AVM-Explorer: Multi-Volume Visualization of Vascular Structures for Planning of Cerebral AVM Surgery

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Abstract

Arteriovenous malformations (AVMs) of the brain are rare vascular disorders characterized by the presence of direct connections between cerebral arteries and veins. Preoperative planning of AVM surgery is a challenging task. The neurosurgeon needs to gain a detailed understanding of both the pathoanatomy of the lesion as well as its location and spatial relation to critical functional areas and white matter fiber bundles at risk. A crucial element during this planning phase is the precise identification of feeding arteries, draining veins, and arteries "en passage". To this end, a variety of imaging modalities for displaying neurovascular structures exists, both tomographic as well as projection based. However, the conventional 2D slice based review of such data is not well suited to help understanding the complex angioarchitecture of an AVM. In this paper, we demonstrate how state-of-the-art techniques from the fields of computer graphics and image processing can support neurosurgeons with the challenge of creating a mental 3D model of the lesion and understanding its internal structure. To evaluate the clinical value of our method, we present results from three case studies along with the medical assessment of an experienced neurosurgeon.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques; I.3.8 [Computer Graphics]: Applications—; J.3 [Life And Medical Sciences]: Health—

1. Introduction

Arteriovenous malformations (AVMs) of the brain are vascular disorders that affect roughly 0.01 - 0.5% of the population. They are characterized by the presence of direct connections between arteries and veins which bypass the capillary bed normally responsible for deoxygenation of arterial blood and the transfer into the venous system. This vascular short-circuit is typically comprised of numerous coiled and convoluted connections, that form the nidus of the lesion. The nidus is comprised of feeding arteries, draining veins, and additional "en passage" vessels, supplying both the AVM as well as important functional areas of the brain.

A precise understanding of the underlying angioarchitecture is a necessary prerequisite for treatment. Especially for a neurosurgical approach, it is crucial to identify all feeding arterial branches beside the draining veins, as this directly affects the surgical strategy. During surgery, all feeding arteries must be ligated prior to the draining veins, in order to prevent rupture of the nidus and intraoperative hemorrhage. Ligation of "en-passage" arteries must be avoided, as this would cause insufficient oxygen supply of connected parts of the brain accompanied by the risk of postoperative neurological deficits.

In this work, we present a system that aims to support neurosurgeons with the difficult task of forming a 3D model of the complex vascular configurations found in cerebral AVMs. It consists of a dedicated image processing pipeline in combination with a state-of-the-art multi-volume renderer that facilitates simultaneous visualization of multiple vascular datasets. The goal of this approach is to facilitate an intuitive understanding of the lesions angioarchitecture, the configuration of feeding arteries and draining veins, as well as its spatial relation to structures at risk inside the brain. This work has been strongly motivated by real-world clinical requirements. Considering the rare occurrence of cerebral AVMs in conjunction with the substantial technical chal-

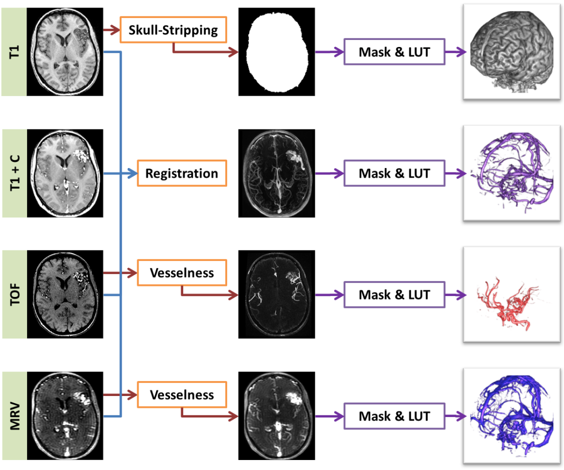


Figure 1: *Schematic overview of our processing pipeline.*

lenge posed to the intervening neurosurgeon, the tremendous potential of presurgical support by means of a 3D patient-individual data workup becomes apparent.

2. Methods

Our visualization framework incorporates a combination of 3D-T_1-weighted images with and without contrast agent, arterial time-of-flight images (TOF), and also MR-Venographies (MRV). Optionally, color-coded DTI images may be embedded into the visualization. Since the quality of the preprocessing results is crucial for the clinical review of the data, we chose to implement a supervised semi-automatic approach for brain segmentation and image registration. The workup for each case can be performed by a medical assistant and requires at most 10 minutes for a trained user. All additional processing steps are calculated fully automatic. In detail, the following processing steps are performed:

2.1. Brain Segmentation

As a first preprocessing step, a segmentation of the brain from the skull is performed. We implemented a semi-automatic approach based on an interactive watershed transformation on a T_1-weighted MRI image [HP00]. The algorithm exploits the connectivity of the brain through the white matter. It is a marker-based approach, that typically requires between 5 and 20 markers to be placed within the image in order to obtain a proper brain segmentation mask. Subsequently, all other datasets are masked with the brain segmentation mask obtained from this step.

2.2. Multimodal Registration

For the purpose of visualization of multiple vascular datasets, a precise matching of the different MRI sequences is mandatory. We utilize a supervised rigid registration process, which incorporates an automatic registration algorithm based on normalized mutual information (NMI) similarity measure [WVA*96], along with the option to manually refine the automatically obtained results. Ultimately, the medical assistant supervising the preprocessing decides on the final registration result.

2.3. Vesselness Filtering

To enhance vascular structures within the images, we apply a multi-scale vesselness filter that has originally been proposed by Frangi et al. [FNVV98]. It is based on an analysis of the Eigenvalues of the images Hessian matrix at multiple scales. The resulting structure tensor can be evaluated, by analyzing the configuration of its Eigenvalues, which differs for tubular-, sheet- or blob-like structures. Subsequently, a vesselness measure can be calculated, which describes for every image voxel its similarity to being part of a tubular structure. The vesselness filter yields excellent results in improving contrast of the vascular tree, especially for the arterial TOF data. For the clinical evaluation, we applied a three-scale vesselness analysis with a Gaussian sigma ranging from 0.3 to 1.4 mm on the arterial TOF images.

2.4. Morphological Brain-peeling

For the arterial TOF images, it may be necessary to attenuate bright structures close to the brain's surface. Such structures may result from the vesselness filter's response to the brain surface. Visually, this results in a halo-like artifact around the surface of the brain, which may occlude the view inside the brain. To handle such artifacts, we implemented a morphological brain-peeling technique that directly modifies the affected datasets using a combination of simple morphological image processing operators. As a first step, a Euclidean distance transformation is calculated on the brainmask obtained from the skull-stripping step. We use the distance map to evaluate a Gaussian function with mean value zero, and a width that corresponds to the depth of the attenuation. The resulting image is inverted, such that its values are transferred into a range between $[0..1]$ and multiplied with the original image. This causes structures within the set attenuation range to be gradually attenuated, instead of being clipped away sharply.

3. Multi Volume Visualization for Surgical Planning

To facilitate interactive exploration of the available datasets, we incorporate direct multi-volume rendering with individual transfer-functions, clipping-planes, and illumintation parameters per volume. Technically, we utilize a dynamic volume rendering framework based on a scene graph, which

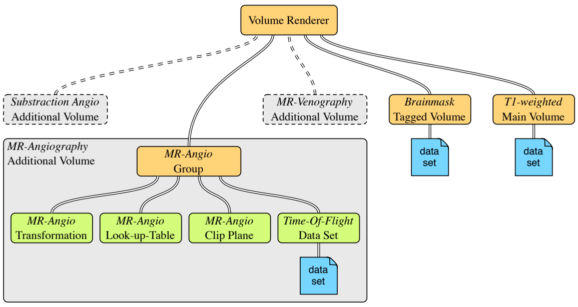


Figure 2: *Illustrative description of the multi-volume rendering scene graph. Every additional volume has corresponding child nodes for clipping, transfer function and the volume texture.*

allows multiple datasets to be appended to the volume rendering dynamically at run-time. Corresponding shading parameters, clip planes and transfer functions can be controlled interactively by the user. Figure 2 illustrates the scene graph for multi-volume rendering. For every additional volume, a subgraph with child nodes of the corresponding visualization parameters is connected to the main volume renderer.

3.1. Independent Clip Planes

To avoid visual cluttering when exploring multiple datasets at the same time, we implemented independent clip planes for each volume included in the rendering. To prevent interaction from becoming too complicated, the orientation of all clip planes is controlled by a master clip plane defined in the 2D viewer. For each individual clip plane, an offset can be defined allowing the user to control how far any volume is supposed to be clipped. When using clip planes in combination with illuminated volume rendering, shading artifacts appear due to falsely calculated gradients along the clip plane. To prevent these, we use the inverted clip plane normals as gradient at the clip plane's boundary [WEE03].

3.2. Focus Of Attention

To allow a focused analysis of the AVM lesion without being distracted by the large number of unaffected vascular structures, we implemented a focus of attention technique. The focus of attention defines the area around a point of interest which can be enhanced in the volume rendering. The focus point is defined in the 2D slice rendering. For every voxel in the final rendering, the distance to the focus point is calculated in a shader, and the color saturation and alpha value are manipulated using a customizable distance measure [RRRP08]. Thus, structures outside the area of interest, such as unaffected vessels, can be attenuated intuitively by the medical expert using a combination of desaturation and transparency manipulation.

4. Results

The software has been installed in the radiology department of our clinical partner, where it has been used to retrospectively analyze three AVM cases that have undergone surgery during the years 2008 to 2010. Analysis of these cases was done by the same neurosurgeon who had performed the actual neurosurgical procedures. The potential usefulness of our application for preoperative planning is discussed by summarizing the findings based on our tool, accompanied with documentations of how they correlate with intraoperative findings.

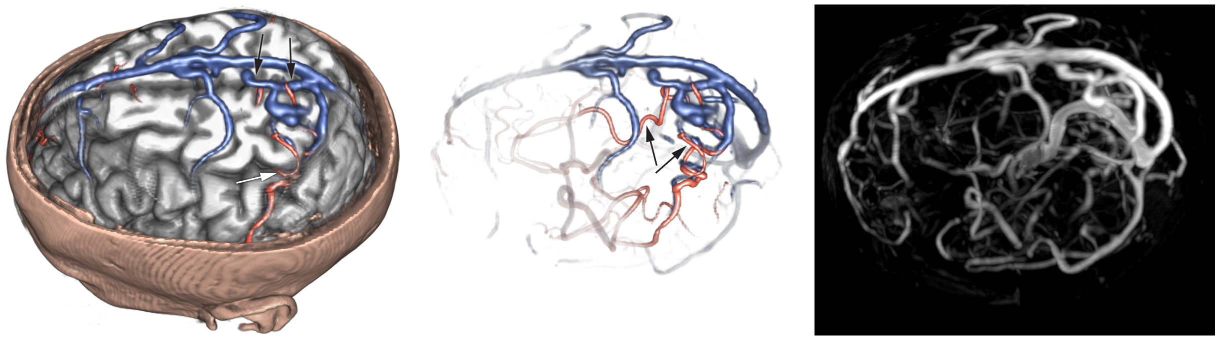
The analyzed cases consist of AVMs classified as Spetzler Martin Grade II and III [SM86]. In two cases, the AVM was located in close proximity to the Broca area required for speech generation. Consequently protection of the language system was the primary challenge in these cases. The third case was a relatively small AVM located in the sensory strip with proximity to the motor cortex, leading to an increased risk of postoperative lower extremity paralysis or paresis. Here, the AVM was located deeply inside a sulcus so there was no surface representation other than the draining vein. Understanding the topography and relation to the motor strip was critical in this case.

In all three cases, our visualization application provided critical understanding of the precise location of the AVMs. MR-Angiography and MR-Venography datasets were used for the identification of the venous drainage pattern and the exact location of the feeding vessels. The focus of attention proved helpful to reduce visual clutter of unimportant vessels. Furthermore, the topography of the feeding arteries in relation to the venous drainage and cortical anatomy was visualized using the clip plane technique. Essentially, the visualization allowed the surgeon to visualize exactly what he encountered during surgery, along with the location of the feeders, and most importantly, identification of “en passage" vessels.

Particularly for the first case, the neurosurgeon concluded, that the volume visualization would have been invaluable for surgery planning. It allowed him to visualize exactly what to expect during surgery without the need for “mental gymnastics” when trying to fuse the 2D data mentally. Visualization of a critical “en passage" artery correlated perfectly with what had been found intra-operatively. Also, understanding of the topography of the lesion would have been significantly simplified, simplifying exploration of the gliotic plane which is important to avoid straying into the normal adjacent cortex and white matter.

5. Discussion and Conclusions

Our volume visualization specifically targets the task of identifying arterial and venous vessels involved with cerebral AVMs. It allows fusing anatomical structures simultaneously with additional vascular, and functional datasets.



(a) (b) (c)

Figure 3: *Visualization results for one case. In (a), the location of the draining veins (black arows) can be explored, incorporating the brain's anatomy. Image (b) shows the a focus view of the lesion identifying feeding arteries (black arrows) and the draining veins. For comparison, in (c) a conventional MIP rendering of the MR-Venography is presented.*

This work has been primarily motivated by the clinical challenge posed to neurosurgeons during the preoperative analysis and risk assessment of AVMs. The multimodal visualization allows a neurosurgeon to intuitively grasp the three-dimensional architecture of an AVM nidus, along with its extent and spatial relation to functionally critical structures. Furthermore, feeding arteries and draining veins can be identified easily utilizing the combination of MR-Venography and TOF-MRA datasets. This simplifies the challenging process of mentally fusing the various dataset in order to form a mental 3D model of the lesion, particularly if a complex angioarchitecture is present. Furthermore, identification of "en-passage" vessels is supported using this technique. This is critical during surgery planning, as disruption of a vessel that is merely supplying branches to the AVM but continuing on to supply critical motor or speech regions would result in poor surgery outcome.

A potential drawback of our method is caused by the circumstance that partially ambiguous presentations of parts of the vascular tree in arterial and venous images could potentially lead to misinterpretation of the data. This, however, relates to the image acquisition technique itself, as opposed to the visualization technique. It needs to be addressed by making careful exploration of all available datasets mandatory during planning, in order to specify the precise nature of the vessels surrounding the AVM nidus. Another aspect relating to the necessity for careful data exploration is the fact that depending on the window settings of transfer function of a dataset, the impression of the lesions size will vary, causing a potential risk of underestimating the lesion's true size. The latter points underline the requirement for careful exploration of all datasets, which needs to be assured by the neurosurgeon performing the preoperative planning.

Overall, our preliminary evaluation indicated a high clinical value of our visualization methods, especially for planning surgery of higher grade AVMs. The performing neurosurgeon repeatedly stated how much the possibilities of the 3D visualization would have helped him plan and perform the resection. For selected cases, he rated the visualizations as invaluable, emphasizing that he would not want to miss such techniques in the future. Consequently, we are planning to perform a prospective clinical evaluation of our method. Beside that, inclusion of CTA and DSA Images into our visualisation is planned for the future.

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