Magnetic resonance velocimetry of the human airways

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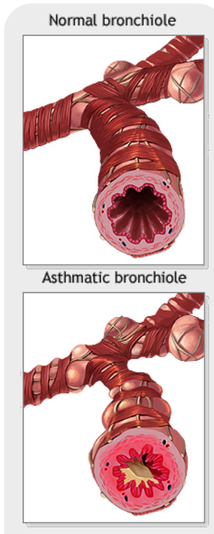
MOTIVATION

Respiratory diseases constitute one of the leading causes of deaths worldwide. Diseased lungs may be significantly structurally altered (shown in the asthmatic lung diagram to the right) which can lead to modified function. Aerosol-drug delivery methods for diseased lungs have a low efficacy, with deposition efficiencies under 30% per inhaled dosage[1]. Meanwhile, the topology of the pulmonary flow and its influence on the deposition of such aerosols is not well understood. A deeper understanding of the airflow and particle deposition in the airways could give insight into the underlying physics of the fluid flow in the lungs. This would provide better models and understanding of the structure-function relationship and as a result improvements in aerosol-drug delivery.

The current work investigates the flow through idealized bronchial generations using advanced experimental methods. The lungs are modeled as simplified bronchial branches spanning two generations. The models are created with high resolution stereolithography and the flow through them is analyzed using magnetic resonance velocimetry (MRV). These experiments further the understanding of the fundamental flow characteristics of various bronchial generations.

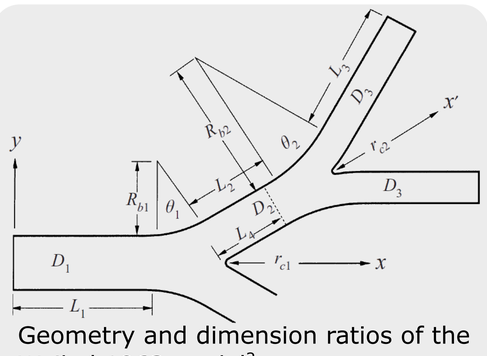


Bronchiole in normal (top) and asthmatic subject (bottom). Adam Medical Encyclopedia.

METHODOLOGY

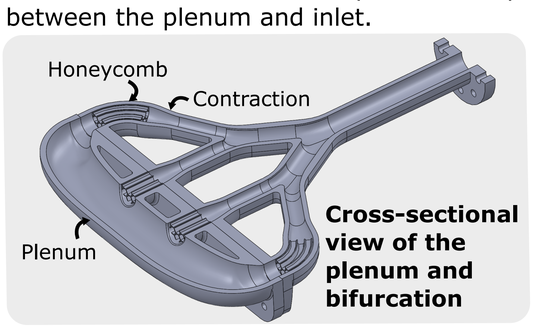
Experiments are conducted in the 3 Tesla Siemens MRI scanner at the Center for Magnetic Resonance Research (CMRR). MRV allows acquisition of three-dimensional velocity fields with the advantages of being non-intrusive and not requiring optical access to the region of interest. This method generates three-component, three-dimensional (volumetric) velocity fields ideal for analyzing complex internal flows such as these.

The model (phantom), based on the Weibel lung model[3], was designed using CAD software at the Minnesota Supercomputing Institute (MSI). The Weibel geometry models the bronchial tree as a series of bifurcating pipes (pictured below right). This idealization allows for multiple generations of bronchial trees to be investigated through dynamic scaling of the incoming flow using non-dimensional inflow velocity. The Weibel geometry forms the test-section of an internal flow loop that pumps the fluid from a reservoir through the test section. The flow loop is bi-directional allowing both inspiratory and expiratory flow regimes. The bifurcation CAD model (pictured below left) is designed as a modular phantom that can be accommodated by the MRI head coil, and provide conditioned inlet flows for both flow regimes.

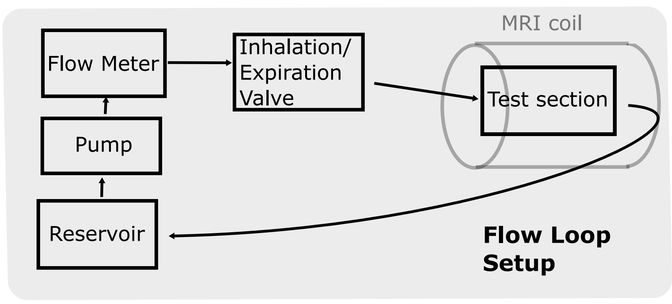


Geometry and dimension ratios of the Weibel 1963 model[2]

A straight pipe is attached to the inflow of the model, ensuring a fully developed inhalation inflow. To create an equal pressure condition at the out flow locations, a plenum connecting to each of the four outflow sections was attached. For the expiratory phase, the curvature constraints imposed by the head coil dimensions were accounted for by including a honeycomb section followed by a 2.9:1 area contraction, serving to reduce the secondary flows at the inlet. The required honeycomb length was calculated such that the pressure drop would remain constant at all daughter bifurcations between the plenum and inlet.

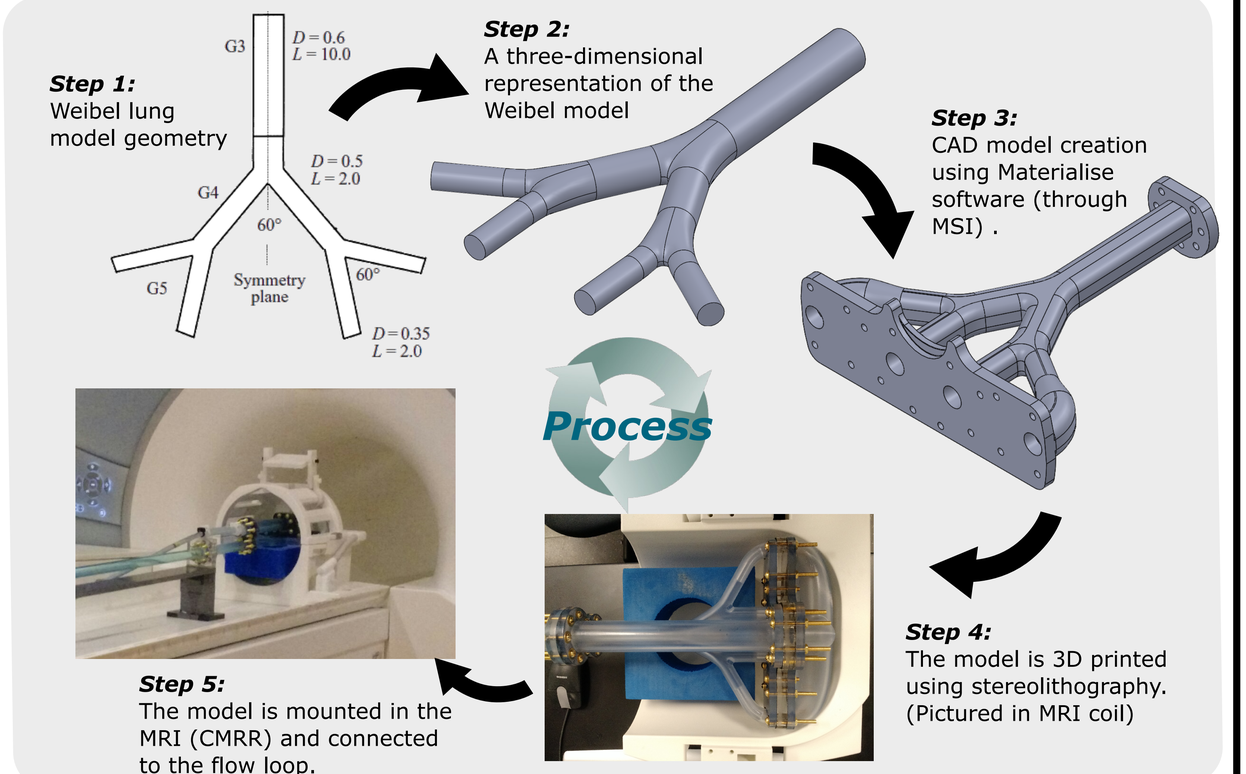


Cross-sectional view of the plenum and bifurcation



Flow Loop Setup

The model (test-section) was mounted in the head coil of the MRI scanner for flow experiments and connected to the flow loop. The MRI acquires phase and magnitude information of the fluid motion providing three-dimensional temporally averaged velocity fields. The fluid is a solution of copper sulfate and water (0.6mol Cu2SO4), doped to maximize the signal-to-noise ratio for the MRV. The working fluid is dynamically scaled to match physiological values of breathing using Reynolds number (ratio of inertial to viscous forces) and the non-dimensional ventilation frequency, Womersley number. Both inhalation and exhalation regimes were investigated at a Re = 4200 using steady flow regimes.



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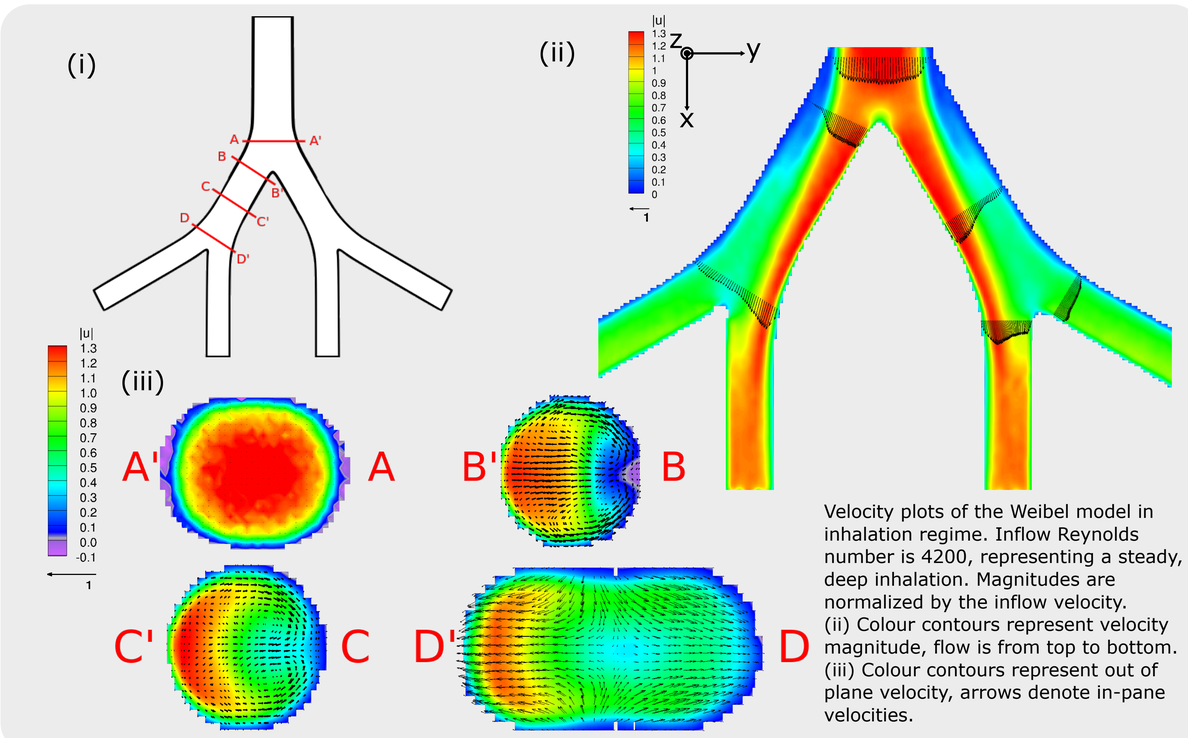
RESULTS



Velocity plots of the Weibel model in inhalation regime. Inflow Reynolds number is 4200, representing a steady, deep inhalation. Magnitudes are normalized by the inflow velocity. (ii) Colour contours represent velocity magnitude, flow is from top to bottom. (iii) Colour contours represent out of plane velocity, arrows denote in-pane velocities.

In this experiment, the flow regime was a steady inflow of Reynolds number 4200, replicating steady, deep inhalation. As shown in the A'-A section of (iii), the inflow has no secondary flows. As the flow approaches the first bifurcation, (ii) shows regions of very low velocity at the wall. At the B'-B location, there is flow reversal due to the wall radius, while the flow near the inner wall accelerates. In addition, secondary flows are formed, including vortices of opposite sign, which are symmetric about the z-plane. The secondary flows weaken as the flow reaches the C'-C region, and the flow has reattached to the outer walls. The out-of-plane velocity profile has also shifted, such that the higher flow forms around the inner wall boundary, wrapping around the slower moving fluid which retains the vortices. At the second bifurcation, the flow stagnates at the carina. Around this stagnation, the flow is pushed into either side of the bifurcation. Because of the out-of-plane profile between B'-B and D'-D, a much high flow rate goes through the middle two bifurcation branches.

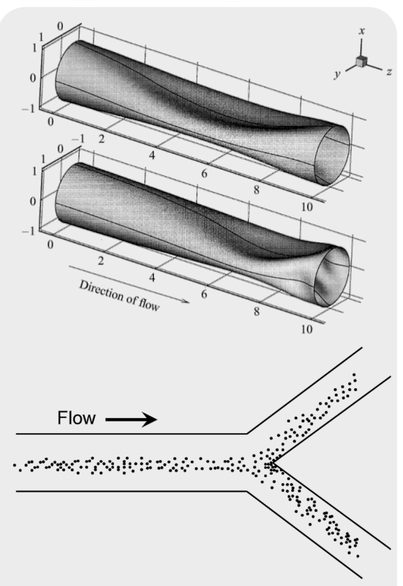
The results show that the flow retains a very similar topology to DNS at Re = 2000, suggesting that the higher velocity, while expected to be fully turbulent at Re = 4200, still retains the same characteristics[2]. The B'-B, C'-C, and D'-D locations all exhibit similar velocity profiles and secondary flows for both Reynolds numbers. In both DNS and experiments, symmetric vortices appear shortly after the first bifurcation. In addition, the increased flow rate and speed of the inner bifurcations is present.

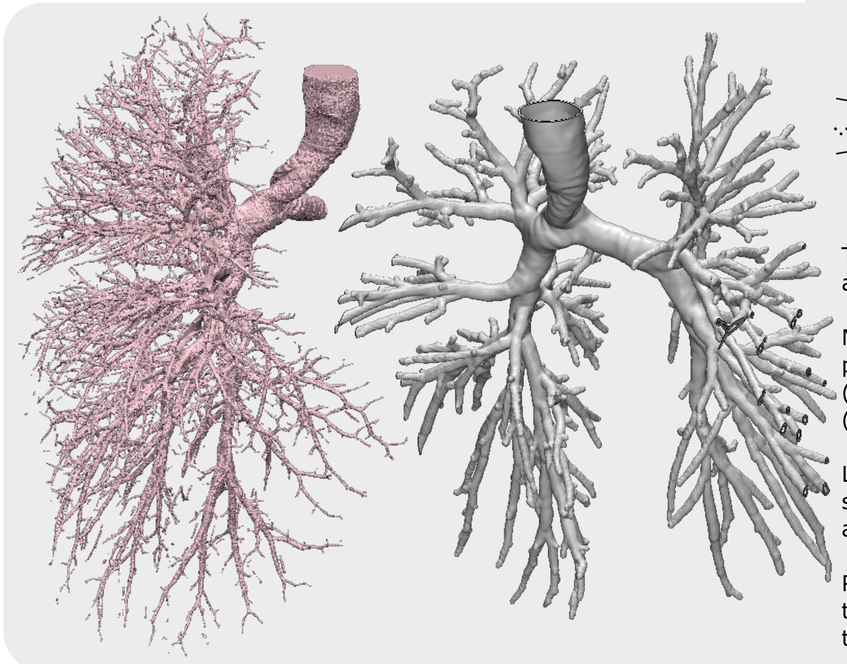
CONCLUSIONS/FUTURE WORK

The flow topology of the Weibel lung model was acquired for Re=4200 experimentally. The results indicate that the same flow topology is observed for this turbulent Reynolds number as observed in DNS simulations at laminar Reynolds numbers.

Comparing these results with the flow fields of realistic human airways can shed light on how these observed secondary flow structure behave in more complex geometries, and what role they might play in particle transport.

Upcoming experiments will focus on oscillatory flow regimes, better representing the pulmonary flow cycle in lung airways. High resolution X-ray computed tomography (CT) scans of lungs will be used to generate patient-specific airway models. Further work will use compliant materials to print these models, to investigate the fluids-structure interaction of the airways. Using a pressurized chamber, these models will be exposed to transmural pressures, resulting in choking of the airways, as seen on the right.





Top: Effects of compliancy when airway is choked. (Heil 1997)

Middle/bottom: Idealized particle transport in solid (middle) and compliant (bottom) bifurcation

Left: 100 micron resolution segmented CT scan of human airways.

Right: CAD of the same model to be 3D printed generated through 3-Matics.

[1] Kleinstreuer C., Zhang Z. and Donohue J. F., 2008, Targeted drug-aerosol delivery in the human respiratory system. Ann. Rev. Biomed. Eng., **10**, 195--220
[2] Comer J. K., Kleinstreuer, C. and Zhang Z., 2001, Flow structures and particle deposition patterns in double-bifurcation airway models., J. Fluid Mech., **35**
[3] Weibel, E.R. 1963, Morphometry of the Human Lung. New York, Academic Press.