

# IMAGE-BASED MODELING OF BLOOD FLOW IN PULMONARY ARTERIES USING A ONE-DIMENSIONAL FINITE ELEMENT METHOD COUPLED TO A MORPHOMETRY-BASED MODEL OF THE DISTAL VESSELS

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## INTRODUCTION

The pulmonary circulation serves the important role of evenly distributing blood throughout the lungs so that gas exchange can occur over as large a surface area as possible. Individuals with unilateral pulmonary stenosis, a narrowing of either the right pulmonary artery (RPA) or left pulmonary artery (LPA), often experience greater blood flow to the contralateral than the ipsilateral lung. An understanding of the impact of the severity of the pulmonary stenosis on the resulting hemodynamic conditions may be gained from accurate modeling.

Theoretical models of pulsatile flow in the pulmonary circulation have heretofore been based on lumped parameter or linear wave propagation approaches. The latter approach, based on solving partial differential equations arising from the principles of conservation of mass and momentum, requires a description of the structure of the vascular tree and the distensibility of its vessels. This morphometric and elasticity data has been assembled and used in the analysis of blood flow in the lung of a dog [1] and a cat [2]. The input impedances of these lung models compared favorably with experimentally measured input impedances.

We have previously described a finite element method to solve the nonlinear, one-dimensional equations used for modeling blood flow in elastic vessels [3]. Prediction of flow with this method has been validated *in vivo* using the case of aortic stenosis in the presence of a bypass graft [4]. Impedance boundary conditions have recently been developed for this method [5].

We describe a new approach to simulate blood flow in subject-specific models of the pulmonary arteries that consists of: (i) a one-dimensional finite element model of the proximal pulmonary arteries created from three-dimensional medical imaging data and (ii) calculation of the terminal impedance of the branch vessels included in the one-dimensional finite element model using morphometry data. We describe the application of this approach to simulate pulsatile blood flow in a model of the pulmonary arteries of a pig imaged using magnetic resonance imaging (MRI).

## METHODS

Anatomic data for the porcine pulmonary arteries were obtained using contrast-enhanced magnetic resonance angiography (CE-MRA) with a 1.5 T MRI system (Signa, GE Medical Systems, Waukesha, WI). A rapid, three-dimensional acquisition was performed with respiration suspended, a phased array receive coil, and the following parameters: TR=4.6 ms, TE=1.0 ms, flip angle=15°, FOV=28 cm, and NEX=1. Cine phase-contrast MRI (4D-Flow) was used to obtain velocity information throughout the cardiac cycle for a volume including the MPA, RPA, and LPA [6]. Planes in this volume were extracted from which flow through the MPA, RPA, and LPA were computed using Tecplot (Amtec Engineering, Inc.).

A geometric model of the resolvable pulmonary arterial anatomy was created from each set of MRA data using custom image segmentation and geometric modeling procedures [7,8]. One such model is shown in figure 1. The termination points of the model are chosen at bifurcations of vessels whose diameters can be clearly discerned from the MRA data.

While a porcine pulmonary morphometric data set is not available, Huang et al. [9] have published a set of human pulmonary morphometric data generated with the diameter-defined Strahler ordering system, including the connectivity, diameters, and lengths of 15 orders of pre-capillary vessels. An order is assigned to each outlet

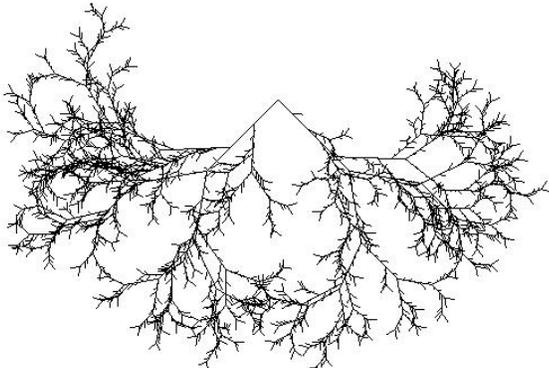


**Figure 1. Geometric model of proximal pulmonary arteries in a pig superimposed with volume rendered anatomic data obtained using CE-MRA**

of the geometric model of the pig lung based on its diameter. Outlets are assigned bifurcations with two child vessels of one order smaller than the parent. From these points to the pre-capillary level, the model of the arterial tree is generated from the human morphometric data.

The software that generates the arterial tree model makes use of a recursive algorithm. Each element's children are generated using the morphometric data and one of several stochastic procedures. The number of children of each order, diameter, length, and number of segments for each vessel can be chosen as the mean value or a random number given in the morphometric data. Because the mean value from the connectivity matrix, which determines the number of child elements of each order, is not a whole number, its remainder is stored for use with the next element of the same order. Figure 2 depicts the six largest orders of a one-dimensional network created from this morphometric data to represent the vessels distal to one of the outlets.

Prescribing a terminal impedance of zero at the outlets of the smallest vessels, the input impedance of each outlet's vascular tree is calculated with the characteristic impedance from Womersley's model of pulsatile flow in an elastic tube and established procedures to convert these characteristic impedances throughout the tree structure to input impedance [10]. Compliance coefficients for the elements of each order can be selected from published data for several mammalian species or an estimate based on these, summarized by Al-Tinawi [11]. The steady component of impedance, or resistance, is calculated with Poiseuille's formula. The apparent viscosity is reduced for the smallest elements to account for the Fahraeus-Lindqvist effect.



**Figure 2. Model created from morphometric data for vessels downstream of one of the branches of the three-dimensional model shown in figure 1**

## RESULTS

The three-dimensional model shown in figure 1 was converted to the format required for the nonlinear one-dimensional finite element software. The algorithm for pulmonary arterial tree generation produced the predicted number of elements of each order. Impedances generated by the algorithm defined above were of the correct order of magnitude to relate the pressure and flow observed in preliminary pig experiments.

## DISCUSSION

In the present investigation, we have assumed that the pulmonary arterial structure of a pig is similar to that of a human, that the distensibility of a porcine artery is similar to that of other mammals, and that the impedance downstream of pre-capillary vessels can be reasonably approximated by a terminal impedance of zero. The validity of a method based on these assumptions must be weighed against its usefulness in the clinical setting. Using this modeling approach as a starting point, modifications can be made so that

applying the impedance outlet boundary conditions and the measured flow at the inlet to the nonlinear one-dimensional model produces experimentally measured pressure values. Possible modifications include varying the terminal impedance and the choice of the initial vessels in the morphometry-based trees that are used to calculate the outlet boundary conditions. It is hoped that these methods will lead to a practical system that can be used for patient-specific modeling of flow in the pulmonary arteries in a clinically relevant time frame.

## ACKNOWLEDGMENTS

The authors would like to acknowledge Mary T. Draney, Brooke N. Steele, Michael Markl, V. Mohan Reddy, Mario L. Trujillo, Robert J. Herfkens, Anne M. Sawyer-Glover, Diane L. Howard, and Wendy L. Baumgardner for their assistance with this project. Ryan Spilker was supported by the Benchmark Capital Fellowship in Congenital Cardiovascular Bioengineering at Stanford University and the Vera Moulton Wall Center for Pulmonary Vascular Disease.

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