Visualizing the path of blood flow in static vessel images for Image Guided Surgery of Cerebral Arteriovenous Malformations

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ABSTRACT

Cerebral arteriovenous malformations (AVMs) are a type of vascular anomaly consisting of large intertwined vascular growth (the nidus) that are prone to serious hemorrhaging and can result in patient death if left untreated. Intervention through surgical clipping of feeding and draining vessels to the nidus is a common treatment. However, identification of which vessels to clip is challenging even to experienced surgeons aided by conventional image guidance systems. In this work, we describe our methods for processing static preoperative angiographic images in order to effectively visualize the feeding and draining vessels of an AVM nidus. Maps from level-set front propagation processing of the vessel images are used to label the vessels by colour. Furthermore, images are *decluttered* using the topological distances between vessels. In order to aid the surgeon in the vessel clipping decision-making process during surgery, the results are displayed to the surgeon using augmented virtuality.

1. INTRODUCTION

Due to the topological complexity, anatomical variability between subjects, and relative fragility of cerebral vasculature, angiographic images are critical for the planning of most modern neurosurgical procedures. Prior to a surgical procedure, neurosurgeons seek to familiarize themselves with a patient's particular vascular anatomy to use as landmarks in surgery and also in order to prevent their accidental damage. In the case of neurovascular surgery, a surgeon will also spend a significant amount of time understanding the structure, path, and branching of a patient's vasculature before and during the intervention.

The process of reviewing and understanding the vessel paths through the parenchymal anatomy is especially time-consuming for procedures involving the resection of arteriovenous malformations (AVMs) of the brain. AVMs are abnormal vascular pathologies consisting of anastomoses of tangled blood vessels where high pressure blood feeding from multiple arteries (*feeders*) shunt directly into engorged weakened veins (*drainers*) without first passing through smaller vessels and capillaries. Due to the abrupt change in fluid pressure, the central mass of the tangled arteries and veins of the AVM, known as a nidus, can rupture and cause severe hemorrhaging, which may result in death.[1] AVMs can also result in non-lethal complications such as epileptic seizures,[2] headaches, and various neurological and cognitive deficits.[3]

Treatment of AVMs includes one or a combination of (1) radiation, (2) embolization, (3) feeder ligation, and (4) surgical resection.[4] In the latter case, the feeding vessels are first clipped to restrict blood flow into the nidus, the draining vessels are clipped, and afterwards, the deflated AVM nidus is resected. The task of clipping the vessels is not trivial due to the difficulty of identifying feeding and draining vessels when viewing the preoperative images or during the actual procedure. This is greatly complicated by the fact that the paths of the AVM vasculature leading into the nidus are tortuous and may not conform to standard topology or known anatomical locations.[5] Furthermore, clipping the wrong vessels may cause the AVM to rupture or alternatively, may cut off blood flow to other regions of the brain.

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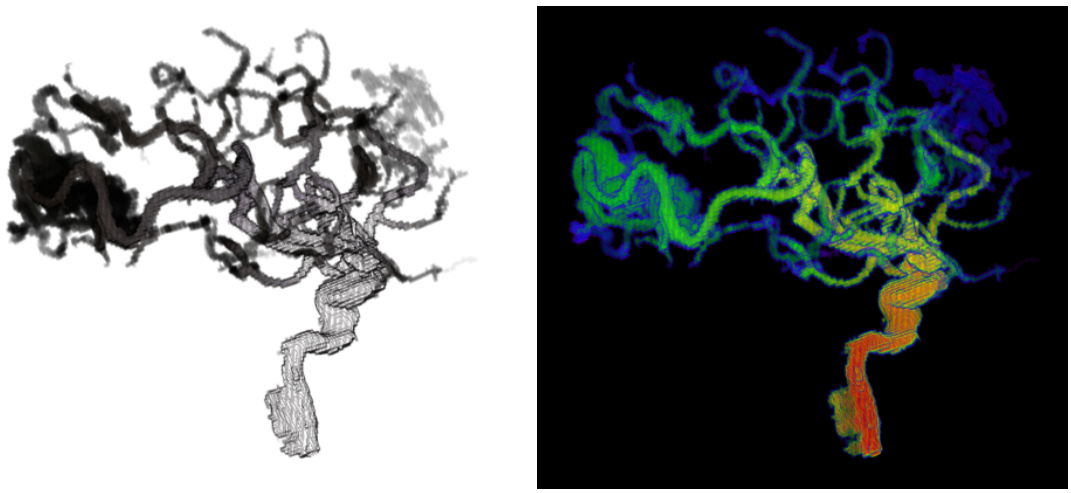


(a) (b)

Figure 1. The flow time map of a carotid artery visualized with (a) its normalized values from 1 to 0 and the same values (b) mapped to spectral hues. The map was generated through level-set front propagation from a seed placed at the base of the carotid artery.

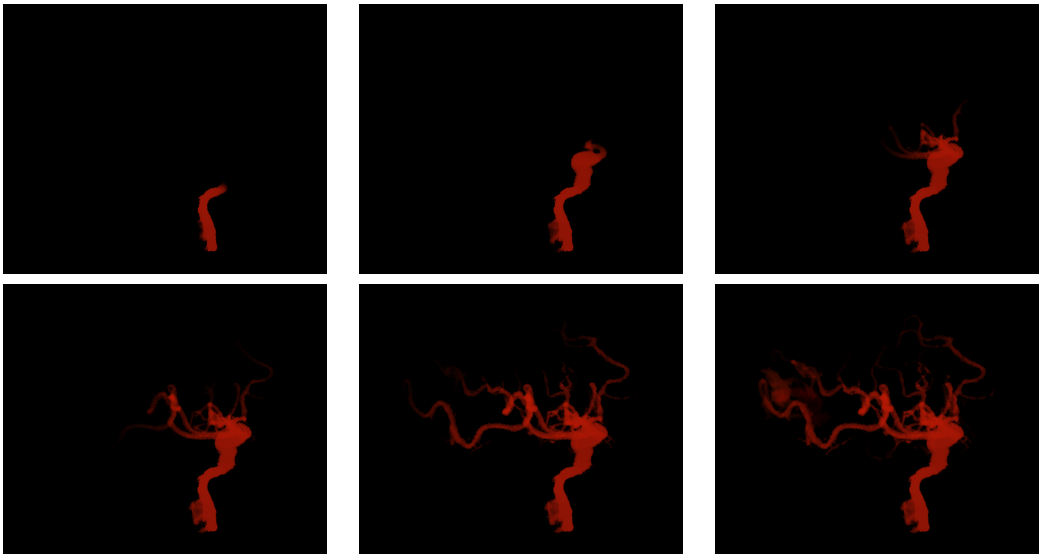


Figure 2. The flow time map of the right carotid artery displayed with different flow time thresholds. The map is the same as the one visualized in Fig. 1.

A simple method from the visualization of blood flow is to use a time-to-colour mapping, such as the spectral (rainbow) colour visualization used in Siemens' *syngo iFlow*[*]. In such a visualization, increases in image intensities in time is mapped to a rainbow spectrum (see Fig. 1b). Another simple visualization method is to render the timed intensity of a contrast bolus in digital subtraction angiography (DSA) with a transparency value (alpha value) cut-off (see Fig. 2). While both such visualizations can effectively show the blood flow path through the branches of a vessel tree, they are typically not as useful for a surgeon since they do not provide sufficient visual cues near the AVM nidus to properly identify which vessels are connected to the nidus, much less, whether a a particular vessel is a feeder or drainer. Furthermore these visualization techniques require the acquisition of time-series images. As such, such visualizations cannot be applied directly nor can they be used for visualization of static vascular images.

Recently, Wieler et al. (2011)[6] proposed a method to improve visualization of cerebral AVM vasculature.

[*]`http://www.siemens.com/press/pool/de/pressemitteilungen/2009/imaging_it/HIM200905040e.pdf`

This method involves preprocessing data from various MR arterial and venous imaging modalities and displaying them in red and blue, respectively. Their method also used the vessel's viewing distance as a focus mechanism for suppressing vessels outside of a region of interest closer to the view plane.

Although straightforward, direct combination and visualization of arterial and venous datasets does not necessarily enable differentiation between the AVM's feeding and draining vessels. Any one of the vessel imaging modalities can ambiguously capture both arteries and veins, and incorrectly label them with the wrong colour. Furthermore region focus and decluttering based on view distances may undesirably highlight vessels adjacent to an AVM nidus but otherwise disconnected from the pathology itself.

This necessitates the development of an AVM vessel visualization method capable of (1) visualizing the course of blood flow, (2) labeling the feeding and draining vessels according to the flows entry and exit from the nidus, (3) decluttering the view scene of less relevant vasculature, and (4) displaying the visualization to a surgeon intra-operatively.

Our proposed visualization method should allow the surgeon to more effectively identify and understand the structure and course of blood flow into the AVM nidus, thus reducing the time needed to locate the feeding arteries and draining veins of the AVM intra-operatively, and also preventing the erroneous clipping of vasculature. This can result in the improved precision of the intervention and subsequently contribute to a patient's surgical outcome.

1.1 Contributions

The contributions of this visualization work are four fold:

1. **Enabling blood flow visualization in static images**: Level-set flow propagation is used to visualize blood flow in static images.
2. **Explicit colour labeling of nidus feeding and draining vessels**: The simulated blood flow was used to explicitly label AVM feeders and drainers.
3. **Surgical scene decluttering using topological distances**: Vessel topological distance information was used to declutter the surgical scene.
4. **Intra-operative AVM visualization**: Display the proposed visualization intra-operatively using augmented virtuality (AV).

2. METHODS

2.1 Vessel Processing

In order to effectively visualize the course of blood flow in conventional static 3D blood vessel images, we need to first synthetically compute and record the time at which the front of a contrast bolus entering a vessel structure will flow through each continuous part of the vessel tree. We will refer to this bolus flow time in the paper as the "flow time".

Our initial datasets consist of static angiographic images, which may include a wide variety of 3D images such as, computed tomography digital subtraction angiography images (CT-DSA), 3D X-ray angiographic images (3DXA), or magnetic resonance angiographic (MRA) images. We processed these datasets using the fast marching method introduced by Sethian (1996)[7] to simulate and visualize flow time of the vessel. The fast marching algorithm is a level-set front propagation method, which evolves a level-set curve based on the intensities in an image. The algorithm produces a map of when in time the front of the level-set curve crosses certain voxels in the volume. By propagating the level-set front through the vessels in the raw images, the paths and time of blood flow in the vessels can be estimated. The vessel images to be processed were first manually seeded to identify the starting locations for front propagation. Given the starting seed point (defined below), the fast marching algorithm runs on a 3D image until all the voxels contained in image have been visited or an end seed point has

been reached. We used the *Toolbox Fast Marching* package[†] implementation of the algorithm in Matlab (The Mathworks, Inc.) for our processing.

For our visualization processing, level-set propagation was run on three raw vessel datasets from a single patient. They consist of (a) one combined arterial and venous-phase CT-DSA image acquired using a Toshiba Aquilion ONE (Toshiba Medical Systems) with an isotropic 0.5mm resolution and (b) two 3DXA images with selective vessel contrast injection acquired using the GE Advantx LC LP+ Biplane Angiographic System (GE Healthcare) with an isotropic 0.4mm resolution. Since feeders branching from ramifications of the right carotid artery and left vertebral artery supplied the patient's AVM, X-ray imaging contrast agent was injected into each of these two arteries for the 3DXA acquisitions.

For proper visualization of the feeding and draining vessels of the AVM nidus, we chose to place seeds in:

1. **The center of the AVM nidus in the CT-DSA image**: One starting seed was placed in the centre of the AVM nidus and the level-set propagation was allowed to run until all non-zero voxels in the image had been reached. This resulted in a flow time map extending from the seed at the nidus to all connected vessel segments in the image. Although this image is effectively the flow time map of the course of blood flowing out of the AVM nidus, we refer to this map as the "*AVM distance map*" since it also properly shows the topological distance from the AVM nidus to any vessel segment in the image.
2. **The right carotid artery 3DXA image**: Two seeds were placed, the starting seed at the beginning of the right carotid artery and the ending seed in the AVM nidus (the same point as that which was used to generate the AVM distance map). This produces a flow time map beginning at the base of the carotid artery to the location of the nidus seed.
3. **The vertebral artery 3DXA image**:Two seeds were placed, the starting seed at the beginning of the left vertebral artery and the same ending seed within the AVM nidus. This produces a flow time map starting from the beginning of the left vertebral artery, which then abnormally crosses to the right hemisphere towards the location of the nidus seed.

The implementation takes approximately 1 hour of processing for each 512×512×180 volume. As this is done pre-operatively the processing time was not a factor. The resulting flow time maps were then normalized from 0 to 1 with the starting seed having the value of 1 and the more distal vessels having a value less than 1 but larger than 0. The background voxels are assigned a value of 0. The map of flow time computed from front propagation can be seen in Figure 1a, with the real values ranging from 1 to 0 mapped from white to black, respectively.

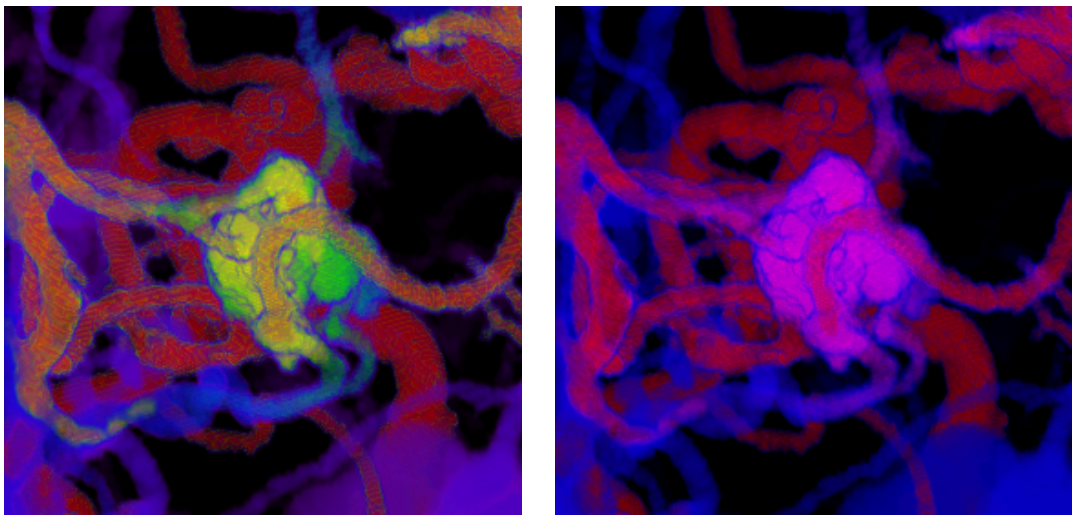
In order to see how the blood flow from the two supplying arteries feeds into the AVM and drains out from the AVM into the surrounding veins, the two 3DXA flow time maps, which showed the blood supplies feeding the AVM nidus, were combined with the AVM distance map (i.e. the CT-DSA flow time map), which showed the course of blood draining out the AVM nidus. This was done by adding 1 to all the non-zero values of the 3DXA flow maps, and then replacing all voxel values in the CT-DSA image that were lower than the 3DXA image with the voxel values of the latter. The combined image is then normalized between 0 and 1. This processing results in a "*combined flow map*" where the values starting from the two supplying arteries begin at 1 and steadily decrease as they lead toward the AVM nidus center set with a value of 0.5, and then from the nidus to the ends of the large veins (value > 0).

2.2 Visualization of Vessel Blood Flow

Visualization of vascular blood flow can be accomplished most simply by adjusting the volume rendering transfer function to map the real numbers of flow time to the colour or the alpha in the manner desired as seen in Figs. 1 and 2, respectively. However these visualizations are of limited use in neurosurgery and as such, more sophisticated methods for showing AVM blood flow are needed.

For the volumetric visualization of the AVM vasculature, we employed a view-aligned volume renderer first described by Jalal et al. (2006),[8] which renders a volume as 2D planes that have been sliced perpendicularly to the view axis toward the view plane from the back to the front.

[†]http://www.mathworks.com/matlabcentral/fileexchange/6110/



(a) (b)

Figure 3. Two different colour mapped visualizations of the flow time focused on the AVM and its surrounding vessels with (a) a spectral colour mapping giving details on the location and courses of each feeding and draining vessel, and (b) a red and blue colour mapping, showing the arteries and veins in the canonical vessel colours.

2.2.1 Feeding and Draining Vessels

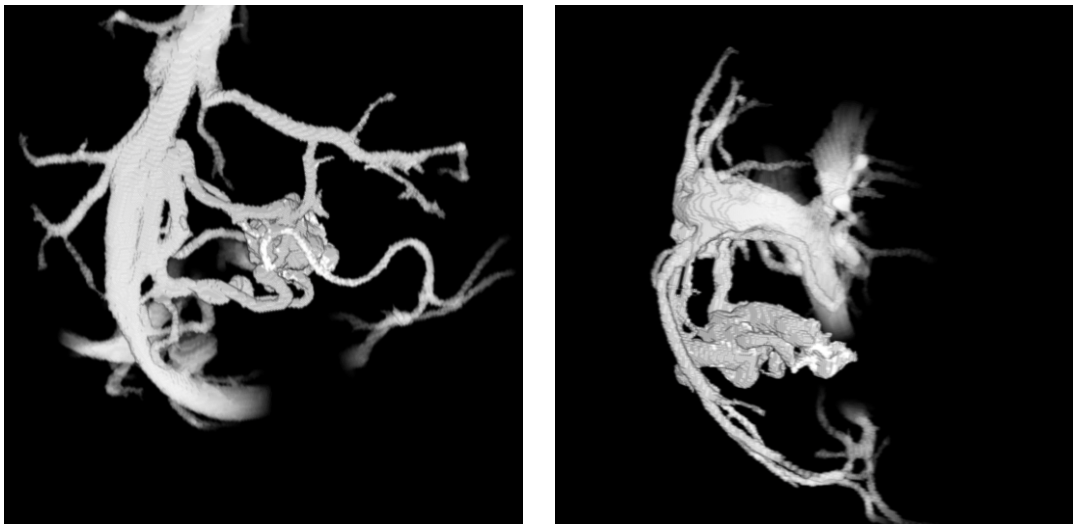
To label the feeding and draining vessels of the nidus we mapped the values of the combined flow map to specific hues of a colour map. However, instead of a rainbow spectral colour map commonly used in the colour mapping of intensity values (see Fig. 3a), we elected to use a tri-tonal colour map, consisting of red, purple, and blue (see Fig. 3b). This colour map corresponds well to the standard colour scheme used in medical texts to depict arteries and veins, as well as the blood flowing to and from specific tissues. We believe this helps the surgeon in interpreting blood flow information so that the AVM feeders and drainers can be easily identified. This colouring scheme has been well received by neurovascular surgeons at our institute when compared to the rainbow colour map and other flow time colour maps that we presented.

The appropriate colour was determined by using the values of the AVM distance map and the combined flow map. Values on the combined flow map higher than 0.5 (location of the seed at the nidus center) are mapped to red while those lower than 0.5 are mapped to blue. This effectively colours draining vessels with flow going away from the AVM as blue, and feeding vessels with flow leading to the AVM as red. The AVM distance map is used to tune the blending of the red and blue to the purple colour at the center of the AVM. This allows the surgeon to select the amount of colour contrast near the AVM nidus to discern between the feeding and draining vessels from the nidus.

2.2.2 Decluttering

Although a full 3D vessel image may be useful for the surgeon in understanding the patients general vascular anatomy, a display of all vessels both inside and outside of the surgical field may not be well suited for intra-operative AVM visualization. Such complete visualizations may actually become a source of distraction to the surgeon or even prevent proper image interpretation, since the neurosurgeon needs to focus on clipping the AVM vessels connected to the nidus and not those disconnected or topologically far from the nidus. As such, good AVM vessel visualization should ideally highlight and allow the surgeon to focus on vessels that are adjacent and connected to the AVM nidus itself, disregarding vasculature that may pass close to the nidus but which does not actually connect.

To present the most relevant vasculature to AVM surgery, we used the values of the AVM distance map as the alpha transparency of the rendered image. This suppresses vessels that are topologically distant to the nidus, allowing the surgeon to focus on the vessels most important to the procedure connected to the AVM. Decluttering using topological distance also has the additional benefit in that the volume can be viewed from numerous viewpoints without obstruction by other vessels (See Fig. 4).



(a) (b)

Figure 4. Two views of the AVM nidus after topological distance based decluttering from (a) a standard view from the cortical surface, which obstructs much of the body of the AVM nidus, and (b) another from the side with the nidus body and tip clearly visible.

2.3 Intra-operative Augmented Virtuality Visualization

To show how the visualizations can be displayed to the surgeon during the AVM surgery, we used augmented virtuality (AV). In AV, *real objects*, which are objects with a physical entity that conform to the laws of physics and time or their representations (e.g. a camera image), are introduced into a virtual environments or digital scene. Our AV set-up includes:

1. A nylon 3D printed patient head phantom.
2. A Sony HDR-XR150 video camera tracked with a 4-point passive tracker attached to the camera base.
3. A 4-point passive tracker attached beside the phantom inside the space used for our AR setup.

The camera position and the phantom positions are tracked through their respective passive trackers using a Polaris Tracking System from Northern Digital Technologies. Using a checker-board calibration grid, the transform for the intrinsic camera parameters is computed and then used to recover the grid to camera transform. Using a calibrated pointer tool, points on the grid were selected in order to recover the grid to tracker transform. Together, this allows us to calculate the camera to tracker transformation.

This set of transformations allows us to move the camera around in the real world, while keeping the head phantom image from the camera well registered with the virtual blood vessel data. All details of the AR setup, including the building of the patient phantom, scene registration, and camera calibration is described in Drouin *et al.* (2011).[9]

3. RESULTS

The results of each step of our image processing can be seen in Fig. 5. Note that prior to the processing, the original vessel dataset, which has been rendered without edge enhancement, is difficult to interpret due to the amount of vessels seemingly adjacent to the AVM nidus (see Fig. 5a). When the AVM distance map is used to suppress extraneous vessels, we can see the effect of decluttering using the topological distance from the nidus centre. The relevant vessels connected to the AVM nidus are shown clearly with high alpha values in the image while vessel segments topologically far away from the nidus are suppressed with lower alpha values (see Fig. 5b). However one cannot easily tell in this visualization which vessels are feeders or drainers. When the combined flow

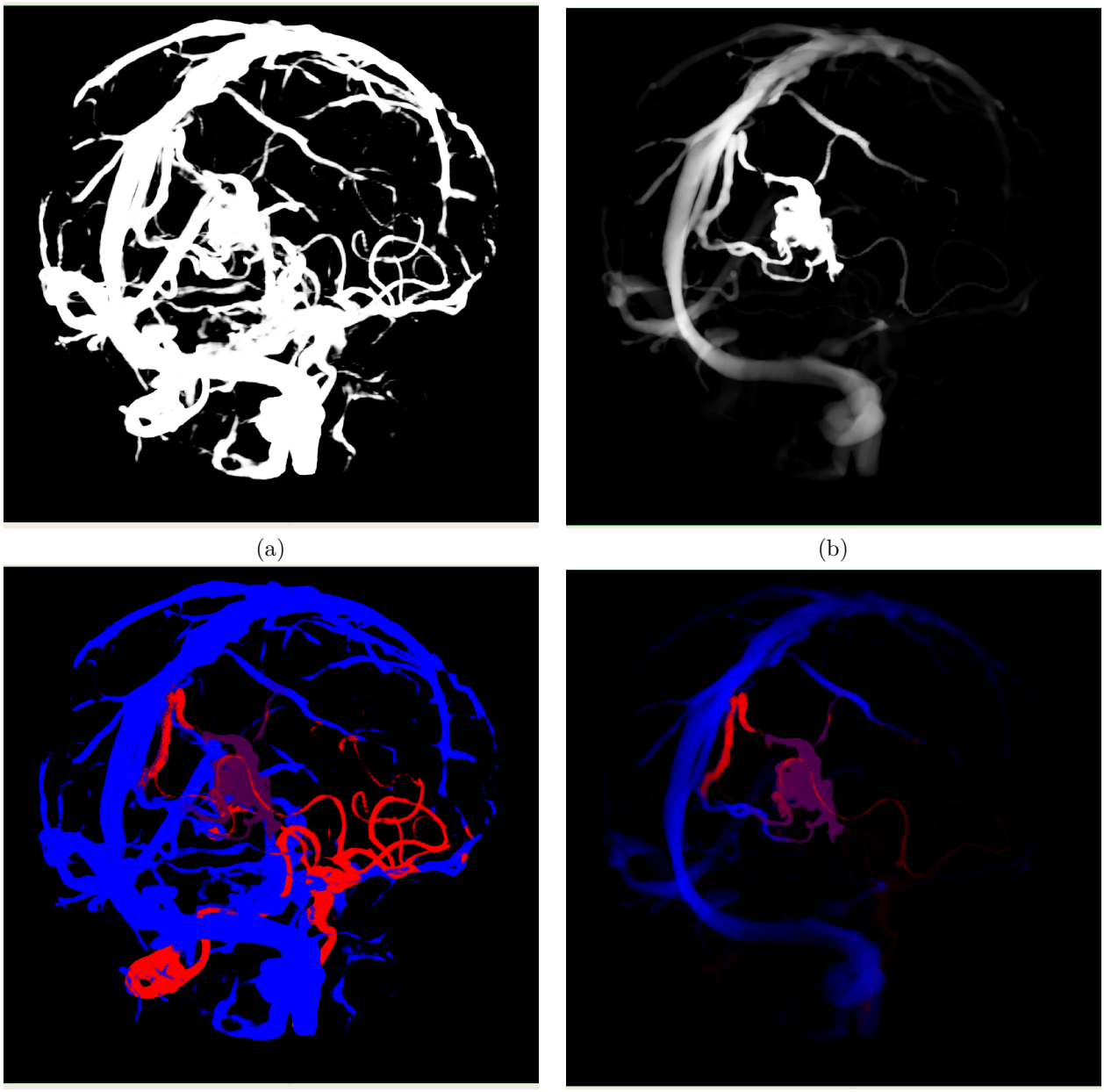


Figure 5. Intermediate stages of the proposed visualization method, with (a) the original vessel image rendered without edges, (b) the same data set with alpha tuned using the topological distance to the AVM nidus for decluttering, (c) the colour labeled flow map with feeding and draining vessels labeled in red and blue, and (d) the final visualization incorporating the decluttering and colour labeling.

map has been applied with the standard medical colour scheme to show red arteries and blue veins connected to the purple nidus, one can clearly see which blood vessels feed or drain the nidus (see Fig. 5c). However, the rendered scene is cluttered by numerous vessels that make the image difficult to interpret. Once again, using topological decluttering, the surgically relevant vessels can be easily seen (see Fig. 5d), enabling the the surgeon to easily identify the feeders and drainers directly connected to the nidus and clip them accordingly.

When the colour labeled vessels and nidus image were combined with the alpha assignment of the AVM distance map, the topologically distant vessels far from nidus are suppressed and the surgically relevant feeding

and draining vessels can be easily seen (see Fig. 5d). This allows the surgeon to easily identify the feeding and draining vessels directly connected to the nidus and clip them accordingly.

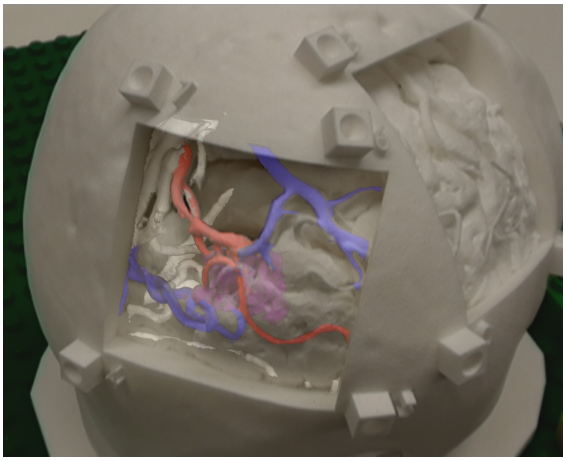


Figure 6. Physical head phantom with AV colour-coding vessel overlay. Feeding arteries are red, the nidus purple, and the draining veins blue. The colour-coding information of the feeding and draining vessels was obtained from the flow maps generated using the fast marching algorithm and labeled accordingly by hand.

We incorporated the resulting images into our navigation system, IBIS (Interactive Brain Imaging System) NeuroNav,[10] a custom developed neuronavigation prototype from the Image Processing Lab at the McConnell Brain Imaging Center (Montreal, QC). In our current implementation, surface models of the pre-operative data are colour-coded and registered to the live camera image and merged using alpha blending. In order to directly use the vessel flow maps, we will in the future integrated volume rendering into IBIS. To date we have used the flow time information in order to manually colour code feeding vessels of the AVM as red, the nidus purple, the draining vessels blue, and non-significant vessels as white (see Fig. 6).

4. DISCUSSION

We have presented our AVM visualization technique based on a robust and well-understood level-set front propagation method. By processing our static vessel images with this technique, we were able to simulate the path of blood flow. Although front-propagation simulates the flow in blood vessels well in most cases, the method will fail if two separate vessels in the image make contact with one other, even by a single voxel. For our case, if we attempted to simulate flow using only CT-DSA images from a seed at the carotid artery, the proximity and intensity of the jugular vein would cause the flow to enter from the artery into the vein, thus producing an erroneous flow time map. This necessitated the use of 3DXA arterial images to estimate the flow. We found that if attention is paid to check the initial vessel images and the resulting flow time image, the problem of using a badly processed images can be averted.

We found that our technique, which simulates blood flow with the level-set method, is in general quite flexible and enables visualization of the flow time information by simply adjusting the transfer function of the renderer. For instance, the flow time map can be visualized as either a color mapped image or as a sequence of flow images showing stages for blood flow through the vasculature. By mapping the flow time anchored at the center of an AVM nidus to specific colour maps, a surgeon will be able to explicitly see feeding and draining vessels leading to and from an AVM nidus while delineating the pathology, by their colour labeling. In Fig. 3 the two colour-mapping visualizations show how the feeding and draining vessels of the AVM can be delineated from the nidus mass itself and that the colour used should allow a surgeon to distinguish between the feeders and drainers. This gives the surgeon the ability to decisively choose which vessels to clip instead of having to try to identify the feeders and drainers either physically or visually while during the operation. Further, the surgeon may choose which of the many types of colour they prefer, making the information presented to them more usable.

The use of the AVM topological distance data also helps to improve the visualization of AVM feeding and draining vessels for intra-operative surgical guidance. Using the topological distance, we can highlight the vessel

segments entering the AVM nidus and suppress vessels that pass close to the nidus but do not actually touch or connect. This visualization allows the surgeon to focus on the vessels they deem most critical for the AVM surgery, effectively decluttering the image to display only what is pertinent at a particular stage of the operation (see Fig. 5a and 5b).

Vessel topological distances differs from Euclidean distances measures such as view distance (between the view point and the object) or absolute distance (between two objects). Although, Euclidean distances could be used to declutter or allow for focusing on the region surrounding the AVM, it does not account for the fact that vascular paths around a nidus tend to be tortuous and a vessel segment that may be close to the nidus might actually be topologically far. For this reason, we believe that the use of topological distance is superior in decluttering of visualizations in AVM vasculature surgery. However, we also believe that decluttering using topological distances can be improved with the use of Euclidean distance measures and as such we intend to explore how these different distance metrics can be used together in order to visualize vascular anatomy for AVM surgery.

The effective combination of colour labeling and decluttering can be seen in (see Fig. 5). While the colour labeling effectively shows which vessels are feeding or draining the AVM nidus, when used alone the amount of structures in the image can be overwhelming in the quantity of vessels visualized. By combining the colour labeling of the vessels and nidus with the topological distance based scene decluttering, the surgeon is able to see which vessels connected to the nidus should be clipped first (see Fig. 5d). Finally, by displaying the flow times and the topological distance via augmented virtuality directly during the surgery, the surgeon is able to more easily find correspondences between the digitally visualized vessel and the physical vessels of the patient in their operative field.

5. CONCLUSIONS

In this work, we have showed a novel method for the visualization of static AVM vasculature images. Our vessel images were processed using level-set flow propagation to produce the simulated blood flow maps and an AVM topological distance map. The results were used for colour labeling and decluttering of our rendered vessel images. This combination allows for the effective visualization of vessels feeding and draining an AVM nidus. Using our augmented virtuality method, we can display our visualization during surgery as an overlay during the surgical procedure. This further aids in the decision making process of AVM nidus clipping, potentially decreasing the operative time by easing identification of AVM vasculature, reducing surgical error, and improving surgical precision.

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