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Short Papers

Coherent View-Dependent Streamlines for Understanding Blood Flow

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Abstract

The expressive visualization of (time-dependent) 3D blood flow along with the vessel wall is essential for understanding vascular diseases. However, the high complexity of the underlying flow data makes the exploration challenging. For the biomedical research, it is necessary to provide methods that allow for rapid flow comprehension, ideally by emphasizing relevant flow characteristics. Therefore, we present a fast approach that visualizes streamlines in a view-dependent way, while taking relevant flow features into consideration. For this, we adapt a well-established non-photorealistic rendering technique – suggestive contours *– for surface meshes to streamline illustrations. The advantages of our approach are confirmed in an informal user feedback with domain experts, who were able to comprehend the overall flow behavior faster.*

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1. Introduction

Vascular diseases, e.g., severe stenosis or aneurysms at the coronary, renal, cerebral or abdominal arteries represent a major health problem. Aneurysm rupture, renal failure, cerebral stroke, and heart infarction are amongst the serious, often fatal consequences. The initiation and progress of vascular diseases is therefore an essential topic of biomedical research. The interplay between morphological changes of the vessel wall and features of the blood flow is an essential aspect. Blood flow data either results from simulation or in case of larger arteries from measurement, e.g., with Phase Contrast MRI. The simulations have the potential to improve treatment planning and the understanding of vascular pathologies [CCA*05, HMWea04]. For the visualization community, the exploration of the time-dependent 3D flow data along with the vessel wall is a crucial challenge. Not only relevant lines need to be identified and displayed; the visualization needs to be at real-time rates, view-dependent and frame-coherent. While previous approaches aimed at adding as much context as bearable [GRT13], we specifically target for a faster grasping of relevant features. Such filtering of salient, representative streamlines provides a help to grasp the patient's situation faster, as occlusion – and therefore the chance to miss clinically relevant features – is reduced. Thereby, the main challenge is to find a trade-off between emphasizing important features and still representing the context flow field, without causing visual clutter. Our approach to the problem is to employ a well-established set of lines – the Suggestive Contours by DeCarlo et al. [DFRS03] – which was frequently applied to surface illustrations. In order to depict the anatomical context, we integrate this surface illustration concept into our streamline visualization, achieving both view dependence and frame coherence, see Figure 1. To ensure the presence of relevant data, we additionally map characteristics like vortex flow to opacity and thus emphasize important regions in-

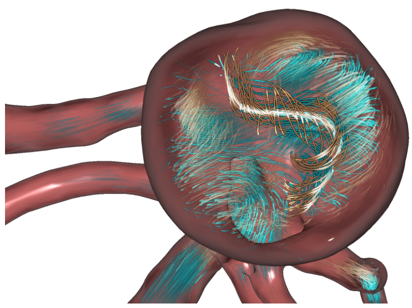

Figure 1: *Example of our visualization technique.*

dependent of the current view. Furthermore, we assess the effectiveness of our work in an informal user feedback and compare our method with existing approaches. Our line selection approach finally enables a swift, explorative navigation in *dense* blood flow data, due to its efficient nature. Particularly the faster comprehension of blood hemodynamics due to the emphasis of relevant features by context reduction has high potential to steer future aneurysm treatment.

2. Related Work

Streamlines, as a dense, geometry-based method for visualizing vector fields, gained much attention in the past [MLP*10]. To ensure representative illustrations, first streamline placement algorithms were designed for 2D vector fields [LHS08, LMG06, MAD05]. For 3D flow visualization, the problem is more challenging due to occlusion. An influential insight was that the choice of lines should be view-dependent [LS07]. By considering the occupancy of lines, Marchesin et al. [MCHM10] addressed occlusion in a greedy algorithm. Their approach was not frame-coherent and thus not applicable to interactive navigation. A view-dependent and frame-coherent approach was introduced by Günther et al. [GBWT11]. They attenuate the opacity of lines regarding the viewport. Xu et al. [XLS10] suggested an information-theoretic approach. This approach does not address occlusion. Lee et al. [LMSC11] proposed a maximum intensity projection of an entropy field to acquire a view-dependent metric that projects much entropy and at the same time minimizes occlusion. This greedy approach is not frame-coherent. McLoughlin et al. [MJL*13] introduced similarity measures for an interactive line clustering, yielding a reduced number of lines. Another view-independent clustering approach was presented by Yu et al. [YWSC12], who proposed a hierarchical streamline bundling for simplifying and visualizing streamlines. Tao et al. [TMWS12] linked the problem of selecting best lines and viewpoints to generate optimal camera paths, later extended for internal views [MWW*14]. Ma et al. [MWS13] approached frame coherence by using both a static set of lines and a view-dependent set of lines, which considers continuity between local views. So far, the approach is partially coherent, since popping artifacts are minimized, yet not completely avoided. Recently, Günther et al. [GRT13] presented a global strategy that is both view-dependent and frame-coherent, and accelerated and extended it to animated lines [GRT14]. While they provide as much context information as possible, we specifically reduce distracting context to enhance the comprehension of important areas. Moreover, blood flow is not everywhere dense. In fact, the space between the vessels is empty, making such exhaustive optimization not appropriate for exploration. Thus, we propose a combination of *view-dependent attenuation* of all streamlines and concurrently *view-independent emphasis* of important features, e.g., vortices. Therefore, we provide an alternative that is readily frame-coherent and excels in speed, both in terms of rendering performance – enabling larger line data sets – and faster comprehension due to the removal of distracting context.

3. Data Acquisition and Requirement Analysis

Although our approach is applicable to explore blood flow data in general, we are particularly motivated by blood flow in cerebral aneurysms. Cerebral aneurysms are a cerebrovascular disorder that is promoted by weakened vessel walls. A possible aftermath of a rupture is a subarachnoid haemorrhage, i.e.,blood leaks into the space around the rupture and can lead to a high fatality rate of 45%-75% [RRW*08]. First, we need to acquire medical image data like MRA, CTA or 3DRA of the vessel. Depending on the contrast, methods like thresholding, region growing or freehand drawing of contours are employed to extract a triangulated surface representation. The mesh quality is improved through remeshing and smoothing algorithms, see [MNP11, Sch97]. Then, a CFD simulation is used to determine a flow field. Inflow conditions are derived from 4D PC-MRI measurements. The vessel surface in combination with the obtained flow field establishes the basis for the visual exploration. A full visualization of the underlying blood flow leads to visual clutter. We focus on a view-dependent blood flow visualization such that features on the streamlines are emphasized. Based on discussions with our domain experts, we decided to emphasize the *vortex cores*. Therefore, we focus on representing streamlines by fading out unessential information.

4. Method

We briefly describe the suggestive contour method on which our streamline visualization is based. Afterwards, we explain the adaption of this technique to the shading visualization. Next, we consider features of the streamlines, i.e., their extraction and visualization in the context of other streamlines.

4.1. Suggestive Contour Method

Suggestive contours are view-dependent and of second order on surface meshes. These lines are defined as the set of minima of $n \cdot v$ in the direction of w, where n is the unit surface normal, v is the view vector (which points to the camera), and w is the projected view vector on the tangent plane:

$$D_w(n \cdot v) = 0, \text{ and } D_w D_w(n \cdot v) > 0. \quad (1)$$

First, one has to evaluate $n \cdot v$ per vertex. Afterwards, the gradient $\nabla(n \cdot v)$ is determined for each triangle. Next, the triangle gradient is used to determine the light gradient $l_i = \nabla(n_i \cdot v)$ for the i-th vertex. Finally, given the view vector v, the light gradient l_i, and the corresponding normalized vertex normal n_i, we project v onto the tangent space of the i-th vertex: $w_i = v - n_i n_i^T \cdot v$. Observing the profile of a surface mesh, one can state that the *suggestive contours* are defined at the inflection points. They describe the transition of a ridge to a valley and vice versa. Next, we adapt this idea to distinguish between flow which is convex and concave according to the observer. Lawonn et al. [LGP13] used this suggestive contour measure for vessels visualization.

4.2. Streamline Visualization

Given a streamline $S = \{\mathbf{p}_0, \mathbf{p}_1, \ldots, \mathbf{p}_n \,|\, \mathbf{p}_i \in \mathbb{R}^3\}$ with consecutive adjacent points $\mathbf{p}_0, \ldots, \mathbf{p}_n$. First, we need to compute the tangent vectors $\mathbf{t}_i$ of all points $\mathbf{p}_i$ by weighting the adjacent line segments according to their length:

$$\mathbf{t}'_i = (\mathbf{p}_{i+1} - \mathbf{p}_i) \cdot \|\mathbf{p}_{i+1} - \mathbf{p}_i\| + (\mathbf{p}_i - \mathbf{p}_{i-1}) \cdot \|\mathbf{p}_i - \mathbf{p}_{i-1}\| \quad (2)$$

$$\mathbf{t}_i = \frac{\mathbf{t}'_i}{\|\mathbf{t}'_i\|}, \quad (3)$$

for all $i \in \{1, \ldots, n-1\}$. For $i = 0$ and $i = n$, we choose $\mathbf{t}_0 = \frac{\mathbf{p}_1 - \mathbf{p}_0}{\|\mathbf{p}_1 - \mathbf{p}_0\|}$ and $\mathbf{t}_n = \frac{\mathbf{p}_n - \mathbf{p}_{n-1}}{\|\mathbf{p}_n - \mathbf{p}_{n-1}\|}$. In the next step, we determine the illumination according to Zöckler et al. [ZSH96]. Thus, we obtain light values l_i for every point $\mathbf{p}_i$. To determine the light gradient on the streamline connecting $\mathbf{p}_i$ and $\mathbf{p}_{i+1}$, we compute the light gradient on every segment:

$$\nabla l_{i,i+1} = (\mathbf{p}_{i+1} - \mathbf{p}_i) \cdot (l_{i+1} - l_i). \quad (4)$$

Finally, we get the light gradient ∇l_i of the point $\mathbf{p}_i$ by rotating the light gradient of the segments $\nabla l_{i,i+1}$ and $\nabla l_{i-1,i}$ onto the tangent space spanned by $\mathbf{t}_i$ and average them. Afterwards, we project the view vector v onto the tangent space of $\mathbf{p}_i$ and obtain w_i. With this, we gain a scalar field on the streamline by assigning $s_i = \langle \nabla l_i, w_i \rangle$ to every point $\mathbf{p}_i$ which is our definition for Eq. 1. Hence, we obtain:

$$D_{w_i}(n_i \cdot v) = s_i. \quad (5)$$

Using this equation, we can distinguish between convex ($s_i > 0$) and concave ($s_i < 0$) flow according to the observer. For $s_i = 0$ we obtain isolines, where for instance the view vector and the streamline normal are parallel to each other. Therefore, we can hide the convex flow which occludes important blood flow characteristics, e.g., vortex cores and we can set the concave flow opaque to preserve the surrounding flow. We employ the scalar field of Eq. 5 to map it to the transparency of the streamline points. If $s_i \geq 0$, then the transparency is set to $c \cdot s_i^{\alpha}$. Otherwise, $c \cdot |s_i|^{\beta}$, where c is a constant and α,β are user-defined values and comparable to the shading exponent. Furthermore, we clamp the values to the [0,1] interval. For our visualization we use two colors. Whenever s_i is greater than zero, we use orange (convex flow) and otherwise cyan (concave flow).

4.3. Vortex Detection

In the next step, we like to depict relevant features such as vortex cores in a view-independent manner. Therefore, we extract the vortices by the λ_2 criterion [JH95], for which we need the underlying flow vector field. Using the Jacobian matrix J, we determine $P = \frac{1}{4}((J + J^T)^2 + (J - J^T)^2)$ and calculate the eigenvalues. If the second-ordered eigenvalue is negative, we have a vortex. The smaller the λ_2, the stronger the vortex. We mirror and normalize the λ_2 such that the minimum becomes 1 and values greater or equal zero become zero. As a standard value we set the opacity to 1, if the normalized λ_2 exceeds the 95% quantile. Medical researchers are also able to choose a sector from which the transparency is set off. Therefore, a slider is provided where the user can adjust the thickness. Adjusting two different values λ_{min} and λ_{max} such that whenever the λ is in $[\lambda_{min}, \lambda_{max}]$ the opacity is set to 1. Furthermore, we offer the possibility to use different features instead the λ_2, e.g., speed.

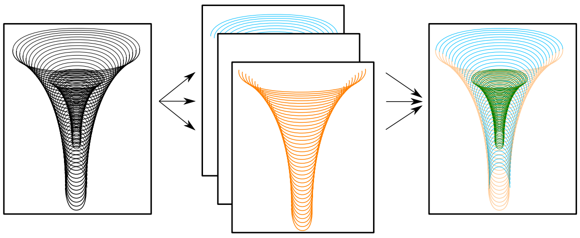

Figure 2: *In the first step, we use Eq. 5 to distinguish between convex and concave flow and detect the vortex core. Afterwards, we assign different colors and transparencies to the three parts and blend them.*

In summary, our method first distinguishes between convex and concave flow according to the observer. Furthermore, it detects important regions, e.g., the vortex core. Afterwards, the three parts are assigned different colors and transparencies. Finally, all fragments are blended using an order-independent transparency method [YHGT10]. Figure 2 illustrates our method.

5. Evaluation

We divide the evaluation into two parts. The first part is about a comparison between our method and [GRT13]. The second part contains an informal user feedback.

Comparison with other approach. The method by Günther et al. optimizes the opacity globally. For this purpose, the algorithm needs an *importance* in [0, 1]. Hence, we use the λ_2 value. The authors divided every streamline into a small number of segments n, averaging for each the *importance*, in Figure 3 we use $n = 10$ and $n = 30$. Hence, it may happen that streamline parts are averaged such that the most salient regions disappear. They can overcome this issue by increasing n, which in turn reduces the update rate of opacities. Furthermore, our approach can readily treat unsteady streamlines. In summary, the method by Günther et al. give visually pleasant results. With respect to the medical application, our method gives adequate visualizations and the parameters are intuitive. Moreover, the technique is much faster and allows for a swift navigation – even with a large number of lines.

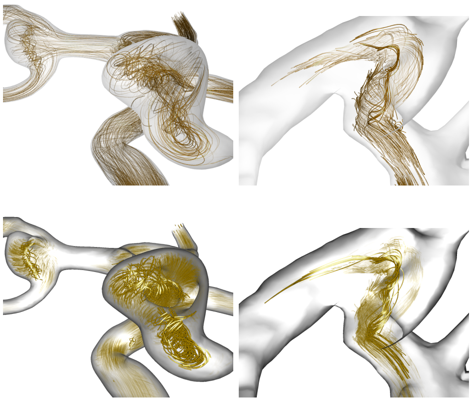

Figure 3: *The technique of Günther et al. [GRT13] (top), and our approach (bottom). Given the high number of streamlines (1.2k; 10k) ours is the only approach that obtains interactive frame rates (42 fps; 33 fps).*

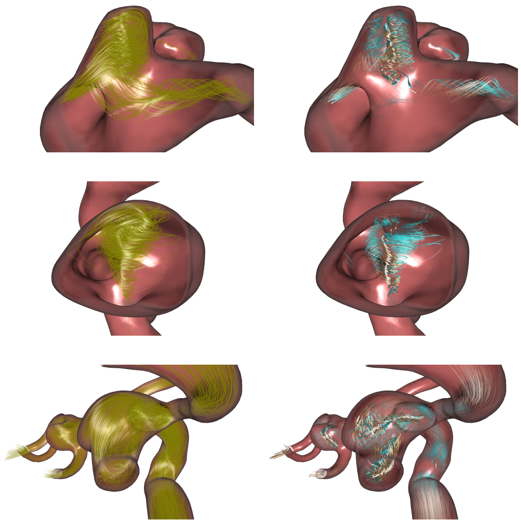

Figure 4: *The initial line set with semi-transparent visualization and our shading approach applied to CFD data from a cerebral aneurysm. The surrounding flow is depicted as well as the essential vortex core. Convex flow which would occlude the vortex core is visualized transparently to guarantee an insight in the vortex core.*

Informal User Feedback. We wanted to determine if our view-dependent approach reduces visual clutter and conveys the progress of the streamlines, see Figure 4. Furthermore, we analyzed if the parameters are intuitive and if the medical researcher is able to handle our framework. We chose five representative vessels with streamlines and asked one physician, two CFD engineers involved in hemodynamic analysis, and five researchers with background in medical visualization for their feedback. During the evaluation, we recorded the participants' spoken comments and the parameter set they were satisfied with. The participants were asked to explore the vessel and to adjust the specific parameters. It was also possible to switch between our technique and to visualize all streamlines with a fixed transparency.

Results. All participants were able to detect important streamline regions. Visualizing all streamlines with a fix transparency failed because of the shear amount of streamlines, which was confirmed by the CFD engineers and the physician. Especially in regions where a vortex occurs but the surrounding streamlines are laminar. The participants needed some time to become sufficiently familiar with the parameters. Most often, they were satisfied with the standard parameter setting. Therefore, only minimal changes were carried out. Furthermore, the participants perceived the view-dependent transparency as convenient. Some of the researcher asked for a different color coding of the vortex core to distinguish from the surrounding flow. Especially the physician asked for an information-based color coding of the vortex core, e.g., speed, whereas the surrounding flow should be illustrated in a subtle color. However, he / she stated that the representation gives a good visual impression of the important flow structures. However, the informal study does not allow for a definitive statement and requires further evaluation. In summary, our technique is able to depict the most relevant features and to denote the surrounding flow. Furthermore, the view-dependent fading is convenient and not disturbing. It gives a hint of the local progress of the flow. The discussion with the physician showed that our framework can be used for streamline analysis, since we provide the ability to emphasize certain features as well as whole streamlines. Therefore, providing an illustration of the vortex core and offer the possibility to change the vortex core size is essential for the examination. Thus, our framework is well suited for blood flow exploration.

6. Conclusion and Future Work

We presented a novel illustration method for streamlines by using the concept of an established feature line method, suggestive contours. Thus, we are able to emphasize only relevant characteristics of the streamlines. Our strategy is to fade out non-relevant characteristics dependent on the camera position. Based on this concept, we are able to provide a frame-coherent visualization technique. Our method was confirmed by a qualitative evaluation. Here, we assessed the ability to depict relevant features. An aspect of future work is to analyze the benefit of a different light position. Furthermore, we also think of substituting the underlying feature line method by a more recent technique, e.g. PELs, see [XHT*07]. Additionally, Pelt et al. [vPBB*10] provide a framework for interactively exploring 4D blood flow. We like to tie in with our method to achieve a visualization for 4D blood flow datasets.

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