Computers & Graphics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Technical Section

# Exploration of blood flow patterns in cerebral aneurysms during the cardiac cycle☆

Q1 Monique Meuschke[a,b,*], Samuel Voß[a,b], Bernhard Preim[a,b], Kai Lawonn[c]

[a] University of Magdeburg, Universitätsplatz 2, Magdeburg 39106, Germany
[b] Research Campus STIMULATE, Universitätsplatz 2, Magdeburg 39106, Germany
[c] University of Koblenz - Landau, Universitätsstraße 1, Koblenz, 56070 Germany

ARTICLE INFO

*Article history:*
Received 10 August 2017
Revised 19 January 2018
Accepted 31 January 2018
Available online xxx

*Keywords:*
Flow visualization
Clustering
Medical visualization

ABSTRACT

This paper presents a method for clustering time-dependent blood flow data, represented by path lines, in cerebral aneurysms using a reliable similarity measure combined with a clustering technique. Such aneurysms bear the risk of rupture, whereas their treatment also carries considerable risks for the patient. Medical researchers emphasize the importance of investigating aberrant blood flow patterns for the patient-specific rupture risk assessment and treatment analysis. Therefore, occurring flow patterns are manually extracted and classified according to predefined criteria. The manual extraction is time-consuming for larger studies and affected by visual clutter, which complicates the subsequent classification of flow patterns. In contrast, our method allows an automatic and reliable clustering of intra-aneurysmal flow patterns that facilitates their classification. We introduce a similarity measure that groups spatio-temporally adjacent flow patterns. We combine our similarity measure with a commonly used clustering technique and applied it to five representative datasets. The clustering results are presented by 2D and 3D visualizations and were qualitatively compared and evaluated by four domain experts. Moreover, we qualitatively evaluated our similarity measure.



## 1. Introduction

For the diagnosis and treatment assessment of cardiovascular diseases (CVDs), the analysis of patient-specific morphological and hemodynamic data is necessary [1]. This work focuses on cerebral aneurysms, characterizing pathologic dilatations of intracranial arteries. Their most serious consequence is their rupture leading to a subarachnoid hemorrhage (SAH), which is associated with a high mortality and morbidity rate [2]. In case of a rupture, a treatment is essential. A frequently used treatment option is *stenting*, where the flow is diverted from the aneurysm sac by an expandable medical implant (stent). However, treatment is also associated with a considerable risk of severe complications, such as post-treatment hemorrhaging, which can exceed the natural rupture risk [3]. In most cases an aneurysm is asymptomatic and will never rupture. But due to the poor prognosis of a SAH, aneurysms are usually treated. Thus, it is highly desirable to better understand the individual rupture risk and to restrict treatment to high-risk patients.

Unfortunately, the aneurysm progression and rupture depends on different factors such as genetics, morphological conditions and hemodynamics, where their interplay is not well understood [4]. Hemodynamic data are characterized by quantitative parameters such as Wall Shear Stress (WSS), and qualitatively, e.g., w.r.t. specific flow patterns, such as vortices. Moreover, flow patterns are assumed to be related to the success of treatment and their distance to the vessel wall seems to be an important factor for the assessment of the aneurysm's state [5].

To investigate the influence of flow patterns on the aneurysm's rupture, medical studies are performed [6]. Therefore, hemodynamic information are used that can be obtained by Computational Fluid Dynamic (CFD) simulations. Flow patterns are extracted and manually classified according to their *complexity* and *stability* during the cardiac cycle. The results were compared between ruptured and non-ruptured cases to identify characteristics associated with rupture. This is a time-consuming process in which flow patterns more distant to the wall are easily overlooked due to visual clutter and occlusion. To uncover correlations between flow patterns and the aneurysm state, more efficient analysis techniques are essential. This requires a reliable grouping of blood flow-representing path lines characterizing individual flow patterns.

☆ This article was recommended for publication by Stefan Bruckner

* Corresponding author at: Research Campus STIMULATE, Universitätsplatz 2, Q2 39106 Magdeburg, Germany.
*E-mail address:* meuschke@isg.cs.uni-magdeburg.de (M. Meuschke).

https://doi.org/10.1016/j.cag.2018.01.012

In this work, we present a method for an automatic clustering of blood flow in cerebral aneurysms over the cardiac cycle. Blood flow-representing path lines were integrated in simulated CFD data and clustered to obtain groups with similar flow behavior. For this purpose, we extend an established similarity measure for streamlines to path lines that incorporates their temporal component. To explore the behavior of individual flow patterns, we provide 2D views linked to a 3D depiction of the aneurysm wall and internal blood flow. The 2D views enable an occlusion-free visualization of flow patterns, including their distance to the vessel wall. The 3D visualization represents the focus upon which the exploration of morphological aneurysm characteristics together with the blood flow information over the cardiac cycle takes place. We integrate these techniques into a framework that we developed in collaboration with domain experts. In summary, we make the following contributions:

- An automatic clustering of intra-aneurysmal flow patterns over the cardiac cycle.
- A linked 2D and 3D view of the aneurysm surface and internal flow patterns for an interactive exploration.

## 2. Related work

Our work is related to partition-based blood flow visualization, as well as the visual exploration of aneurysm data.

### 2.1. Partition-based flow visualization

Partitioning techniques decompose flow into areas of common structure to investigate hemodynamics. Graphical representatives of flow regions can be computed to generate a visual summary or a subsequent visualization can be restricted to regions with specific properties, e.g., vortices. Such techniques are mainly based on integral curves, since in contrast to local vectorial flow data, they represent continuous flow patterns. The partitioning is performed in a user-guided [7–9] or automatic fashion [10–14]. Less frequently, local flow vectors [15] or aneurysm wall properties [16,17] are employed.

User-guided techniques partition integral curves based on *line predicates* (LP) [18], which are Boolean functions that decide if integral curves fulfill properties of interest. Gasteiger et al. [8] applied LP to CFD data of cerebral aneurysms to extract flow features, e.g., the *inflow jet* – the structure of high-speed, parallel aneurysm inflow and the *impingement zone* – the region where the inflow jet hits the wall with high impact. Based on this, a comparative visualization for evaluating various stent configurations was presented, integrating morphological and hemodynamic data [19]. Born et al. [7] utilized LP to identify relevant flow features such as jets and vortices in measured cardiac data. Köhler et al. [9] used different local vortex criteria as LP to filter path lines that represent aortic vortices.

Automatic techniques employ a data-driven approach and utilize clustering methods to group integral curves based on a similarity measure. McLoughlin et al. [14] introduced a streamline similarity measure by computing geometrical features based on the underlying vector field and used an agglomerative hierarchical clustering (AHC) with average link for partitioning. Their method was applied to time-dependent data by extracting the geometrical features from the vector field of the corresponding time step. However, the temporal component was not directly considered. Two geometrically similar path lines occurring in non-overlapping time intervals would have a high similarity. Oeltze et al. [13] compared multiple streamline clusterings in the context of aneurysm hemodynamics. Streamline similarities were computed based on line geometry [20]. They conducted a quantitative evaluation of k-Means, AHC, and spectral clustering (SC) w.r.t. cluster purity measures, where SC as well as AHC with average link and Ward's method performed best. Furthermore, a visual summary of blood flow was proposed, containing one representative streamline per cluster to reduce visual clutter. Englund et al. [10] employed a partitioning approach for the exploration of aortic hemodynamics. They used the Finite-time Lyapunov Exponent to measure the separation of path lines and coherent areas are derived. Liu et al. [11] measured path line similarities using an octree. The space is divided into cubes either by equidistant length or by adaptive length that depends on the features of the underlying vector field. A sequence is assigned to the path lines that incorporates the passed cubes, where the similarity is based on the longest common sequence. Meuschke et al. [12] compared multiple clustering methods of path lines representing aortic vortex flow. Path line similarities were computed based on the spatio-temporal coordinates of line endpoints and the line's average distance to the vessel centerline. AHC with average link performed best in separating vortices.

We introduce a time-dependent clustering of flow-representing path lines by extending an eligible approach for streamline clustering [20]. In contrast to the streamline similarity measure by McLoughlin et al. [14], our method directly incorporates the temporal component. If a flow pattern occurs, decays and reoccurs during the cardiac cycle, our method results in several clusters. This is required, since stability of flow patterns is an important criterion in medical studies to predict the rupture risk [6]. Existing methods are not able to represent instable flow patterns by different clusters. Moreover, compared to existing time-dependent clustering approaches [11,12], we are not dependent on the centerline or the underlying partitioning of the space.

### 2.2. Visualization and exploration of aneurysms

To visualize the aneurysm morphology, Hastreiter et al. [21] presented a direct volume rendering (DVR) method. Tomandl et al. [22] introduced a standardized vessel depiction using DVR for a more objective assessment of the aneurysm morphology.

Several works parametrize the aneurysm surface to generate more abstract representations. Goubergrits et al. [23] mapped the aneurysm to a uniform sphere to analyze statistical WSS distributions. Meuschke et al. [24] generated a 2D aneurysm map by using *least squares conformal maps* [25] that provides an occlusion-free overview visualization. Tao et al. [26] presented the *VesselMap*, a 2D mapping of an aneurysm and parent vasculature formulated as a graph layout optimization problem.

For the simultaneous exploration of anatomical and vectorial flow data, Gasteiger et al. [27] introduced the *FlowLens*, an interactive focus-and-context approach. However, outside the lens area, the flow cannot be observed. To improve this, Lawonn et al. [28] provided a vessel visualization such that the morphology can be better perceived and the flow is always visible. For a more detailed analysis, Neugebauer et al. [17] developed a qualitative exploration of near-wall hemodynamics in cerebral aneurysms. Several 2D widgets are used to simplify streamlines at different surface positions. Gambaruto et al. [29] analyzed flow features that are potentially related to aneurysm rupture. They extracted critical points related to WSS, vortices and surface shear lines, which are visualized using standard techniques such as glyphs, vortex-isosurfaces, and streamlines. Lawonn et al. [30] presented a framework for an occlusion-free blood flow visualization by using illustrative techniques. Meuschke et al. [24] extended this approach to investigate morphological and hemodynamic data simultaneously by providing a low-occlusion 2.5D view linked to a 3D aneurysm depiction.



Please cite this article as: M. Meuschke et al., Exploration of blood flow patterns in cerebral aneurysms during the cardiac cycle, Computers & Graphics (2018), https://doi.org/10.1016/j.cag.2018.01.012