Whole-Brain Vascular Reconstruction, Simulation, and Visualization

Thomas Marrinan Ian Gould Chih-Yang Hsu 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.

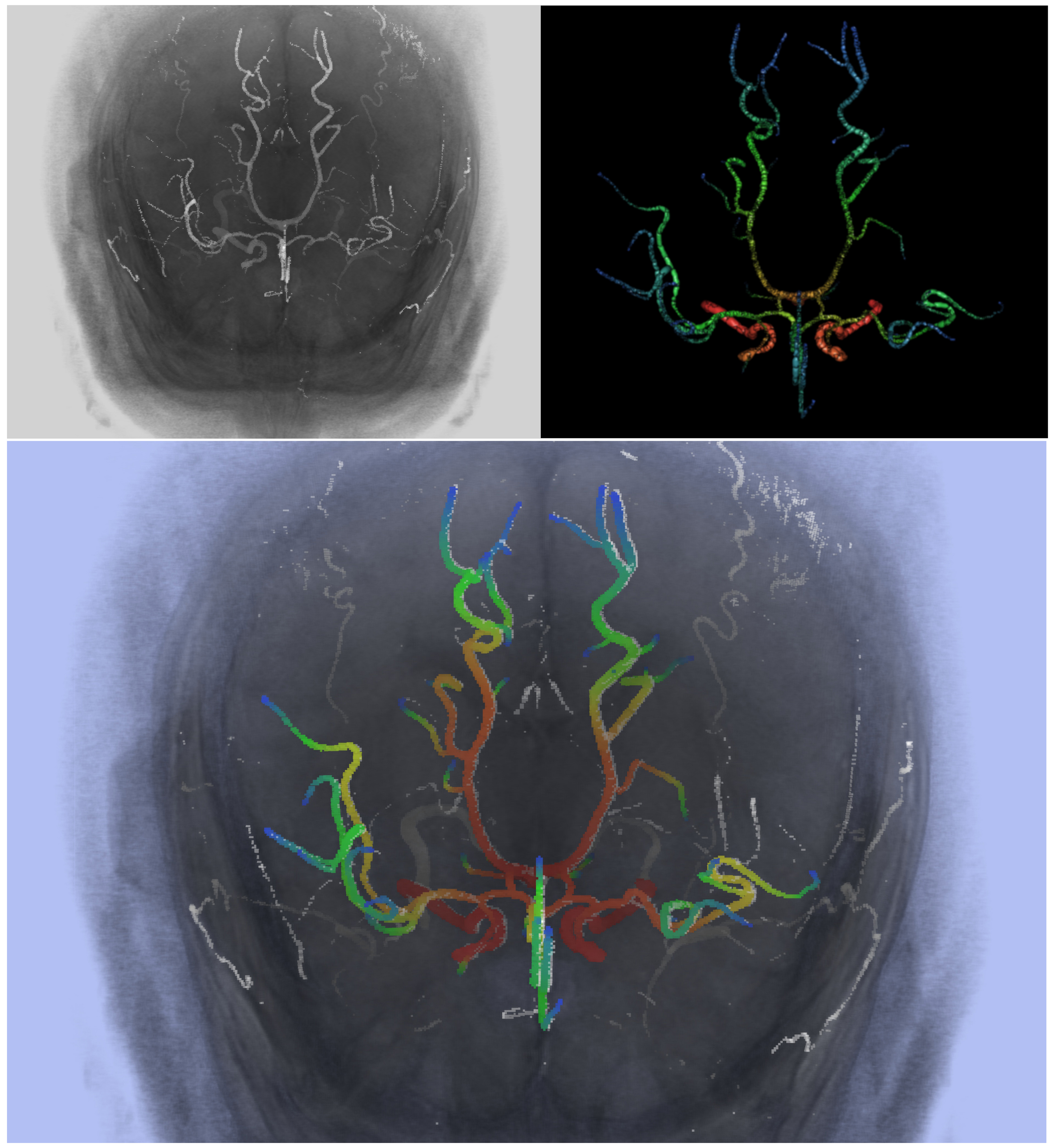
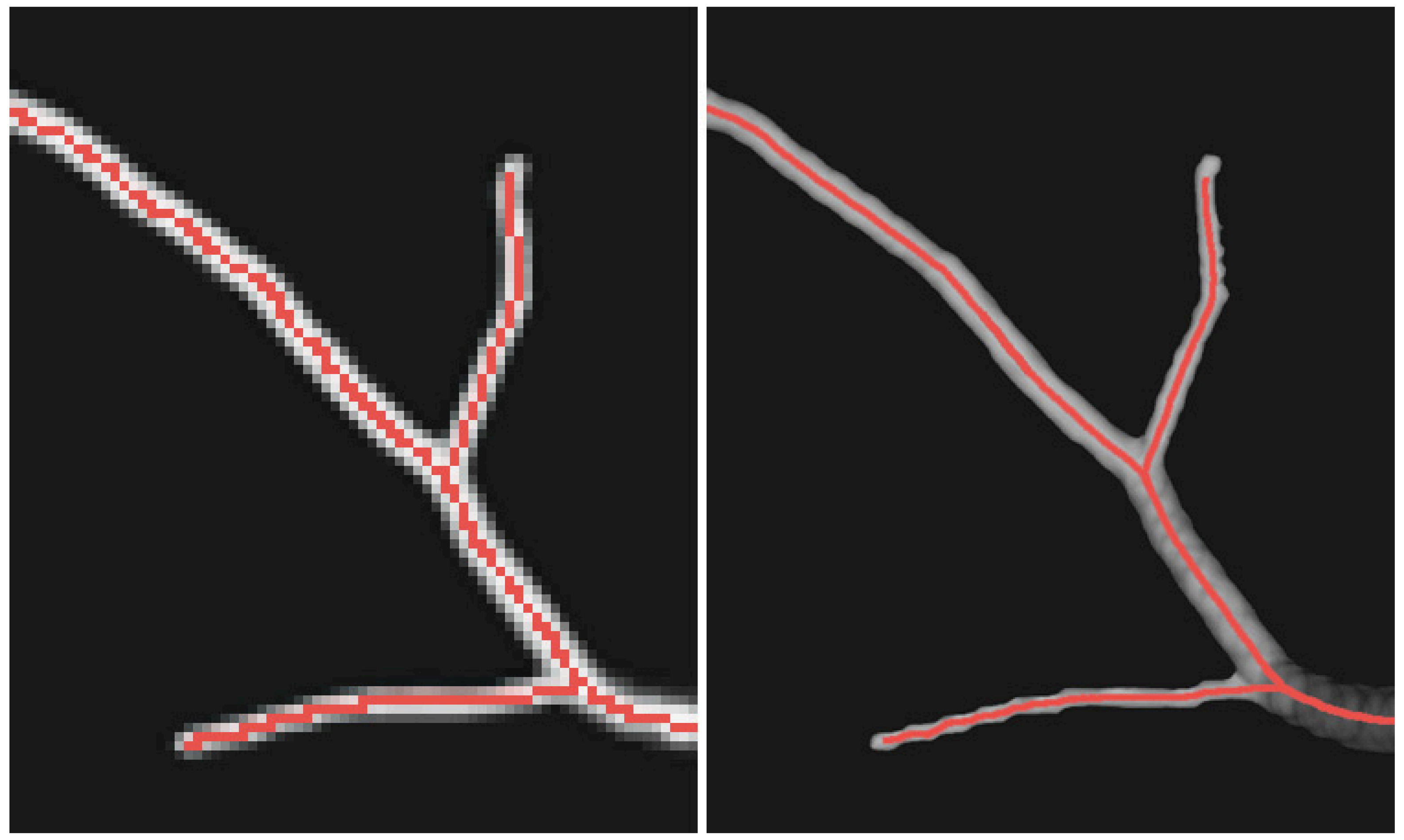


Image Centerline Extraction

Centerlines, combined with proper diameter, form geometrically good representations of tubular objects. By applying centerline extraction to medical images, a tubular network, such as blood vessels, can be segmented and separated from other tissue. Centerlines can be extracted directly from images since they exist on local ridges, defined by image color intensities [1]. To achieve smoother results, we utilize another centerline extraction method that is based on polygonal surface reconstructions of three-dimensional images [2].



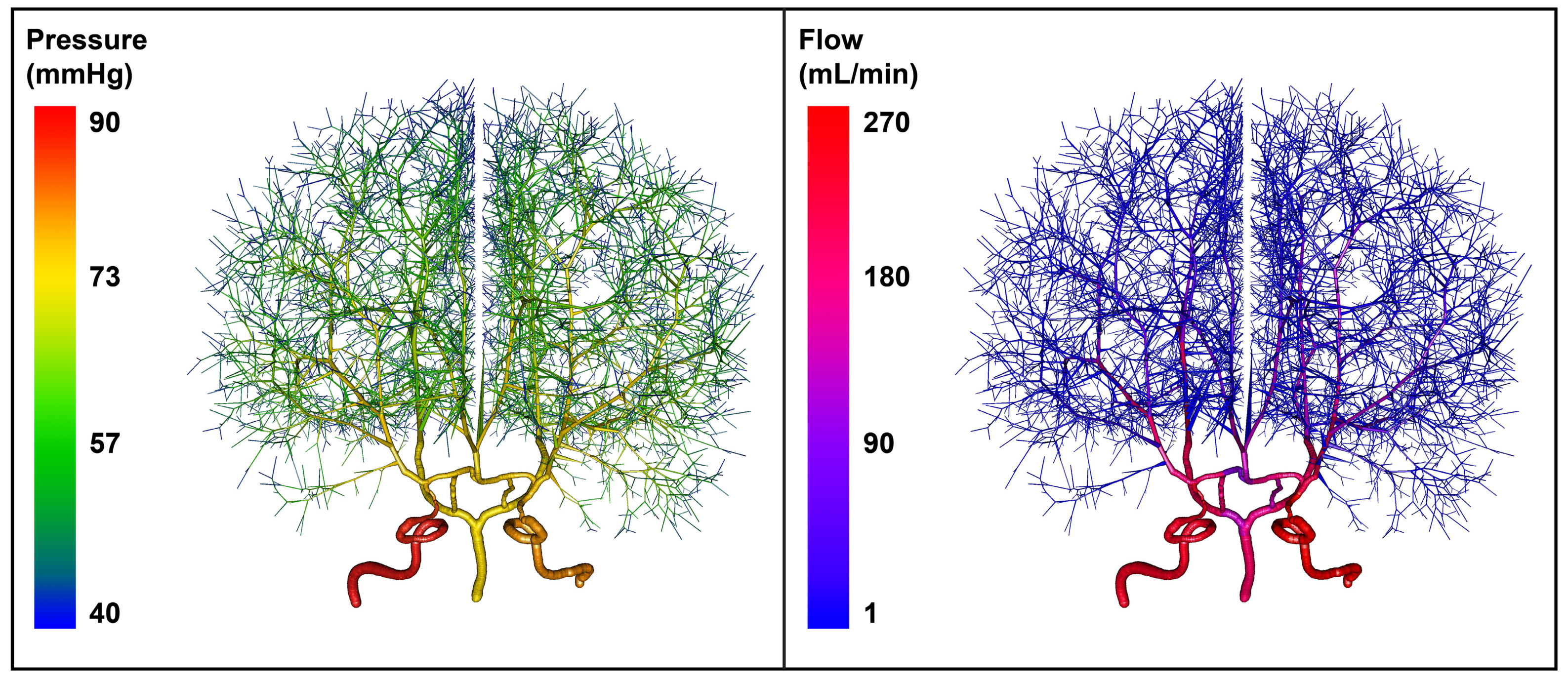
Blood Flow Simulations

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 with morphological considerations to construct blood vessels beyond the resolution of a given medical image [3,4]. Arterial and venous networks 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.

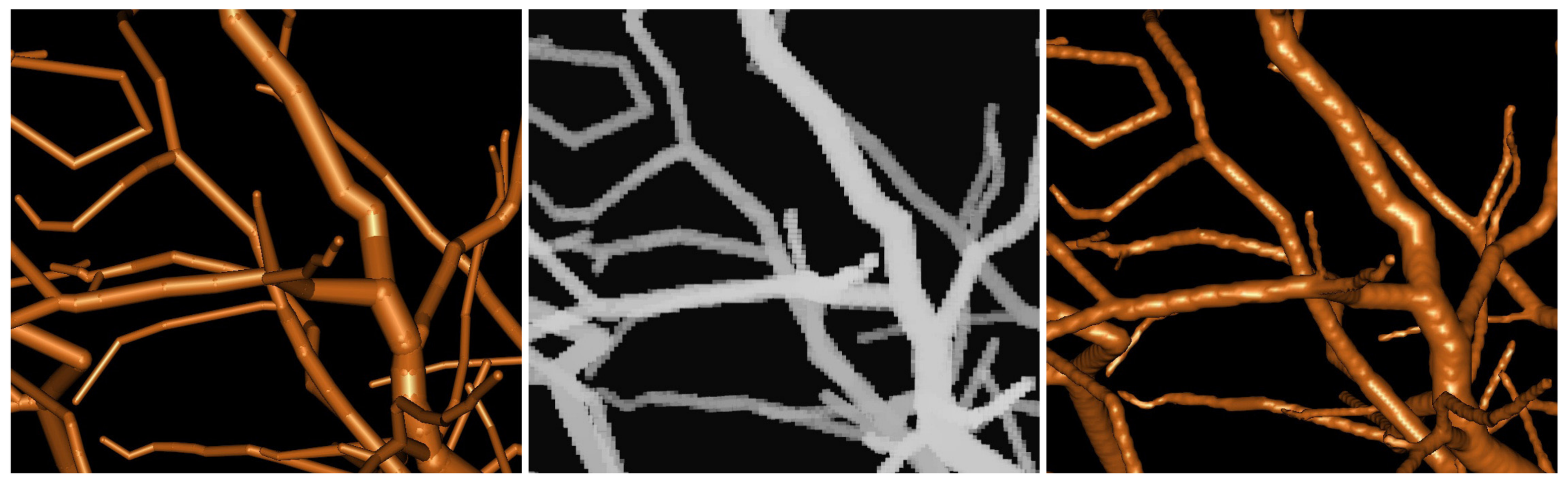
In order to run flow simulations over this combined network, inlet boundary conditions were assigned to the arterial section (left and right internal carotid artery, basilar artery), and outlet boundaries were assigned to the venous section (left and right jugular veins). Resistances for each vessel 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.

Artificial Vessel Visualization

Once the simulations are complete, each vessel has a scalar value associated with it for each simulated property, such as pressure and flow. We utilize these values in visualizations to color the vascular network and allow for quick interpretation of data.



One of our visualization accomplishments has been to view our artificially enhanced whole-brain vascular network in a similar style as real vessel reconstructions. Since our vascular model is a series of connected tubes, we could simply render them as a series of colored cylinders. While this does accurately depict the vascular structure, it fails to display nuances that occur on the vessel wall. In order to simulate reconstructed vessels from medial images, we voxelize our model to create a three-dimensional image. We then use a marching cubes algorithm on the generated image to result in a polygonal reconstruction of the structure [5]. Alternatively, we use a discretized version of the marching cubes algorithm to create a series of polygonal surfaces that retain image intensities, which is used to color surfaces based on the simulation data [6].



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Thomas Marrinan | tmarri2@uic.edu | 312.996.3002 Department of Computer Science | **University of Illinois at Chicago** | Department of BioEngineering **Dr. Andreas Linninger** | linninge@uic.edu | 312.413.7743