Comparing Healthy and Diseased Vascular Networks to Better Understand Pathologies

# Abstract

# 1 Introduction

By recognizing the self-similarity (a property where at any magnification, a smaller piece of an object is similar to the object as a whole) in vascular systems, relationships between vessel characteristics at different levels of the network's hierarchy can be recognized. These relationships could be important for identifying differences between the diseased state of a system versus the healthy state of a system. Observations have been shown to be important for drug delivery, tumor growth, and could potentially reveal some insights for stroke recovery.

The West, Brown, and Enquist (WBE) model, built upon the structural and physical properties of the cardiovascular system, suggests that metabolic rate is a function of body mass with a scaling exponent of 3/4 confirming the empirical observations known as Kleiber’s law. It is useful in determining vessel radii and vessel lengths in a vascular network. The model rests on three core assumptions. 1) Vessels within the same level of hierarchy are equivalent, meaning they share the same radius, length, and flow rate. 2) The vascular system minimizes energy loss caused by impedance (blood wave reflections at vessel junctions) and dissipation (energy lost due to friction on vessel walls). 3) The vascular network is space filling, meaning the network must span the body to enable all cells to be locally fed by a capillary. By recognizing that total blood volume is proportional to the sum of the service volumes at each level of the vascular network, ratios between radii and length at different levels of the vascular network can be calculated. These assumptions lead to the conclusion that scaling exponents for radius and length at different hierarchies of a vascular network can be used to find information about an averaged network. By analyzing real data, we recognize that many of the assumptions made in the WBE model neglect some characteristics of real vascular systems, for example, loopy veins and asymmetry. Loopy veins are prevalent in the brain, where activity levels and oxygen demand are high. Asymmetry of vessels is shown in the coronary arteries, which must transition quickly to capillaries in order to supply blood to the heart. Four current methods, based on the assumptions of the WBE model, can be used to determine the scaling exponents for radius and length ratios between the child and parent vessels . Scaling exponents can be calculated using the conservation-based method, the ratio-based, the distribution-based method, and the regression-based method.

Prior methods of obtaining vascular data such as casting and angiography are inefficient and time consuming, and these methods are prone to errors. By utilizing a new software, Angicart, based upon image processing techniques, we are able to generate the geometric properties of a vascular system including the radius and length of the vessels. Angicart is written in Ocaml and processes vascular images by assuming that the network takes on a tree-form (meaning it fails to recognize loopy veins). A new version of Angicart has been developed, written in C++ in order to make the software more user-friendly, and is able to identify loopy veins. This paper first attempts to validate the methods for vessel extraction from 3D vascular images. Here, we compare data from two versions of software, Angicart, which already exists and has been tested, and a new version of software written in C++, which needs to be tested in regards to handling tree-like networks (vascular networks that lack loops). If we can validate that the new software works, we will use it to analyze loopy networks such as those seen in stroke recovery.

Using software to extract data on the structural properties of vessels from 3D vascular images, we can predict properties such as metabolic rate, growth rate, and drug delivery. By acknowledging the gaps in the original WBE model, we can improve the assumptions of the framework and better understand real vascular networks. Using four different methods to calculate scaling exponents and comparing data from healthy systems to that of diseased systems, we recognize relationships that can lead to further knowledge on how to treat these conditions.

# 2 Methods

## 2.1 *angicart*

Angicart was used to extract data from the vascular network. It is a software that is written in OCaml and takes MRI images, then outputs a .tsv data file including the geometric properties of a vascular system (i.e. radius and length). Angicart is able to read DICOM-format tomography images, then select points along the vascular network by using a threshold value. This threshold is used to determine the brightness of the voxels (3D pixels) that will be recognized as part of the network, and the software then groups these voxels into segments. In order to eliminate false data points, angicart finds the largest connected component of the scan and then proceeds to remove points it has generated by using an erosion algorithm. This algorithm "erodes" (takes away points from the edge of the vessel) until it can no longer remove points (until holes are present in the skeleton). The erosion algorithm is used to calculate branch points and tips of the model. The software then takes this decomposed model and regenerates the surrounding data points, which are necessary in calculating the observed radius of the vessels.

## 2.2 C++ version

The new version of angicart, written in C++, has the ability to recognize loopy networks.

## 2.3 Analyzing the data

The scaling exponents a and b were calculated using the conservation-based method, the ratio-based method, the distribution-based method, and the regression-based method. I wrote MATLAB scripts to calculate the scaling exponents using each of these methods, detailed below.

### 2.3.1 Conservation-based method

We check to make sure the children are smaller than the parent, in order to maintain simplicity. By showing the distributions of the measured scaling exponents, we take the mean of the exponents and the 95% confidence intervals for these measurements. The exponents a and b are calculated using the equations:

### 2.3.2 Ratio-based method

Similar to the conservation-based method, the ratio-based method checks that the length and radius of the children vessels are smaller than those of the parent. By plotting the relative frequencies of the radius scale factor, , and the length scale factor, , we

### 2.3.3 Distribution-based method

### 2.3.4 Regression-based method

# Results and Analysis

# Discussion