Whole-Brain Vascular Reconstruction, Simulation, and Visualization

Thomas Marrinan* University of Illinois at Chicago
Ian Gould† University of Illinois at Chicago
Chih-Yang Hsu‡ University of Illinois at Chicago
Andreas Linninger♈ University of Illinois at Chicago

ABSTRACT

Current techniques in medical imaging and analysis primarily focus on recording information about one specific physiological property at a time. Various modalities such as magnetic resonance, computed tomography, and digital subtraction angiography are each suited towards different tasks. In order to improve surgical planning, physicians would benefit from patient-specific computational models built from medical images. These models could be used in order to run simulations and simultaneously gather physiological information that would otherwise require multiple imaging modalities or be impossible to measure with current technology.

We present a pipeline for processing medical data and executing computational simulations to enhance the information conveyed in standard medical imaging. Our work focuses on the whole brain, where we've developed tools that allow vasculature to be analyzed in three-dimensions, at high resolutions, and with multiple relevant data sets overlaid on the vascular structure. In order to avoid confusion and misinterpretations, we have the ability to render simulated data such that it mirrors raw medical images and vascular reconstructions.

Keywords: Medical image reconstruction, computer simulation, voxelization, vasculature.

Index Terms: I.4.1 [Image Processing and Computer Vision]: Digitization and Image Capture—Imaging Geometry; J.3 [Life and Medical Science]: Health

1 INTRODUCTION

Interpreting physiological phenomena in the cerebral vasculature often involves analyzing multiple observational properties. When devising a surgical plan, such as in cases of stroke or aneurysm, physicians utilize medical images to retrieve relevant data about the structure and blood flow properties of the patient's cerebral vasculature. However, these images are analyzed qualitatively and often limited to recording one property at a time.

Computed Tomography (CT) images allow physicians to view the vascular structure and measure cerebral blood volume (CBV), cerebral blood flow (CBF), and mean transit time (MTT) as aggregate properties. Magnetic Resonance Imaging (MRI) allows physicians to obtain similar data as CT, as well as diffusion of water and oxygen. Digital Subtraction Angiography (DSA) allows physicians to view the vascular structure and measure dynamic blood flow rates. Single-Photon Emission CT (SPECT) and Positron Emission Tomography (PET) use radioisotopes to measure pharmaceutical uptake in the tissue.

Due to the limited resources in emergency centers and the time it takes to complete a single medical scan, retrieving medical images from each of the listed modalities is not feasible in a clinical setting. Because of these limitations, developing a computational model of the vasculature that can accurately simulate physiological phenomena would be useful to physicians when devising a surgical plan. This would result in the additional benefits of having a holistic and united phenomenological view of quantitative data, and the fact that some relevant pieces of data that cannot be measured by any existing modality, such as blood pressure at each individual vessel, would be accessible.

2 METHODS

Centerlines, combined with proper diameter, are geometrically good representations of tubular objects. By applying centerline extraction to medical images of the brain, a tubular network of blood vessels can be segmented and separated from other tissue. One centerline extraction method is the Aylward-Bullitt method, which takes advantage of utilizing the Eigen analysis of the Hessian matrix for a given medical image [1]. Centerlines exist on local ridges, defined by image color intensities. This method uses the maximum Eigen vector as an indicator of the traversing direction of the vessel and keeps tracking until threshold criteria are not met. Additionally, Aylward and Bullitt proposed an algorithm for diameter detection based on applying an adaptive convolution kernel to the normal plane of the center-points. Another centerline extraction method is based on polygonal surface reconstructions of three-dimensional images. Antiga minimizes the energy from a given seed point to a target point [2]. Therefore, the shortest path between two given points must travel on the centerline. The diameter detection algorithm in this method is approximating the radius at the center-point with projections and maximal spheres.

Using either method, seed points for inlets and outlets must manually be assigned. Centerline extraction from a whole-brain MRA image took around 30 minutes including manual selection and algorithm run-time. Extraction results from both of these methods can be seen in figure 1.

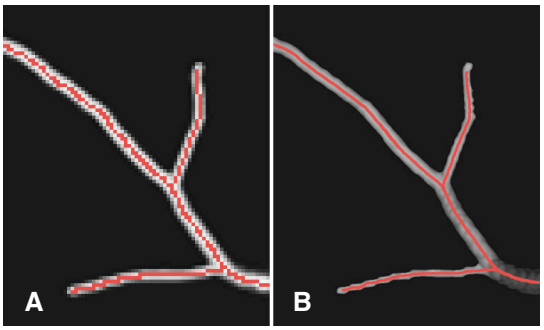

Figure 1: Centerline extractions. A – extraction directly from medical image. B – extraction from smoothed polygonal surface reconstruction.

These three-dimensional tubular networks were used to conduct patient-specific hemodynamic simulations of cerebral vasculature. Reconstructed networks were enhanced with a space-filling constrained growth algorithm to construct blood vessels beyond the resolution of a given medical image [3]. Morphological considerations were applied for the construction of the network to match morphological properties [4]. Arterial and venous networks

* tmarri2@uic.edu
† iangould@uic.edu
‡ chsu33@uic.edu
♈ linninge@uic.edu

were constructed to ensure that terminal nodes for both trees were located within close proximity of each other, and a simple capillary mesh was used to connect them. This simple capillary was constructed to ensure both the steady flow and dynamic convective properties of the microvasculature capillary bed.

In order to run flow simulations over these networks, inlet boundary conditions were assigned at terminal nodes of the arterial section (left and right internal carotid artery, basilar artery), and outlet boundaries were assigned to the terminal nodes of the venous section (left and right jugular veins). Resistances for each vessel were assigned using the Poiseuille formula, and steady-state flow patterns across the vascular network were predicted by solving a set of linear algebraic equations, which were constructed by rigorous application of conservation balances. These simulations allow us to accurately predict volumetric flow rates, pressure drops, and other steady-state properties at each vessel in the network. Convective dye simulations were performed utilizing these simulated values, which allows for prediction of transit time and contrast agent concentration throughout the vascular network. These predicted values match well with measurements of blood flow through the Circle of Willis obtained from phase-contrast MRA coupled with time-of-flight. Small vessel transit time predictions are in good agreement with measured values obtained from peak-to-peak DSA analysis and microvasculature washout times.

Once the simulations are complete, each vessel has a scalar value associated with it for each simulated property. These values are used in visualizations to color the vascular network and allow for quick interpretation of data. We have the capability to view the network in three distinct visual styles, as seen in figure 2. First, the vessels can simply be rendered as a series of colored cylinders. Second, the vessels can be voxelized (registered against a three-dimensional grid) to create a three-dimensional image. This image can be viewed directly with volume rendering. Third, a marching cubes algorithm can be performed on the image created for our second visual technique. This results in a polygonal reconstruction of the structure in the image [5, 6]. Alternatively, a discretized version of the marching cubes algorithm can be used to create a series of polygonal surfaces that retain image intensities, which is used to color surfaces based on the simulation data [7].

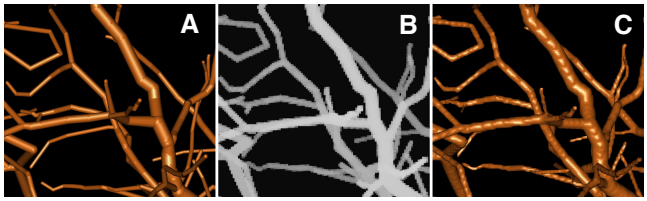

Figure 2: Render Styles used to illustrate the vascular structure. A – network with each vessel rendered as a cylinder. B – voxelized network depicted as a three-dimensional image using volume rendering. C – surface reconstruction of image using a marching cubes algorithm.

3 Results

We have reconstructed vasculature on both the micro and macro levels. We have a simulated vascular network for the cerebral functional blood unit (FBU) on the microscopic scale. The FBU is a cylindrical network that is 0.7mm in diameter and 3.0mm tall, and is responsible for diffusing oxygen into brain tissue. We also have a reconstruction of the major arteries throughout the whole brain. Figure 3 shows both a FBU and the major arterial network colored by simulated blood flow and pressure.

Simulations for retrieving predicted values for blood flow were executed by applying boundary conditions at feeding inlets and draining outlets of the vascular networks. Transit times from simulated angiography in the FBU agree well with the one-second capillary washout period observed in full brain angiograms. Aggregate CBV and CBF in the full arterial network agree well with CT measurements in healthy patients.

Visualizations of simulated DSA, three-dimensional images, and reconstructed vessels are used to convey information to physicians such that they utilize similar visual properties to that of raw medical images. Preliminary assessment by physicians demonstrates that we match the visual impact of existing clinical tools used to view raw medical images, and that our structures lead to additional insight about the cerebral vascular system.

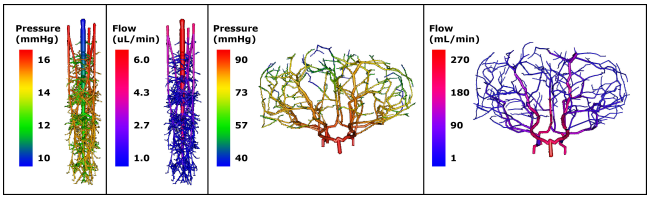

Figure 3: Blood flow simulations. Left – pressure and flow results for the microvascular FBU. Right – pressure and flow results from the full brain major arterial vessels.

4 Future Work

We look to continue our progress by fusing the macro and microvasculature in order to create a physiologically consistent full-brain model. We are working to completely automate the reconstruction process, so that we can convert medical images into finalized simulated networks with little or no human interaction. We are also exploring ways to quantify and resolve potential errors in our vessel extraction process that arise from medical image resolution. Once these steps are made, it is our goal to deploy our tools in a clinical setting for the use of surgical planning.

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