a view towards the centerline of the vessel is almost not occluded while higher opacities near the visual edge of the vessel convey hints about its shape. The back side of the vessel is rendered opaque, using a dark blue color. It acts as a canvas for the light colored streamlines.

The placement of the streamline seed points implicitly influences which parts of the flow will be visible. Since we are interested in the in- and outflow, we choose the vertices of the ostium plane mesh as seed points. Due to the bilinear interpolation approach used to generate the plane mesh, we initially gain an inhomogeneous distribution of the seed points that is unrelated to the underlying geometry and the flow (see Fig. 3(a)). Thus, the ostium plane is remeshed, using an advancing front method. Due to a Delaunay triangulation with almost identical Voronoi regions the uniformity of the vertex distribution is increased (see Fig. 3(b)). Since this distribution is not regular in the sense of a rectangular Cartesian grid, the underlying uniformity is almost not perceivable while the whole surface is sampled with the same rate. An under- or overrepresentation of flow parts, that could be caused by an unfavourable random seed point placement, is avoided.

Streamlines traced from the ostium plane can provide instantaneous insights, e.g. which portion of the laminar inflow enters the aneurysm. For further visual exploration of the qualitative nature of the flow, with respect to velocity and direction, specially designed lookup tables are applied to the streamlines.

- **Slow/Fast Flow Enhancement.** Areas of low flow velocity are equivalent to areas with a higher chance of thrombosis. Endovascular treatment tries to induce a thrombosis within the aneurysm. Thus, a lookup table that enhances slow flow areas supports the qualitative estimation of treatment success. We propose a velocity-based color scheme as it is presented in Figure 4(a). It is based on complementary colors: orange to yellow is used to encode lower velocities while blue to white encodes higher velocities. The opacity correlates inversely to the velocity in an exponential manner. Thus, the faster laminar flow does not occlude the slow and turbulent flow within the vessel and aneurysm, yet acts as contextual information (see Figure 4(a)). For certain research fields, e.g. questions concerning the remodelling of the parent vessel flow in order to support thrombosis, the fast flow is of major interest. To switch the focus-context relation, we apply the same color scheme, but with inverted opacity (see Fig. 4(b)).

- **In-/Outflow Enhancement:** To visually separate in- from outflow, we benefit from the anatomically guided placement of the seeding points. Since they lie on the ostium plane, we can simply use the integration time. Since the ostium plane is oriented towards the aneurysm, streamlines encoding the inflow bear a negative integration time and outflow streamlines a positive integration time respectively. Nevertheless, we have to consider that due to the ostium plane orientation, this applies only to streamline in the parent vessel. We choose a color scheme that encodes inflow from white to blue and outflow from orange to yellow. Green marks the separation at integration time zero (see Fig. 4(c)). In- and Outflow can also be presented separately, to visually enhance regurgitations or the influence of the parent vessel flow on the outflow.

4.2. Ostium Scope

The ostium separates the aneurysm from the healthy parent vessel. Thus, the flow profile at the ostium is a central parameter to evaluate the success of treatment options that alter the inflow to induce a thrombosis within the aneurysm or reduce the physical stress. Features of this profile are: the regional distribution of in- and outflow, direction and velocity of flow and the volumetric flow rate. Except for the volumetric flow rate, the features can be directly derived from the underlying vector field.

The volumetric flow rate R_i is calculated for each of the k triangular elements of the ostium mesh:

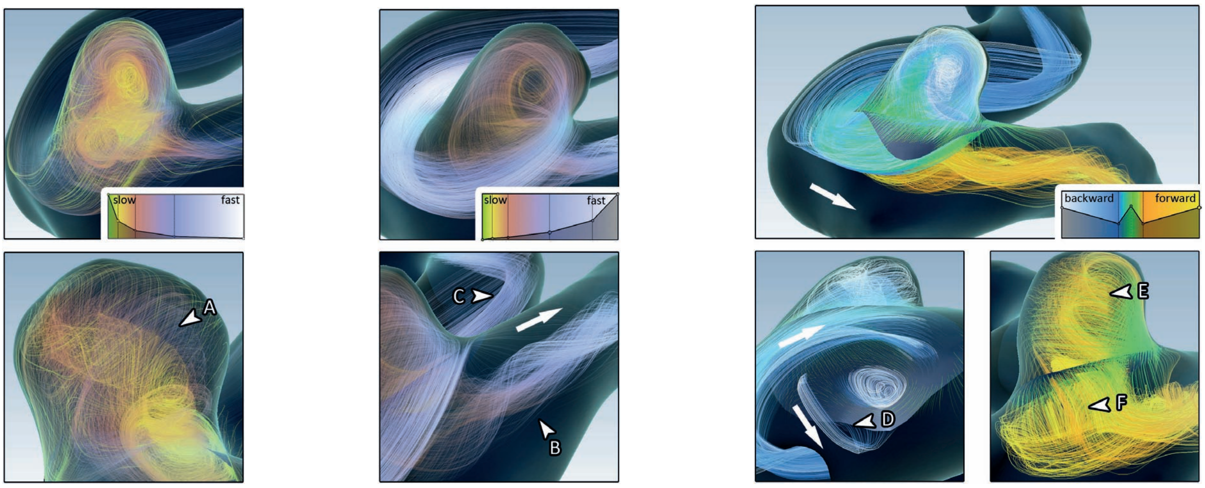
$$R_i' = \left(A_i(\vec{v}_i \cdot \vec{n}_i) \sum_{i=0}^{k} R_i \right) / R_{\max}$$

Where A_i is the element area, $\vec{v}_i$ is the velocity vector of the flow through the element and $\vec{n}_i$ is the element's normal vector. R_{max}, the maximum element-wise volumetric flow rate, is used for normalization. This is necessary, since the volumetric flow rate is area-dependent. The normalization ensures that the overall volumetric flow rate profile is independent from the tessellation and allows for a comparison of profiles on different ostium meshes. Each profile feature is represented by an individual visualization technique, combined in a multi-parameter visualization on the ostium plane. The choice of each technique was deduced from informal expert interviews.

The flow velocity is color-coded on the ostium plane. To gain conformity with the streamlines of the global scope, a similar yellow/orange-to-blue/white color scheme is applied. The volumetric flow rate is represented by a contour line overlay. Orange contour lines mark the inflow (positive flow rate), blue contour lines the outflow (negative flow rate) and a red contour line (flow rate zero) the separation between in- and outflow area. Radiologists confirmed that the number and density of the contour lines is suitable for qualitative flow rate representation. The simple, binary color scheme reduces a visual interference with the color-coded velocity on the ostium plane.

At this level of detail, the multi-parameter visualization provides information regarding two scalars, velocity and volume flow, and a qualitative representation of in- and outflow areas (see Fig. 5(a)). To add a visual representation of the flow direction we employ glyphs and short streamlines that are placed and seeded respectively at the vertices of the ostium mesh. Cone shaped glyphs are interpreted intuitively to encode direction. Nevertheless, a glyph encodes direction just at a single position, the vertex of the ostium plane. Thus, short streamlines are added to convey more detail of the flow field close to the ostium. They help to emphasize directional flow structures like vortices (see Fig. 5(b)). In order to reduce visual cluttering, the glyphs and streamlines are rendered half-transparent, using white color. The underlying, color-coded scalar information is still perceivable.

To further support the interpretation of scalar and directional information on the ostium plane, we include contextual information about the surrounding flow as a third level of detail. As in the global scopes, we employ streamlines. To prevent the streamlines to occlude too much of the ostium plane, their number is halved. Also, they are rendered in a special way: we use the same opacity map that was used when visualizing the slow flow in the global scope, but this time, a desaturated, white (low velocity) to black (high velocity) color table is used. Additionally, streamlines encoding higher velocities are blurred. The result is a cloud-like



(a) Slow Flow Enhancement (b) Fast Flow Enhancement (c) In-/Outflow Enhancement

Figure 4: *Global Scope Overview (upper row - overview, lower row - details): By applying the slow flow enhancement, the flow structures within the aneurysm become visible. A slower inner vortex is enclosed by a faster one while the surface near flow is slow again (A). The fast flow enhancement shows how the flow changes from laminar (C) to turbulent (B). When only representing one of the flow directions, structures like regurgitations (D) or the change of the vortex orientation (E - F) due to the collision with the parent vessel flow become visible. The arrows encode the flow direction.*

flow representation (see Fig. 5(c)). In still images, information on the ostium plane is still perceivable. When rotating the view around the ostium plane, the blurred contextual streamline provide clear hints about structures (e.g. vortices) in the surrounding flow.

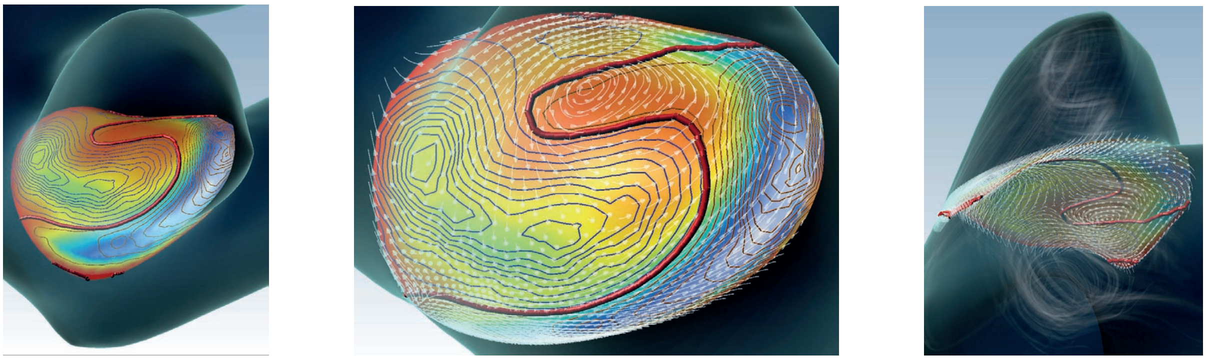
The context information helps to relate between features in the global scope (vortex) and the ostium scope (mixture of in-/outflow area). Nevertheless, this level of detail is not necessary all the time. Thus, we propose three levels of detail that can be selected through templates: the first level includes the scalar information about volume flow and velocity as well as the in- / outflow areas. The second level adds the flow direction by means of desaturated glyphs and short streamlines while the third level incorporates blurred streamlines as context information.

4.3. Local Scope

In cases, where sparse flow representation of the global scope and the anatomy-guided flow section of the ostium scope do not provided the required amount of flexibility and detail, the user should be enabled to manually probe the flow. This can take place in two anatomic domains: the parent vessel and the aneurysm. Appropriate *widgets* must be provided for this interactive task [TS07]. As described in the requirement analysis, the widget handling needs to be simple. Thus, we constrain the widget transformation with respect to specific anatomical landmarks given in the parent vessel and the aneurysm. Informal evaluations revealed that this kind of restriction is appropriate and not considered as disturbing. We chose a planar layout that enables us to employ dense flow visualization techniques like Line Integral Convolution (LIC). Additionally, we apply height fields and glyphs to represent the velocity profile and flow directions.

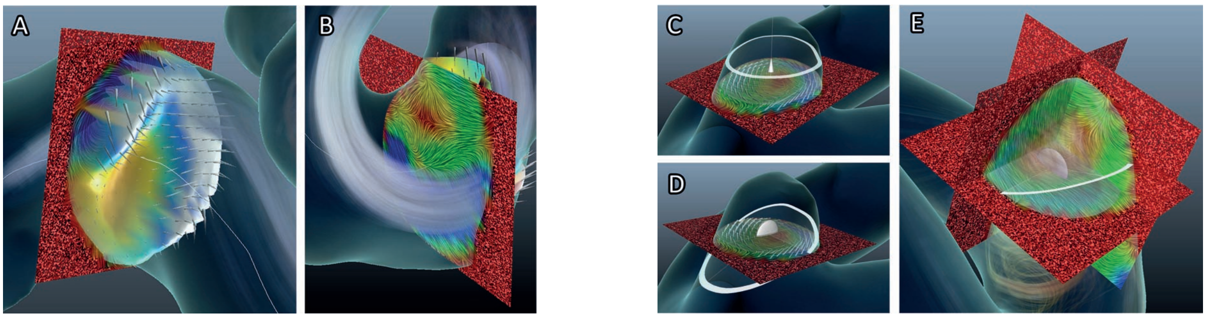
Parent Vessel Exploration Widget. This planar widget is orthogonally oriented and centered with respect to the parent vessel centerline. Thus, the user can move the widget along the centerline and probe the complete parent vessel without accidentally misplacing the widget. A screen space projection of the centerline is employed and the point closest to the mouse coordinates is used to place the widget on the according position on the world space centerline. Thus, a natural and fast change between visually but not geodetically close centerline points is possible, without traversing the whole centerline.

The velocity profile of the flow that intersects the widget plane is represented by a height field. The same color scheme as applied to the ostium height field is used. To encode the flow direction, desaturated glyphs are placed on the height field. To provide further visual hints about the qualitative characteristic of the flow, we employ LICs on the planar backside of the widget (see Fig. 6(a)). Additionally, we provide global scope streamlines as context, using the same blurred context rendering style as for the ostium scope (see Fig. 6(a)). To provide different levels of detail, we propose a strategy similar to the one used for the ostium scope: Beginning with scalar values (height field - velocity), directional



(a) Velocity and Flow Rate (b) Added Velocity Glyphs & Short Streamlines (c) Added Contextual Streamlines

Figure 5: *Ostium Scope Overview: At the first level of detail, velocity (color coded) and volumetric flow rate (contour lines) are represented, while the red contour separates in- from outflow (a). Short streamlines and cone-glyphs provide directional information; structures like vortices become visible (b). Blurred contextual streamlines help to relate between global scope vortex and ostium plane vortex - view from below (c).*



(a) Parent Vessel Exploration Widget (b) Aneurysm Exploration Widget

Figure 6: *Local Scope Overview: The context for the parent vessel widget is provided by blurred global scope centerlines. A height field represents the velocity profile (A) while a LIC on the backsides conveys flow characteristics (B). The aneurysm widget provides two transformation modes: Translation along the central aneurysm axis (C) and rotation around the widget center (D). By selecting a point on the widget plane, additional probing planes can be added (E). In (E) blurred streamlines are added as context while in (C) and (D) glyphs encode the flow direction.*

information (glyphs - flow direction) and context (blurred streamlines) can be added optionally.

Aneurysm Exploration Widget. Similar to the parent vessel widget, the translation of this widget is constrained with respect to the central aneurysm axis (CAS). Thus, it cannot be accidently positioned outside the aneurysm. In its initial state, the widget is orthogonally oriented with respect to the CAS. We also provide the possibility to rotate the widget. A click on the broad border of the handle activates the rotation mode while a click on the center enables translation (see Fig. 6(b)). The border point, selected when entering rotation mode, also defines the rotation direction. The rotation axis lies on the widget plane. It is orthogonal with respect to the axis given by the selected border point and the widget center. The mouse position is orthogonally projected onto the screen space representation of the rotation axis. The screen space distance of the projected point and the widget center defines the rotation angle. Thus, the rotation is aligned to the mouse movement during rotation. Since any rotation vector can be defined by selecting a point on the handle border, no additional keyboard inputs or viewpoint changes are necessary to freely rotate the widget within the aneurysm. As a visual transformation cue, the widget handle stays at its initial position while the probing plane is moving.

Except for the height field, the same visualization techniques as for the parent vessel widget are used for aneurysm exploration widget. Up to three orthogonal planes can be positioned by a single mouse click on the probing plane, defining the intersection point of the planes (see Fig. 6(b)). The layout of the planes resembles a scheme radiologists are used to from dealing with volume datasets (coronal, saggital and axial image slices). The additional planes can be shifted by selecting another point on the widget plane and the rotate accordingly. Similar to the parent vessel widget, the blurred rendering of the global scope streamlines serves as visual context (see Fig. 6(b)). The aneurysm widget provides the same three optional levels of detail as the parent vessel widget: scalar (color - velocity), directional (glyphs - flow direction) and additional context (blurred streamlines).

5. Results

The implementation of our approach is based on the Visualization Toolkit (VTK) and the prototyping environment MeVisLab. To evaluate our exploration strategy, we choose five representative datasets. For two patient scans the flow was derived from CFD. They contained a small saccular aneurysm (2mm ∅) at the left vertebral artery (An_01 - see figures of the previous sections) and a larger basilar aneurysm (7mm ∅) (An_02 - see Fig. 7(a)). Due to the complex configuration of the parent vessel, we included one of the datasets of the Visc stenting challenge 2009, also with CFD derived flow data (An_03 - see Fig. 7(b)). As an example for measured flow data, a 7 Tesla 4D PC-MRI scan was applied to a phantom that contained three artificial aneurysms, two of which (An_04: 8mm ∅, An_05: 10mm ∅ - see Fig. 7(c) and Fig. 7(d)) were included into the dataset base. All CFD simulations were steady-flow and from the measured flow data one time-step was extracted. The complexity of the volume flow grid ranged from app. 180.000 (small saccular aneurysm) to $4,6 \cdot 10^6$ (VISC dataset) elements. Depending on the ostium shape 2500 to 3500 seed points were used. For our prototypic system, the preprocessing time, including data loading, ostium generation and stream tracing ranged from 10 to 40 sec. on a mid-class system (Core 2 Duo 3.16, 4GB Ram, nVidia GForce 9600GT). Tasks during the actual exploration, e.g. viewpoint change, change of color scheme for global scope or widget interaction, could be performed at interactive rates (15 - 30 fps).

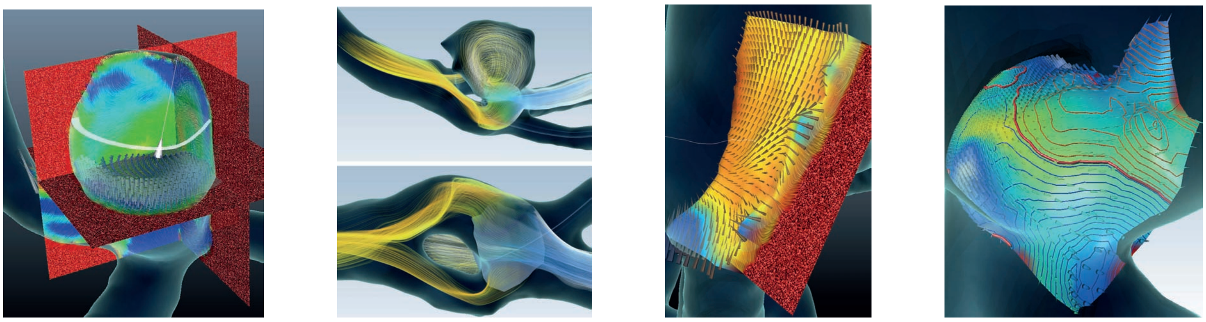
6. Informal User Feedback

We conducted three interviews with two board-certified radiologists (expert A / B), who were not involved in the initial design process. The goal was to gain qualitative feedback that will be used to design a quantitative study with a higher number of participants. The feedback from the first interview (expert A) was also used to gain more background knowledge as preparation for the second interview cycle (expert A / B). Our approach aims at satisfying the requirements (see Section 3.3) by providing three anatomy-driven scopes, visualization templates and guided interaction. Thus, the interviews were designed to find out, if the requirements were principally met and which details might need improvement.

During the interviews, the experts freely interacted with the exploration tools that were applied to the datasets An_01 to An_05. The interviews were divided into sections, one for every scope. The experts were asked to evaluate the feasibility and describe possible limitations of each scope. In the ostium scope, the experts were confronted with an alternative design, where an additional height field was used to visualize the volumetric flow and the flow direction was encoded with velocity-scaled colored glyphs (see Fig. 7(d)). This was the initial version of the ostium scope visualization, as it was presented to expert A in the first interview. The current version (no height field, desaturated equally scaled glyphs, short streamlines) was derived from the feedback of this interview. After the scope sections of each interview, we asked the experts to give an overall feedback about the usability of the multi-scope approach. To mimic an alternative, as it is given by current commercial flow analysis tools (e.g. Ensight), we abandoned the anatomy-driven constraints of our approach. We provided the opportunity to freely select from the same set of visualization techniques that were used in the different scopes and the experts where able to parameterize them. Additionally, the widgets of the local scope could be moved without axis-constraints.

The experts clearly preferred our approach over the unconstrained alternative. When working with the alternative, it could be observed, that both experts tried to mimic parts of our anatomy-guided approach. As an example, they put high manual effort in aligning the widgets with the centerline or central aneurysm axis respectively. Nevertheless, the experts stated that in rare cases an unconstrained interaction might be necessary and should be included as an option. Overall, the experts considered the multi-scope approach as suitable for the qualitative exploration of flow inside aneurysms. Also their order from global to local was appreciated. The three-scope design was stated to be complete, no additional scopes are needed. Regarding the global scope, the expert liked the idea of separate views for slow/fast flow and in-/outflow. The color scheme was considered comprehensible, although radiologists are used to a red-blue color scheme to encode velocities (e.g. ultrasound workstation). How to adapt the proposed color scheme to resemble the red-blue color scheme without losing visual details will be investigated in additional interviews and the final survey.

With respect to the ostium scope, the layout derived from the initial interview was considered to be suitable and provides all necessary information about the flow profile at the ostium. It was interesting to see that the experts had problems to interpret the scalar nature of the height field used in the initial layout. We suppose, that radiologists are more used to overlays (volumetric flow contour lines) than distorted geometry (volumetric flow height field). However, this needs to be investigated in further studies. The expert stated the blurred contextual flow rendering to be useful in special cases, but preferred to switch between global and ostium scope to relate between flow and ostium profile.



(a) An_02 (b) An_03 (c) An_04 (d) An_05

Figure 7: *Exploration of different datasets: The aneurysm exploration widget in translation mode in a large basilar aneurysm(a). The VISC dataset has a complex bifurcation below the aneurysm, the in-/outflow enhancement exhibits a central inflow (b). The parent vessel widget (c) and the ostium scope (d) applied to measured flow data.*

The handling of the widgets of the local scope was considered easy to learn. Even the more complex free rotation of the aneurysm exploration widget was not problematic. We assume that this is related to the fact that no additional viewpoint change is necessary to define the wanted rotation angle. The experts stated, that the information conveyed by the parent vessel widget was clearly understandable, yet, in some cases hard to perceive due to an unfavourable camera position. As an alternative, they suggested an additional viewport showing the widget profile in a static fashion or an adaptive camera that automatically finds a suitable view on the widget. The expert preferred the aneurysm exploration widget with its basic planar layout. The addition of orthogonal planes was stated to be very complex and only necessary in special cases and therefore should be optional.

The feedback, given by the experts, will be considered in the next iteration of our approach. This version will be evaluated in a number of expert interviews and the results derived from those interviews will form the basis for the design of a quantitative study. The design of this study will be oriented at the work of Laidlaw et al. [LKJ*05]. For each scope, the users will have to fulfil specific tasks, like finding and describing flow structures (global scope), finding features in the inflow profile (ostium scope) or navigating the widgets to provide detailed information about given spatial regions (local scope).

7. Conclusion

We presented a multi-scope approach that supports a workflow to visually explore flow at different levels: a global overview of flow in the aneurysm, the ostium flow profile and the local probing with special widgets for the aneurysm and the parent vessel. Informal interviews with radiology experts confirmed the general usefulness of three distinct scopes and guided interaction during widget placement. The feedback of the informal interviews will be used to further improve the approach and design an adequate user study.

In its current state, the applied visualization techniques are suitable to explore steady flow simulation results or a single time step of measured flow/unsteady flow simulation respectively. The global scope of our approach is suited to explore vortex structures within the aneurysm while our ostium scope represents in- and outflow regions at the ostium. Mantha et al. [MBHM09] have shown that those two features, the aneurysm vortex and the in-/outflow region, are stable over the phase of a pulsatile flow cycle. This is true for varying aneurysm shapes and can even persist, if the flow parameters are changed beyond normal physiological conditions. They conclude, that these two features may be analysed based on less time consuming steady flow simulations. Thus, in its current state, our approach fits to the requirement of this analysis task. However, even if Mantha et al. provide evidence that these two features might play a major role for the development of therapy strategies, it is still unknown which additional time-dependent parameters might also be important. The adaption of our anatomy-guided exploration approach to time-dependent data remains open for future work. Due to the planar layout used in the ostium and local scope, we believe it might be possible to include time as an additional visual dimension. However, new strategies are required to cope with the associated problem of visual clutter. Due to the three-dimensional nature of the global scope, an adaption to time dependent data makes it necessary to employ different visualization techniques. We assume that topological extraction may be appropriate to support this task. This needs to be researched in greater detail based on a broader range of datasets.

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