Computational Fluid Dynamics Simulation of Airflow in Sheep Lungs

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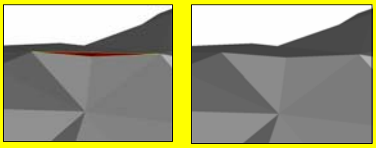
Introduction: To understand the determinants of regional ventilation in the lung, it is important to understand the interaction between gas properties and airway geometry. Hyperpolarized Helium and stable Xenon gases have been used extensively in conjunction with MR and CT respectively for evaluating the regional ventilation of the lung. Our approach is to model the Xenon washin and washout in subject specific airway trees (sheep and human) using Computational Fluid Dynamics (CFD) compared, measured and predicted regional lung function. The sheer complexity of the tracheobronchial tree has limited previous studies to small and piece wise simulations leading to some form of approximations. A procedure for generating a three-dimensional volume mesh for the sheep airway (~9 generations) from CT based STL format is described. Also the results of CFD simulations of airflow in the aforementioned geometry is presented.

Methods: Volume Mesh Generation using Magics and Gambit

The procedure for generating a volume mesh involves three processes:

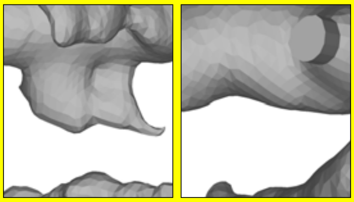
1) STL Manipulation

The software used for STL editing and repair is called Magics from Materialise. Triangles with inverse normals, bad edges, gaps etc in the STL file are repaired using a set of automated tools in Magics. A smoothing algorithm is applied to the surface. With *a priori* knowledge, the regions with noises like bulbous outgrowth from the airway branch are located and cleaned. The terminal airways are trimmed so that they can be specified as outlets. The newly formed face is extruded if the clipped branch is very close to the parent branch to capture any vortices or eddies due to the bifurcation. The final surface is subdivided into seven units to facilitate volume meshing of the individual subunit with varying mesh densities.



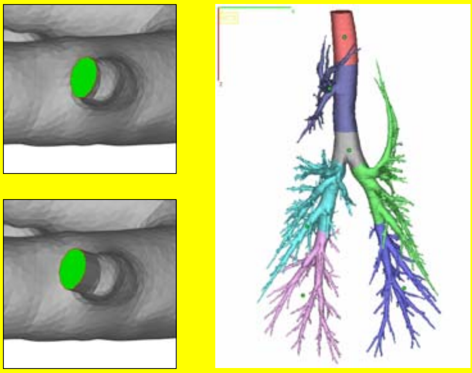
(Left) region with an inverted triangle (red). (Right) after fixing the triangle using an automated tool in Magics.

Surface of the sheep airway before and after smoothing.



(Left to Right) Region with a bulbous outgrowth; Same region after cleaning.

(Top left to Right): polyline defined such that it is nearly perpendicular to the central axis of the airway branch; terminal branch trimmed along the polyline; close up view of the new face.



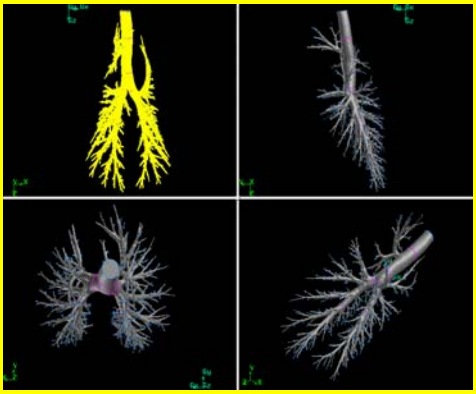
(Top left & Bottom left): Clipped terminal airway before and after extrusion. (Right) Final surface divided into seven subunits, each color represent one unit.

2) Surface mesh generation

The short edges and the hard edges in the surface geometry are removed in Gambit. All the faces representing a subunit are stitched to create a virtual volume. Each subunit is meshed separately using a specified number of interval counts depending upon the mesh refinement required.

3) Volume mesh generation

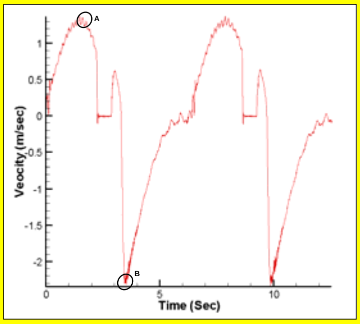
Volume mesh is generated using the T-grid meshing scheme. It consists primarily of tetrahedral mesh elements. Each volume or subunit is meshed separately. The final mesh consists of 3.4 million tetrahedral elements, with 451 outlets and a total of 465 boundary conditions.



Volume mesh for the complete airway (top left). volume mesh in different orientation, with mesh in invisible mode, showing the inlet and the outlets (blue).

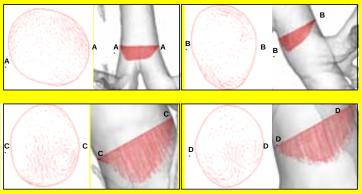
Computational fluid dynamics simulation

Computational methods: The finite element code couples the incompressible Navier-Stokes equations with the level set method. The implicit Taylor-Galerkin approximation together with the fractional four-step algorithm is employed to discretize the governing equations. Velocity boundary conditions were applied at the inlet face. This included steady state inhalation, exhalation and time-dependent breathing pattern. At the outlets both pressure and outflow boundary conditions were used for comparison.

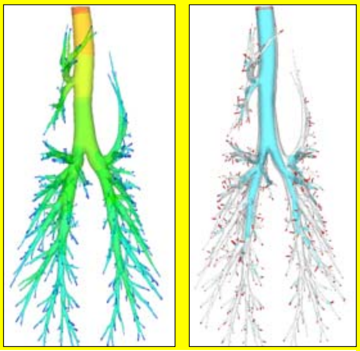


Velocity with respect to time measured during CT based experiments. Point A used for steady inhalation; Point B used for steady exhalation.

Results: The flow in the trachea is skewed and not fully developed unlike flows noticed in Weibel based geometries. Beyond the bifurcation, the flow is skewed towards the inner wall in the plane of the bifurcation due to the centrifugal instability. It can also be noticed that the flow is asymmetric about the plane of the bifurcation. Beyond the second bifurcation the flow is complex.



Velocity vectors along the diameter and in-plane. Top Left: In trachea. Top Right: Midpoint of generation 1. Bottom Left: Midpoint of generation 4. Bottom Right: Midpoint of generation 6.



(Left): absolute pressure during inhalation; (Right) absolute velocity.

Conclusion: A novel approach to generate an unstructured volume mesh for a topologically truthful geometry using Magics and Gambit has been presented. Also CFD simulation of airflow in a sheep tracheobronchial tree (~9 generations) has been demonstrated.

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