Visualizing Carotid Stenoses for Stroke Treatment and Prevention

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Abstract

Analyzing carotid stenoses – potentially lethal constrictions of the brain-supplying arteries – is a critical task in clinical stroke treatment and prevention. Determining the ideal type of treatment and point for surgical intervention to minimize stroke risk is considerably challenging. We propose a collection of visual exploration tools to advance the assessment of carotid stenoses in clinical applications and research on stenosis formation. We developed methods to analyze the internal blood flow, anatomical context, vessel wall composition, and to automatically and reliably classify stenosis candidates. We do not presume already segmented and extracted surface meshes but integrate streamlined model extraction and pre-processing along with the result visualizations into a single framework. We connect multiple sophisticated processing stages in one user interface, including a neural prediction network for vessel segmentation and automatic global diameter computation. We enable retrospective user control over each processing stage, greatly simplifying error detection and correction. The framework was developed and evaluated in multiple iterative user studies, involving a group of eight specialists working in stroke care (radiologists and neurologists). It is publicly available, along with a database of over 100 carotid bifurcation geometries that were extracted with the framework from computed tomography data. Further, it is a vital part of multiple ongoing studies investigating stenosis pathophysiology, stroke risk, and the necessity for surgical intervention.

CCS Concepts

• ***Human-centered computing*** → ***Scientific visualization;*** • ***Applied computing*** → *Life and medical sciences;*

1. Introduction

A crucial component of clinical stroke care and prevention is the detection, classification, and possibly surgical removal of arterial stenoses, i.e., local vessel constrictions which are often due to atherosclerotic plaque. The majority of strokes, about 87%, are caused by restricted blood flow to the brain [DFMD08]. A predilection site for stenosis development is the carotid bifurcation, where the brain-supplying internal carotid splits off the common carotid artery. Therefore, sophisticated clinical workflows are in place for screening the carotids. Typically, a computed tomography angiography (CTA) and a sonographic assessment are used to determine the morphological and hemodynamic properties of potential stenoses. Physicians face multiple challenges when analyzing the resulting images. The derivation of geometrical properties of a stenosis, e.g., the shape, length, minimal diameter, and plaque distribution from slice-based depictions is not intuitive, as multiple successive images need to be mentally combined. Yet, a comprehensive understanding of these parameters is central to determining the ideal treatment approach. Furthermore, integrating the results from multiple modalities, like CTA and sonography, is challenging. Important hemodynamic properties, such as peak velocity and the extent of poststenotic turbulence, are only visible using Doppler sonography. However, many morphological parameters are better derived from CTA imaging. Additionally, we frequently heard that the skill of the physician executing the screening is highly correlated with the quality of the results. A central value is the *stenosis degree*, since it is used as a threshold determining the need for surgical intervention [FEB*99]. It can be attained from both CTA and sonography, however, our clinical collaborators repeatedly alluded that considerable fluctuations of the stenosis degree exist depending on observer and modality, limiting its validity in practice.

The clinical decisions made in acute stroke care and stroke prevention are highly case-specific. The risk of stroke always needs to be weighed against the risk of complications from intervention and different surgical strategies exist, e.g., plaque removal or stent insertion. The pathophysiology of developing stenoses and the interplay of anatomical and hemodynamic factors are not yet fully understood. Therefore, the decision for intervention is often based on few measurable factors and strongly relies on the impressions and experience of the attending physician. Due to the prevalence

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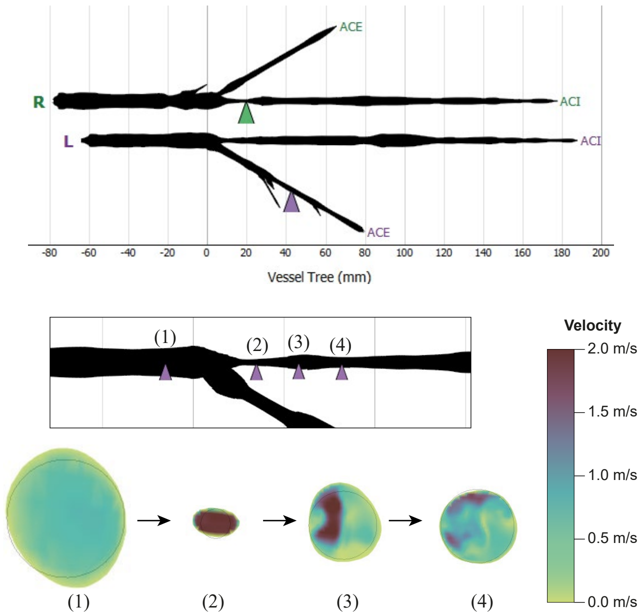

Figure 1: *Map of the carotids (top). The user can drag a probe to explore cross-sections of the flow (bottom). Usually, the velocity profile should be homogeneous with slower flow in proximity to vessel walls (1). Velocity increases in stenoses (2), followed by visible turbulence (3, 4).*

of stroke, stenosis formation and risk assessment remain a major research area [Gor19].

The project outlined in the following is a collaboration between visualization and hemodynamic simulation researchers, as well as radiologists and neurologists working in stroke care. To address the challenges outlined above, we refined the most promising methods from blood vessel and flow visualization and adapted them for the exploration of carotid hemodynamics and morphology [EMKL21]. On this basis, we developed novel methods for the spatiotemporal exploration of vascular models employing map-like abstractions [EMML22, ERM*21]. Further, we introduce tools to efficiently detect stenoses and perform automatic, highly accurate stenosis degree classification [EvDH*23]. At the core of this work lies a multi-stage, unified software framework, which combines pre-processing and data exploration tools, making them readily available to clinical practitioners and researchers. We use interactive visualizations for data inspection and adaption that guide the user through the processing stages. We could show that streamlining data processing and enabling retrospective user control have a major impact on user trust in medical visualization pipelines and increase the data validity, ultimately making sophisticated visualization systems usable in routine. Our developed framework has a modular and extendable architecture and is available as an open-source platform: `https://github.com/PepeEulzer/CarotidAnalyzer`.

2. Visualizing Stenosis Morphology and Hemodynamics

Recent advances in computational fluid dynamics (CFD) make deriving blood flow properties entirely on the vascular geometry increasingly conceivable [CL13, SHS18, SRT*20]. Computed flow information could substitute or complement sonographic assessments, as the vascular geometry can be extracted reliably from CTA volumes. Using CFD, high-resolution hemodynamic information can also be gained from stenotic regions where ultrasound signals are distorted or occluded. As dedicated methods for exploring the derived flow properties of stenoses were lacking, we adapted and refined a combination of techniques from flow visualization for this purpose, coupling spatiotemporal navigation, dimensional reduction, and contextual embedding. The methods were developed and evaluated with an interdisciplinary group of medical practitioners, fluid simulation, and flow visualization researchers [EMKL21]. The core user tasks we filtered in this process are comprised of analyzing the flow field itself, integrating it with the anatomical context, exploring wall-related parameters, and deriving objective markers to classify the stenosis and suggest the ideal treatment approach. If stenosis candidates are found, the spatiotemporal data space needs to be navigated to assess relevant attributes such as its diameter, length, and peak blood flow velocity. We found that map-like abstractions are particularly suitable to handle overview, navigation, and partly even quantification of data attributes in vessel trees. Such *vessel maps* have been used extensively in various visualizations of cardiovascular structures, however, they were largely developed independently of one another and no guidelines for their creation existed. Therefore, we distilled the core properties and application areas of vessel maps and provide a taxonomy in a state-of-the-art report [EMML22], upon which we base the development of our methods.

2.1. Visualizing and Contextualizing Flow

Flow visualization methods were developed specifically for aneurysms, aortic blood flow, and nasal air flow [MVE*22, OJMN*19]. We extend this line of research by investigating how clinically relevant insights can best be gained from flow in stenoses. When exploring the hemodynamics of a stenosis, physicians are particularly interested in quantifying flow velocities and assessing the occurrence of turbulence depending on the temporal flow evolution. In practice, they also often compare these attributes in the left and right side carotid. We facilitate these tasks in an aggregated exploration framework composed of multiple linked views [EMKL21]. We show a 3D reconstruction of the vessel with integral lines giving an overview of the flow field. Based on the velocity field, we compute the inlet flow rate, which we plot over the simulated cardiac cycles. The plot is used as an intuitive framing for the simulation time and can be directly used to navigate the temporal dimension. For focus-and-context probing of the spatial dimension, we developed a vessel map that shows the vessel branches and diameter (see Figure 1). The map is simultaneously used to provide an overview that is unaffected by 3D occlusion and to enable efficient spatial navigation. By dragging a marker across the map, the user sets a probe that is automatically oriented in the 3D scene to produce an orthogonal cross-section of the vessel volume. The probed section is shown directly below the map and a property of the flow field, usually the velocity, is color mapped.

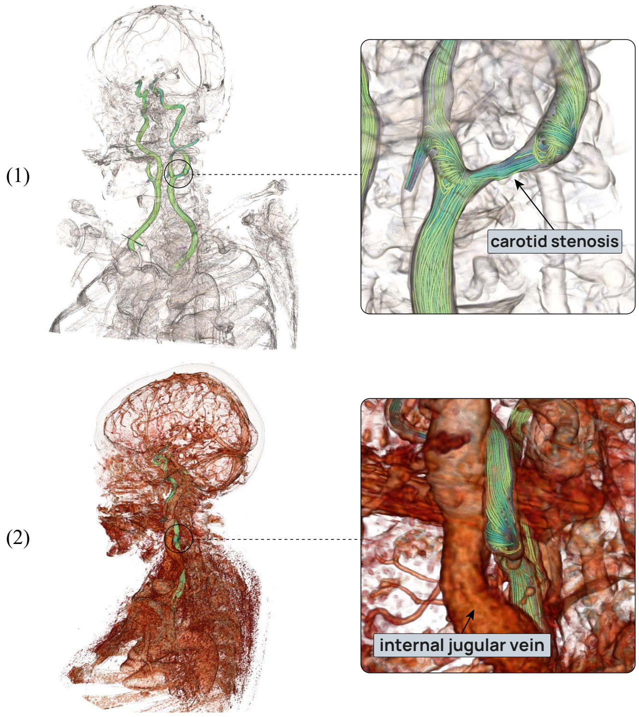

Figure 2: *The contextual volume rendering shows that a stenosis is located in the upper neck area (1). Adjusting the thresholding and opacity (2) reveals that the internal jugular vein is in front of this stenosis, potentially complicating surgery.*

For continued analysis, the flow field needs to be viewed in the context of the vessel morphology, wall composition, and surrounding anatomy. Using the traditional approach of dual modalities, CTA and sonography, linking the dynamic flow and static morphology information is not directly possible. By deriving the flow field from the CTA volume, we can integrate the information in a uniform depiction. The user can enable a contextual volume rendering where we embed the 3D vessel reconstruction (see Figure 2). To implicitly regulate the transfer functions, we provide controls over the image intensity threshold and opacity. With this, the position of a stenosis can be intuitively understood. The volume rendering is particularly helpful to explore neighboring anatomical structures which might be at risk if surgery is considered. Furthermore, to analyze the wall composition, the cross-sectional probes not only slice the flow volume but also the CTA image. Thus, when probing the vessel, the user can not only explore the internal blood flow but also the vessel wall to, e.g., analyze the occurrence of plaque. In a user study with an interdisciplinary focus group (two radiologists, two neurologists, and two fluid mechanics researchers), we saw that the vessel map was extensively used as a navigational tool. The physicians reported that dragging the marker on the map is exceptionally well suited for probing, as they could instantly and intuitively evaluate the lumen diameter, shape, and condition of the wall over a picked vessel segment.

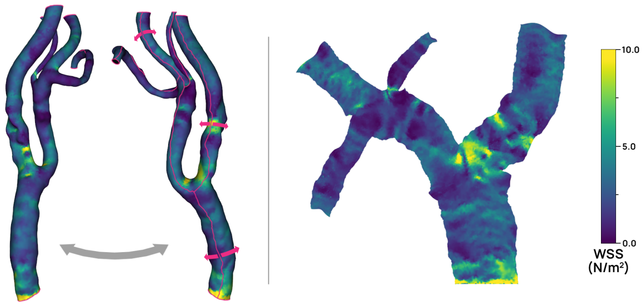

Figure 3: *A surface parameter (wall shear stress) is color mapped to a carotid artery. In a 3D projection (left) interaction is required to examine the whole surface. We developed a fully automatic method to cut and flatten vessel trees, which shows the full surface while retaining its proportions and layout (right).*

2.2. Visualizing Wall-Related Parameters

Some wall-related parameters, like plaque thickness, directly influence clinical decision-making. Others, like wall shear stress, are of particular interest to researchers investigating stenosis formation. In both cases, exploring these fields on the vessel wall encounters issues. Slice-based views require mental reconstruction of many images, while 3D surface renderings necessitate interaction and may be self-occluding. A solution is the transfer of the surface geometry to the 2D domain, creating a vessel wall map. Existing approaches for the flattening of vessel surfaces, however, either create patches and do not show a continuous domain [AS04, BGP*11, GSK*12], do not preserve the surface area [MK15], or only consider a very limited region of the vessel with a specific geometry [CCR20]. We proposed a novel method to cut and flatten vascular geometry that results in an intuitive mapping between the 3D and 2D domains [ERM*21]. It is a global approach that creates a single patch and results in minimal area distortions while keeping the layout close to the original structure. On top of that, it is fully automatic, requires no user interaction, and the sole input is the uncut vessel geometry. For an intuitive mapping, we introduce *natural vessel cuts*, which follow the orientation of the vessel branches and thus result in a comprehensible unfolding of the geometry. They are a global solution for minimizing deviation from the minimal principal curvature of the surface and do not suffer from the ambiguities that exist when using a centerline projection to create the cuts. After cutting, we compute an as-rigid-as-possible surface parameterization that maps the geometry to the 2D domain as a single patch. We fix the inlet boundary to generate evenly oriented results. An example is shown in Figure 3. While developed in the scope of this project, the method is generic and can be applied to any similarly complex tube-like surface. The created wall map resolves the need for tedious 3D interaction as the whole surface is visible at once. We found the map particularly beneficial for exploring temporal surface attributes.

2.3. Objectifying Stenosis Degree Computation

A fundamental factor in carotid screening is the classification of stenoses according to a standardized stenosis degree, where 100%

corresponds with total occlusion. When deriving the stenosis degree from CTA images, the minimum inner diameter of the vessel is compared to the normal poststenotic diameter. Measuring these values, however, is not a trivial task and our clinical partners unanimously claimed that the resulting degree is subjective to the observer. To derive an objective quantification, we propose an automatic classification of the stenosis degree based on the extracted model, which we use to compute numerically optimized diameters [EvDH*23]. Our method builds on a centerline fitting approach that maximizes the radius of inscribed spheres [AEIR03] and, therefore, computes the minimal internal radius at any point of the model. We display this information to the user in two linked views. One shows diameter plots of the vessel branches, the other a 3D view of the vessel surface. Candidates for stenoses can be easily spotted as local minima of the diameter plots. By brushing a region of interest in the plot, the user can set local thresholds for stenosis classification. The selected region is segmented and visually highlighted in the 3D model. The computation of the stenosis degree is instant and automatic and we display the result next to the corresponding region in each view (see Figure 4). If required, the user can also read out additional information, such as the computed diameters and the stenosis arc length.

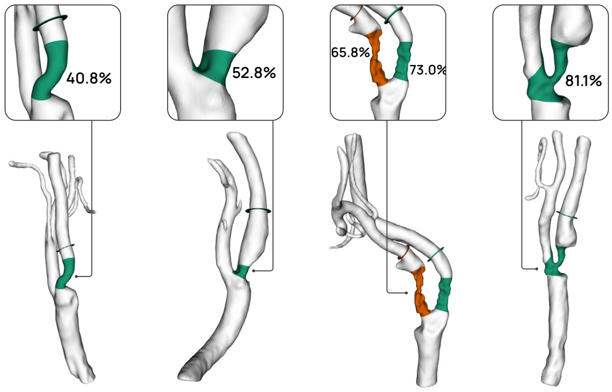

Figure 4: *Exemplary results of the stenosis classifier with increasing stenosis degree from left to right. The disc glyph marks the sampling point for the poststenotic reference diameter.*

3. Enabling Clinical Applicability

Model-based vessel visualization provides a wide range of specialized tools for aiding clinical analysis tasks. It also opens up the possibility of automatic feature classification as, for instance, demonstrated by the stenosis degree computation. The drawback is that advanced model-based vessel visualizations tend to have a high adoption cost, as they typically depend on multiple fragmented tools for data curation and processing. This issue may also negatively impact user trust. With highly processed data, how can users assure the correctness of what they see? Recently, we approached this challenge by proposing a fully integrated pipeline for segmentation, pre-processing, and visual analysis of the carotids [EvDH*23]. The pipeline interface enables interactive and retrospective user control over all data processing stages. We target increasing user trust by making the underlying data validatable on the fly, decreasing adoption costs by minimizing external dependencies, and optimizing scalability by streamlining the data processing.

The sole input to the pipeline are unmodified CTA scans. In the image volume, the user can select a region around the carotid bifurcation, which is then automatically cropped and propagated to a convolutional neural network that we trained to predict labels for carotid lumen and plaque. The network uses a U-Net architecture from MONAI [CLBe22]. In most cases, it creates quite accurate segmentation results in less than a second. If the result needs to be corrected, we provide multiple manual tools to perform quick corrections directly within the pipeline interface. Based on the extracted vessel model, centerlines and radius information are computed, where the user can change which branches are of interest in a visual interface. As the pipeline is build as a modular framework, the user can then immediately switch to a visualization module, where the processed data can be explored. Stenoses can be directly assessed and classified based on the extracted vessel geometry. If computed flow fields are to be explored, we provide tools to export the vessel geometry and import flow fields, as accurate CFD simulation may take up to several hours and is currently limited to non-time-critical applications.

We tested our framework in the clinical workflow of four neurologists who treat stroke patients. We found that visualizing the processing steps and enabling retrospective control allows users to better understand the different processing stages and assure the correctness of what they see. In some of the cases, the stenosis degrees determined by the physicians with our framework differed considerably from the degree given in the patient's radiology report. Remarkably, when asked which value they thought to be more accurate, all participants claimed they would rather trust the application than the report, as they found the numerical derivation comprehensible and were able to assure the correctness of the geometry.

4. Conclusion

We presented a collection of adapted and novel techniques to visually explore the morphological and hemodynamic properties of stenosed vessels. We developed tailored visualizations of parameters used in clinical stroke treatment and prevention, as well as research on stenosis risk assessment. Our target users repeatedly reported that the developed methods make experimenting with suspected stenosis sites considerably more effective than when relying on image-based representations only. We found that integrating visually guided data extraction and visualization into a single framework considerably increases user trust in the depictions and makes on-site pre-processing a viable option for clinicians. The framework is currently in use and has been applied to process and analyze over 100 carotid bifurcation geometries [EL23]. It is open-source and built to be easily extendable. Also, it is a pivotal component of two ongoing studies. One compares hemodynamic properties over a collective of 60 stroke patients to investigate the impact of flow on the pathophysiology of carotid stenoses. In the other, the framework is used to compute stenosis degrees which are a component of a prediction model for stroke risk assessment.

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