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Computational investigation of airflow dynamics in human airways

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Computational Investigation of Airflow Dynamics in Human Airways

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Outline

- Introduction
- Computational Setup
- Preliminary Results
- Summary

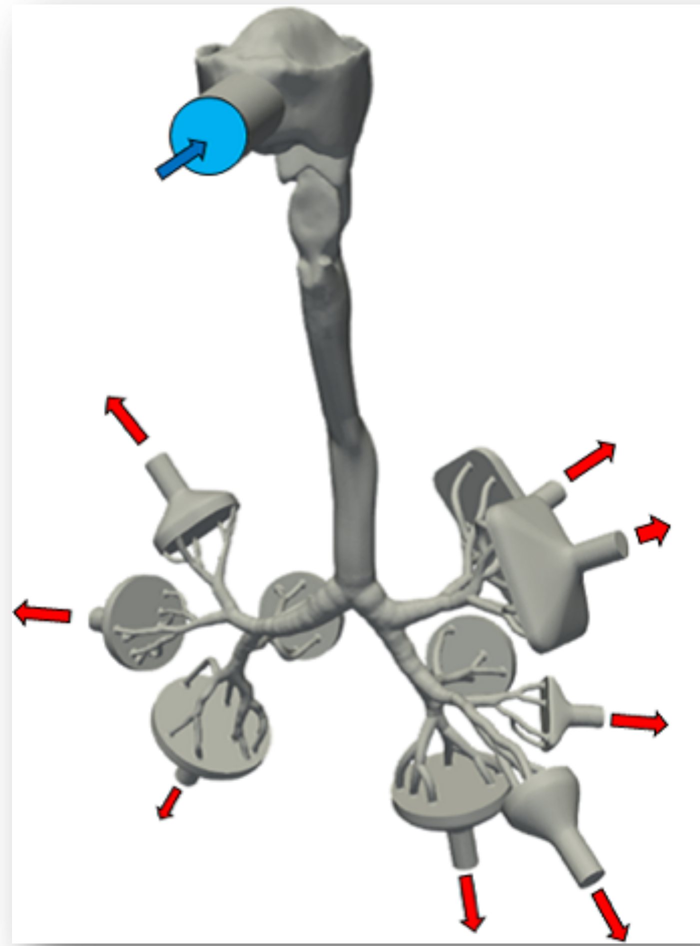
Introduction

- Aerosolized drug delivery is key to treatment of pulmonary ailments such as asthma, COPD, lung tumors, pulmonary infection[1,2]
- Improved regional deposition of inhaled drugs crucial for maximizing drug efficiency and minimizing side effects
- Advanced imaging techniques such as MRI, HRCT, PET, and QCT:
  - Enabled objective assessment of phenotype of airways through *in vitro* and *in vivo* experiments
  - Information tend to be limited for effective treatment
- Computational tools useful to examine airflow patterns and localized deposition in respiratory airways[3-10]
- Computational investigation is challenging due to geometric complexities, wide range of flow patterns, aerosol dynamics, etc.
- **Objective:** to establish a computational framework for investigation of regional aerosol deposition within upper airways
- **Current focus:** investigate flow pattern in a realistic extrathoracic airways

[1]Busse (2001); [2]Finlay (2001); [3]Stapleton (2000); [4]Matida et al. (2004); [5]Jin et al. (2007); [6]Jayaraju et al. (2007); [7]Dehbi (2011); [8]Longest & Holbrook (2012); [9]Nicolaou & Zaki (2013); [10]Koullapis et al. (2018)

Computational Setup

- SimInhale case[1] is considered in this study
  - A Benchmark Case
  - Geometry available in STL format
  - Reduced from respiratory airways comprising of up to 12th generation
  - Comprise of 1 inlet and 10 outlets
  - Retains pathways with diameter greater than 3 mm retained
- Results available for 3 inhalation flow rates
  - 15 L/min, 30 L/min, 60 L/min
  - First two cases exhibit laminar to turbulent transition and last case is fully developed turbulent flow
- Data available for comparison of both flow field and particle deposition

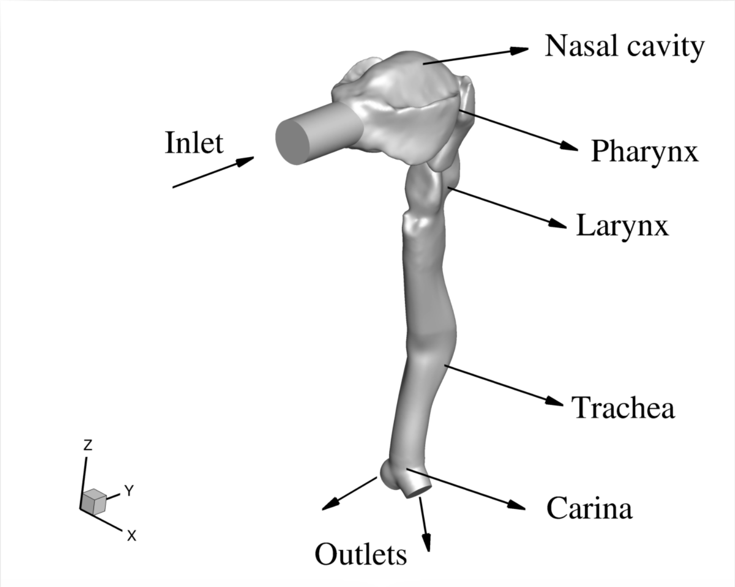


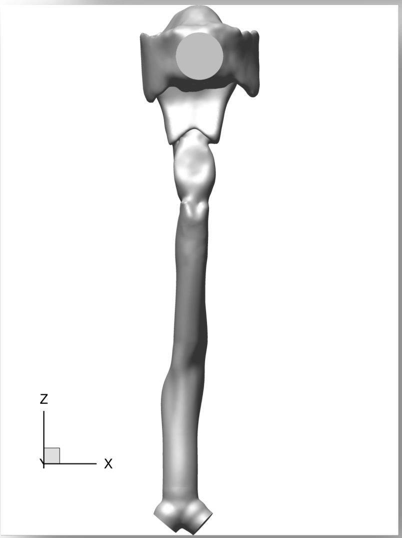
SimInhale Model[1]

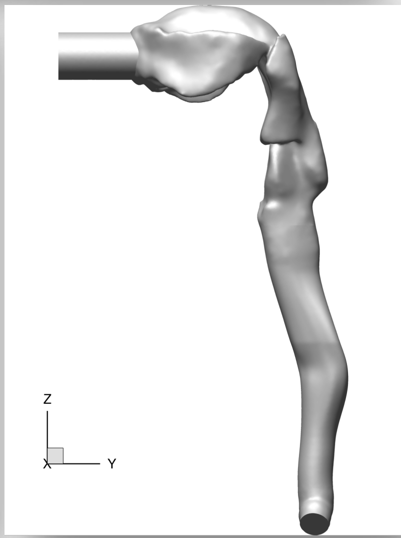
[1]*Koullapis et al. (2018)*

Computational Setup

- **Domain:** truncated SimInhale geometry comprising of extrathoracic airways
- **Details of computational mesh:**
  - Number of cells: 1.6 M
  - Tetrahedral cells with 3 prism layers adjacent to walls
- **Boundary conditions:**
  - Turbulent inlet conditions with 10% turbulence intensity ($Re_{in} = \frac{U_{in} d_{in}}{\nu}$ = 936)
  - Two outlets (parts of left and right bronchus)
  - No-slip boundary condition specified on all walls
- Large eddy simulation (LES) performed using an in−house customized version of OpenFOAM[1] solver: LDKM[2] used for closure of eddy viscosity





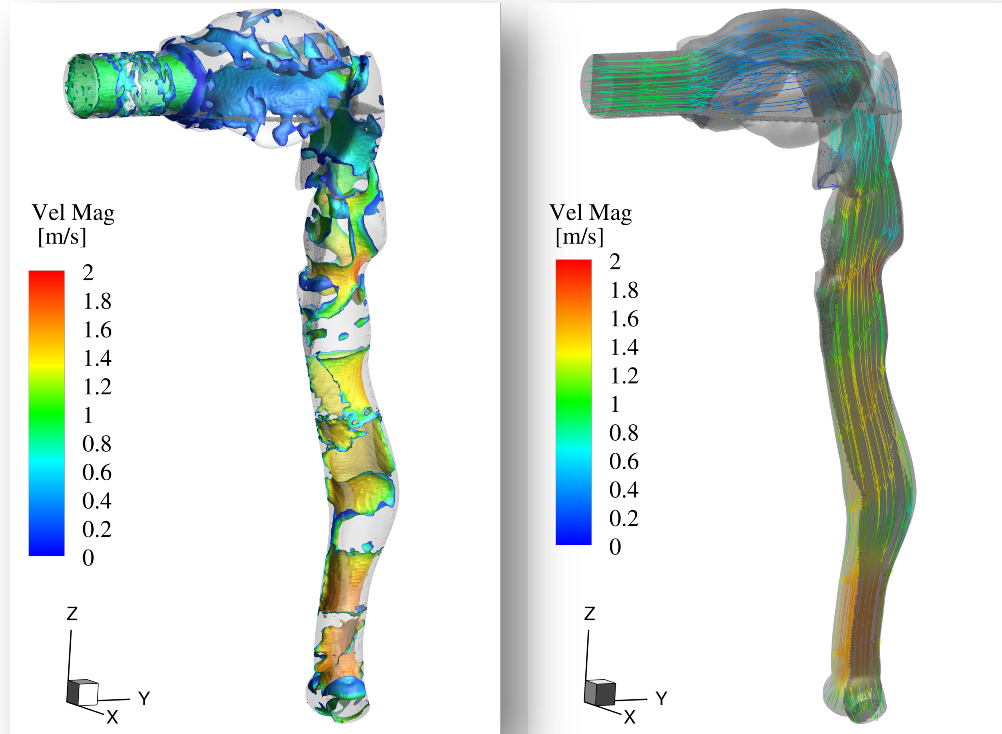


Truncated Model

[1]www.openfoam.com; [2]Kim & Menon (1999)

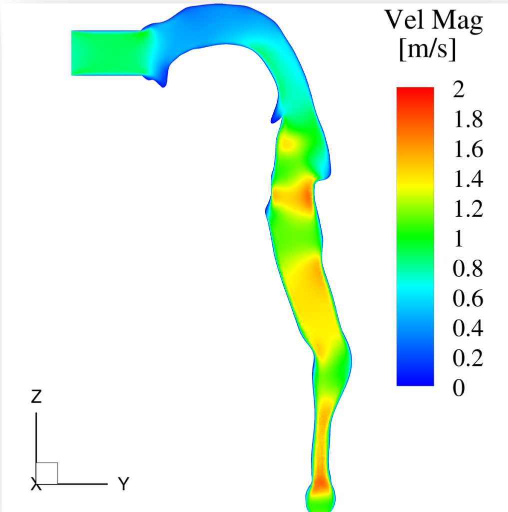
Preliminary Results: Flow Structures

- Q-criterion and streamlines show complex 3D flow patterns: flow separation, reattachment, shear layers, etc.
- Complex geometry with curvature and bends modulate flow field:
  - Expansion in nasal cavity region reduces velocity magnitude
  - Constriction in larynx region accelerates flow
  - Shear layer occurs post larynx region
- Such flow patterns can significantly affect local aerosol deposition

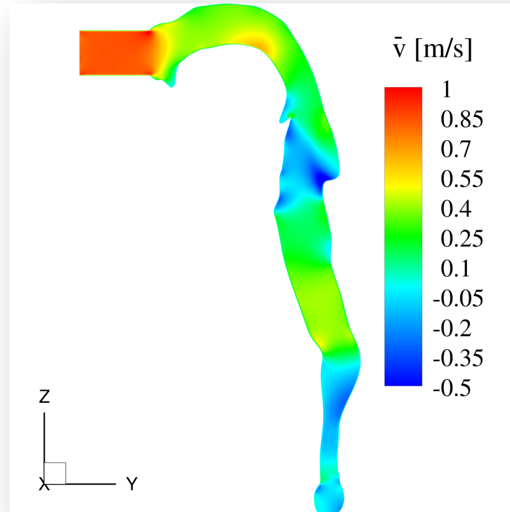


Q-criterion Streamlines

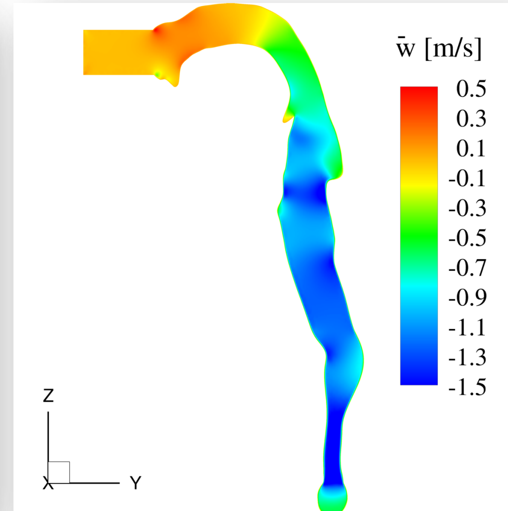
Preliminary Results: Instantaneous Flow Field



Velocity magnitude

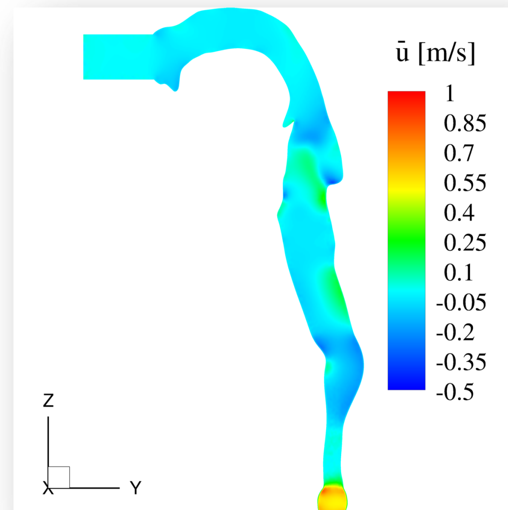


y-component of velocity



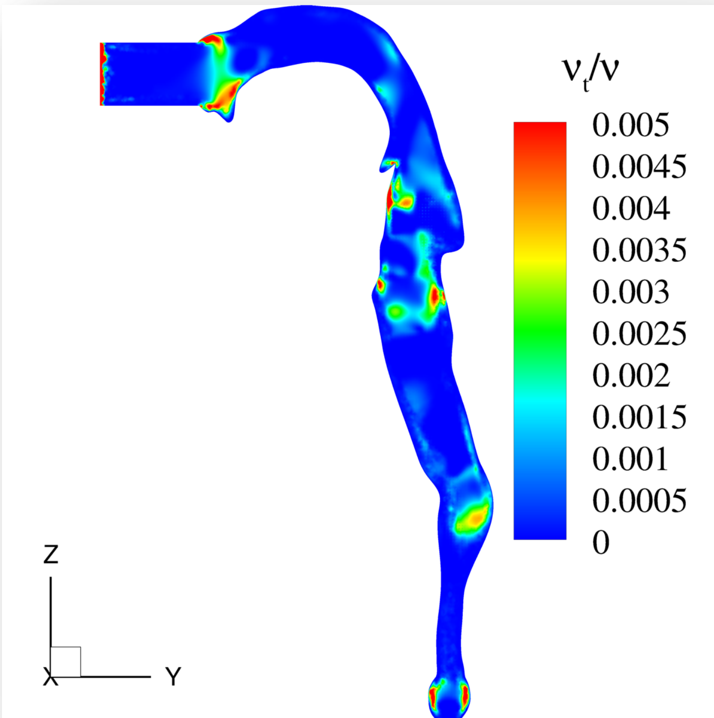
z-component of velocity

- Significant variation of velocity field in central sagittal plane observed as flow occurs through extrathoracic airways
- Effect of airway curvature and bends lead to formation of shear layers and flow separation

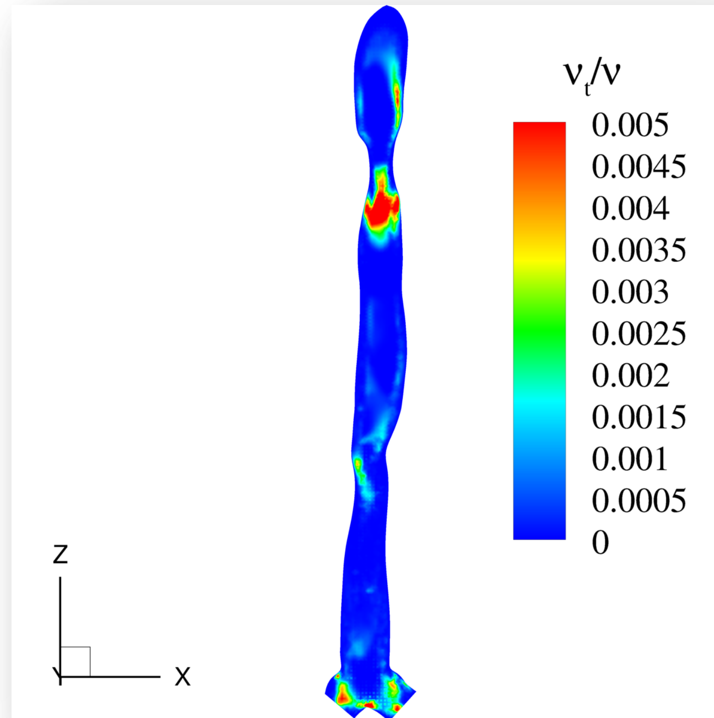


x-component of velocity

Preliminary Results: Instantaneous Eddy Viscosity



Central Sagittal Plane



Central Frontal Plane

- Ratio of eddy and kinematic viscosity used to identify regions where contribution of subgrid-scale (SGS) model is significant
- Significant SGS contributions evident in near-wall regions, shear layers, expansion/contraction regions

Summary

- LES of airflow within extrathoracic airways performed using truncated geometry of SimInhale case
- Preliminary results show complex 3D flow patterns due to airway curvature and bends
- SGS contribution is evident in different parts of airway regions
- Future Work:
  - Perform validation study by comparing with available statistical data
  - Examine sensitivity of results to different SGS models
  - Simulate aerosol dynamics and compare regional aerosol deposition with experimental data