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Technical Section

VesselMap: A web interface to explore multivariate vascular data ☆

Jun Tao [a,*], Xiaoke Huang [b], Feng Qiu [c], Chaoli Wang [a], Jingfeng Jiang [d],
Ching-Kuang Shene [e], Ye Zhao [b], Daphne Yu [c]

[a] Department of Computer Science and Engineering, University of Notre Dame, Notre Dame, IN 46556, United States
[b] Department of Computer Science, Kent State University, 800 East Summit Street, Kent, OH 44240, United States
[c] Siemens Corporate Technology, 755 Colledge Road East, Princeton, NJ 08540, United States
[d] Department of Biomedical Engineering, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, United States
[e] Department of Computer Science, Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, United States

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ABSTRACT

Hemodynamics plays a key role in the pathological evolution of vascular diseases such as vascular stenosis, plaques and aneurysms. Augmented visualization of relevant hemodynamic and geometric data accelerates engineering designs of diagnostic and therapeutic methods for those vascular diseases. However, four dimensional (4D) hemodynamic data are intrinsically complex. Consequently, exploration of this information has not been streamlined, despite its importance. In this paper, we propose a web interface to explore multivariate hemodynamic data, thereby facilitating the visualization of spatial and temporal relationships among those hemodynamic parameters of interest. The main thrust of this web system is the proposed VesselMap methodology, a 2D representation of vessel structures that provides an overview of all query results without any visual occlusions. Furthermore, in this framework, quantile–quantile plot was also used to compare spatial variations in parameter distributions, thereby greatly aiding in extracting local characteristics of hemodynamic parameters.

Using "patient-specific" computational fluid dynamics (CFD) simulations, realistic flow velocity fields were obtained. Based on those CFD-simulated velocity fields, we performed an empirical evaluation to confirm the usefulness of our approach for biomedical engineering applications. We concluded that the proposed VesselMap methodology allowed users to rapidly interact with hemodynamic data of interest, enhancing efficacy of information retrieval.

1. Introduction

Visualization of medical data has already been used extensively to show anatomical structures topologically using photo-realistic surfaces or volume rendering. Moving forward, a more integrated visualization approach is needed in order to quantitatively connect processes of a disease with abnormalities at various spatial and temporal levels in biomedical research. Integral to this approach is an efficient way to retrieve quantitative information from complex medical data. In this work, visualization of vessel data in and around cerebral aneurysms was used to demonstrate a novel web-based visualization approach of this kind. Vascular data in this paper are referring to complex three-dimensional geometric data, hemodynamic data (e.g., time-resolved 3D blood velocity) and other parameters derived from hemodynamics.

We envision that visual exploration of hemodynamic parameters and their spatial distributions facilitates engineering design of therapeutic methods toward treating cerebral aneurysms. Benefits of having such a web-based visualization tool are twofold. First, the proposed tool provides a flexible but systematic way for biomedical engineers to explore flow data with their own criteria. For instance, some vascular stents were designed to open up arteries (i.e., structural integrity of vessel) while other stents were designed to divert blood flow. Second, interdisciplinary studies of this kind often involve researchers located at different geographical locations. A web-based tool will enable collaborative reviewing of experimental or computer simulation results, reducing burdens on engineers for conducting a large-scale study. Furthermore, we intend to provide an unobscured viewing of 3D and 4D vessel data which may enhance the collaborative reviewing process over the Internet. It is recognized that labeling a 3D volume in a consistent way and communicating it with peers over the Internet could be a difficult task, because the relative positions of vessel branches may vary due to the change of viewpoints. Now there are a large amount of time-resolved flow data spatially

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* Corresponding author.

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registered with the vessel anatomy. Web-based collaborations involved in quantitative flow analysis without the right tools would be much more difficult.

Toward this end, we propose VesselMap, a novel web-based solution to assist biomedical experts in reviewing vessel data and analyze the relationships among different properties of blood flow. The VesselMap is centered on a scheme that enables 2D illustrative visualization of parameters for true 3D or 4D data. Using this scheme we first flatten the 3D vessel structure and its corresponding parameters onto a 2D plane. Then, all subsequent interactions can be operated in 2D. This provides an easier way to specify and label regions of interest and eliminates potential (angle-dependent) viewing occlusions. It also serves as a clearer and paper-friendly overview, since rotation and zooming are not available on a printed report. Furthermore, a segmentation scheme is used to divide data into sub-groups for any parameters of interest, in order to provide comparative investigations of flow characteristics. Data from sub-groups generated from the aforementioned segmentation scheme can be effectively displayed on the same 2D illustration, and their inter-group differences are evaluated and displayed in a difference matrix. It is worth noting that an inherited benefit of the proposed visual exploration method stems from the availability of statistical information, such as histograms of different properties. Users can query flow characteristics within the entire volume or a region of interest by simply interacting with histograms. The proposed system is flexible and can be adapted for different applications. Particularly, in this paper, some benefits of the aforementioned visualization strategy are going to be demonstrated through visualization of particle transport in and around cerebral aneurysms. Clinical applications include deliveries of chemical agents to either dissolve clots in the blood stream [1], or occlude vascular aneurysms [2,3] and stop hemorrhage from ruptured aneurysms or arteries [4]. Flow visualization is also important for designing flow-diverting stents to occlude cerebral aneurysms or bleeding sites. Finally, the web-based environment places a minimum amount of effort to setup and requires only the displayed information to be transferred.

2. Related work

Computed tomography angiography (CTA) is commonly visualized with *maximum intensity projection* (MIP) and *direct volume rendering* (DVR) techniques. To enhance the perception of vessel structures, researchers often approximate the vessel surface using model-based or model-free surface rendering approaches. The model-based surface rendering approach utilizes the information of centerline and radius, and approximates the vessel surface using models, such as truncated cones [5], B-splines [6], subdivision surfaces [7], or convolution surfaces [8]. The model-free surface rendering approach extracts the isosurface using algorithms such as marching cubes [9] based on a given threshold. Instead of approximating the vessel surface, Lathen et al. [10] proposed spatially varying transfer functions. This approach locally shifts the transfer function to enhance the perception of low intensity structures. Mistelbauer et al. [11] used halo rendering to enhance the lumen of a vessel structure. Schumann et al. [12] used the multi-level partition of unity implicits (MPUI) approach to reconstruct the surfaces.

Unlike approaches based on MIP or DVR, other approaches flatten the vessel structures and map the corresponding information to 2D images. One of the commonly used approaches in this category is *curved planar reformation* (CPR). Kanitsar et al. [13] introduced CPR as a curved cutting through the data set along the centerline of a single vessel. Then, they extended the CPR approach to multi-path CPR (mpCPR) that supports multiple vessel branches and spiral CPR that flattens the vessel along a spiral to show its interior [13]. Kretschmer et al. [14] extended the mpCPR approach and used a bilateral filtering to remove undesired depth discontinuities. Mistelbauer et al. [15] proposed an approach based on CPR that aggregates the information around the centerline along circular rays. Borkin et al. [16] introduced a 2D vessel visualization method that uses a tree diagram to represent the structure of a coronary artery tree. Each branch is straightened and displayed as a tape with varying widths, which represents the diameter of the vessel. Zhu et al. [17] presented a work that produces a flattened visualization of vessel branches. Two algorithms were proposed in this work. The first one is a conformal mapping algorithm by minimizing two Dirichlet functionals, and the second one adjusts the conformal mapping to produce a flattened representation that preserves areas. Marino and Kaufman [18] flattened treelike structures based on their extracted skeletons. A radial planar embedding was adopted to layout the skeleton on a plane. Neugebauer et al. [19] designed a multi-perspective 2D projection map. Combined with a standard 3D visualization, a correlation tool was provided to make correspondence between the 2D map and 3D model. Won et al. [20] presented an uncluttered single-image visualization of vascular structures The centerlines were first extracted, so that the vascular structures could be represented by multiple tubes. Each tube was then laid out on 2D by minimizing a score function to avoid occlusion. Instead of flattening the vessel structures, Neugebauer et al. [21] selected appropriate viewpoints to reveal the anatomic characteristics of cerebral aneurysms.

Other than scalar volumes, vascular data sets often come with a simulated blood flow field as well. Recently, different flow visualization techniques have been developed specifically for these data sets. van Pelt et al. [22] used various techniques to depict the blood flow and associated characteristics in different styles, together with an evaluation to measure the value of those visualization styles. Köhler et al. [23] extracted vortices in blood flow data sets using line predicates and highlighted the corresponding regions. van Pelt et al. [24] proposed to semi-automatically place and align a probe in the blood flow field, which serves as a seeding basis. Then, particles, integral lines and integral surfaces are used to convey distinct characteristics of the flow field. Born et al. [25] found the representatives of a line bundle, and used streamtapes with arrow heads to visualize the line bundles. The tape-like structure provides a clear picture of how the representatives diverge and merge. Oeltze et al. [26] proposed to cluster the streamlines and use the cluster representatives for a clear view. They conducted a qualitative study on using different similarity measures, including geometry-based similarities and attribute-based similarities. Angelelli and Hauser [27] presented a solution to straightening tubular flow for side by side visualization, which facilitated the comparison of different visualizations or time steps of the same flow.

Due to the presence of multiple fields, some vessel visualization approaches also provide contextual information. Straka et al. [28] proposed VesselGlyph which combines both DVR and CPR. It depicts the vessels using CPR which is naturally placed in a DVR anatomic context. Mistelbauer et al. [11,15] provided optional context rendering that displays the volume outside the lumen of vessel as well. Gasteiger et al. [29] presented a focus+context approach called FlowLens that uses some predefined lens templates to combine visualization results of different properties. The property of focus and property in context are both selected by the users. Lawonn et al. [30] introduced an adaptive surface visualization of vessels to highlight the animated pathlines and emphasize nearby surface regions. Lawonn et al. [31] combined the blood flow animation with wall thickness visualization. The wall thickness was mapped onto the vessel surface, which could