A Numerical Study of Airway Resistance and Particle Deposition in Normal and Asthmatic Lungs

Sanghun Choi[1,2], Eric A. Hoffman[3,4,5], Merryn H. Tawhai[6], Mario Castro[7], and Ching-Long Lin[1,2]

[1]Department of Mechanical & Industrial Engineering, [2]IIHR-Hydroscience & Engineering,
Departments of [3]Biomedical Engineering, [4]Medicine and [5]Radiology, The University of Iowa, Iowa City, IA, USA
[6]Auckland Bioengineering Institute, The University of Auckland, Auckland, New Zealand
[7]Washington University, St. Louis, MO, USA

ABSTRACT

Rationale:
Computational fluid dynamics (CFD) has become a popular tool for studying particle deposition in the lungs because they can be used to track individual particle motion and quantify particle deposition in a region of interest. In the study, we apply a high-fidelity CFD model together with CT image based airway models to study airway resistance and particle deposition in both normal and asthmatic lungs. The objective of this study is to investigate numerically the effect of constricted airways, as in the asthmatic lung, on airway resistance and particle deposition.

Methods:
Two human airway models are constructed from CT volumetric images. One subject is normal, and the other is asthmatic. The subject-specific physiologically realistic flow boundary condition is derived based on air volume difference between two CT lung images of the same human subject. Because turbulent laryngeal jet is induced at the glottal constriction in the trachea, a large eddy simulation (LES) technique is adopted to capture turbulent-transitional-laminar flows in the central airways. A constant inspiratory flow rate of Q=3.42×10^{-4} m^3/s is imposed at the inlets of the two airway models. In order to understand the characteristics of deposition of pharmaceutical aerosols or bacteria in both models, particle transport simulations are performed on LES-predicted air flow fields. Particle size of 2.5 µm is considered. Airway resistances $R = \Delta p/Q$, where Δp is the pressure drop and the unit of R is Pa/(m^3/s), for various generations of airway segments in both models are shown in Table 1 for comparison.

Results:
The result shows significant pressure drop (~ 200 Pa) and airway resistance (~7420 Pa/(m^3/s)) in the asthmatic lung, especially in the right upper lobe (RUL) and the left lower lobe (LLL). It is found that local high pressure drop is associated with local high air speed due to constricted airways. Figure 4 shows that particles tend to be deposited in the RUL and LLL. The color contours of air speed in figure 3 show that that local airway constriction induces high air speed and increases particle deposition in the constricted regions and at their downstream bifurcations.

Conclusion:
The obstructed airways can induce high airway resistance and subsequently increase particle deposition in the constricted regions and at their downstream bifurcations.

References

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J. Choi, M. H. Tawhai, E. A. Hoffman and C.-L. Lin (2009). On intra- and intersubject variabilities of airflow in the human lungs, *Physics of Fluids*, Vol. 21

Acknowledgements

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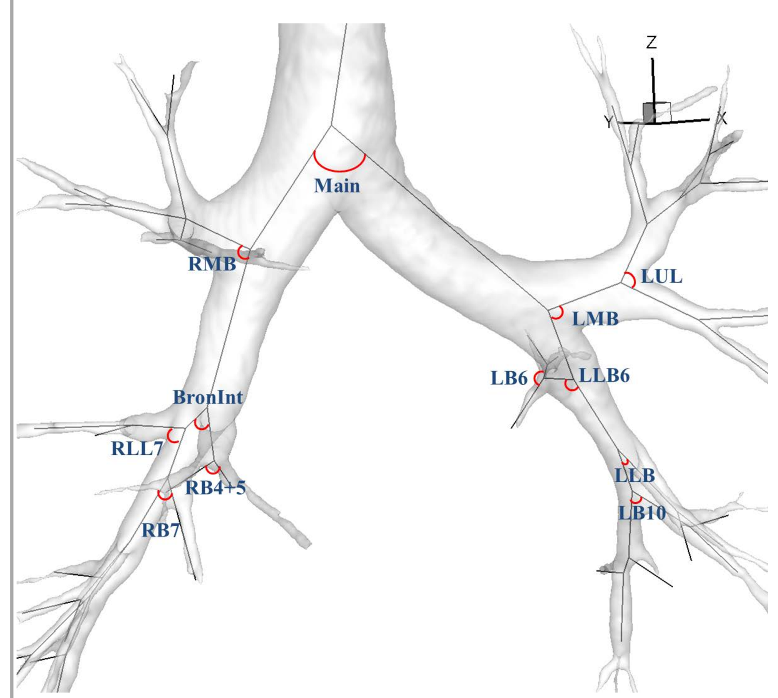
Comparison of bifurcation angles

- CT image-based geometry is used for the simulation.
- Bifurcation angle is one of the important parameters to determine flow characteristics.

$$Angle = \cos^{-1}\left(\frac{\mathbf{d1}\cdot\mathbf{d2}}{|\mathbf{d1}||\mathbf{d2}|}\right)$$



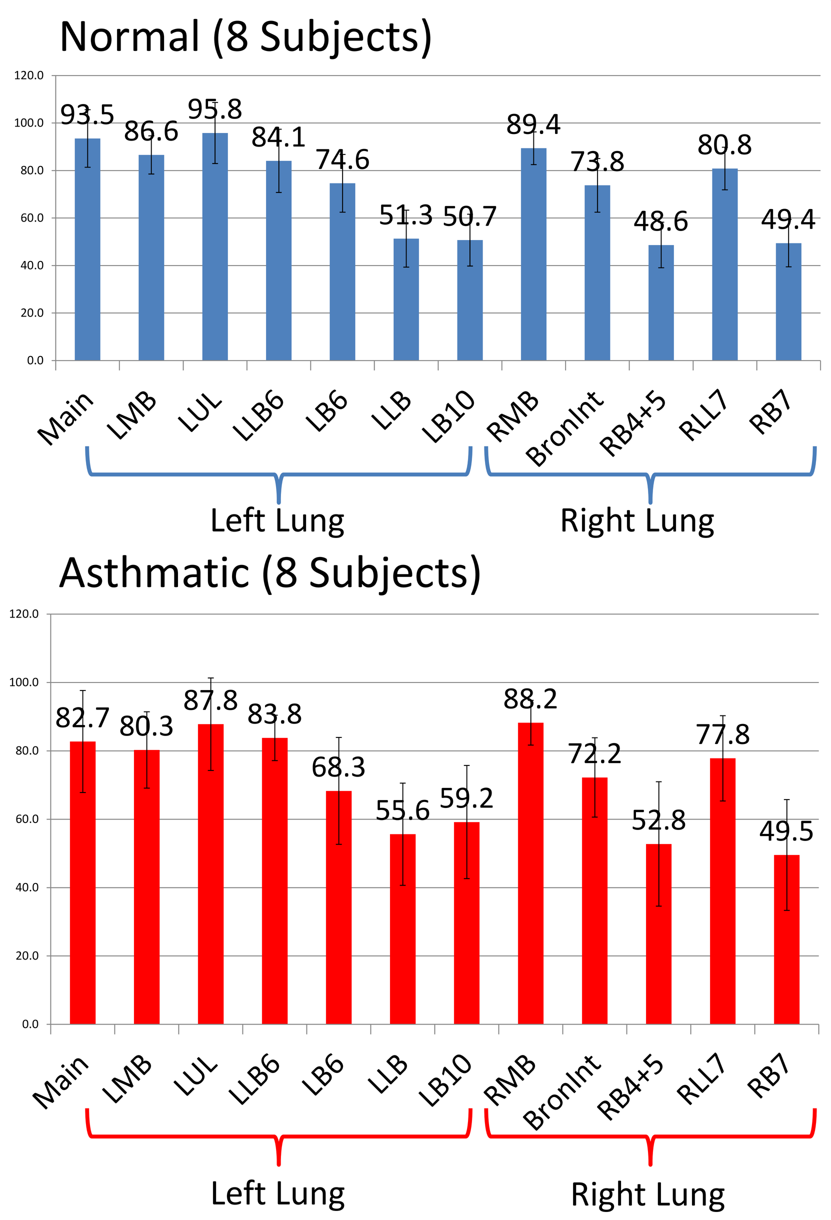
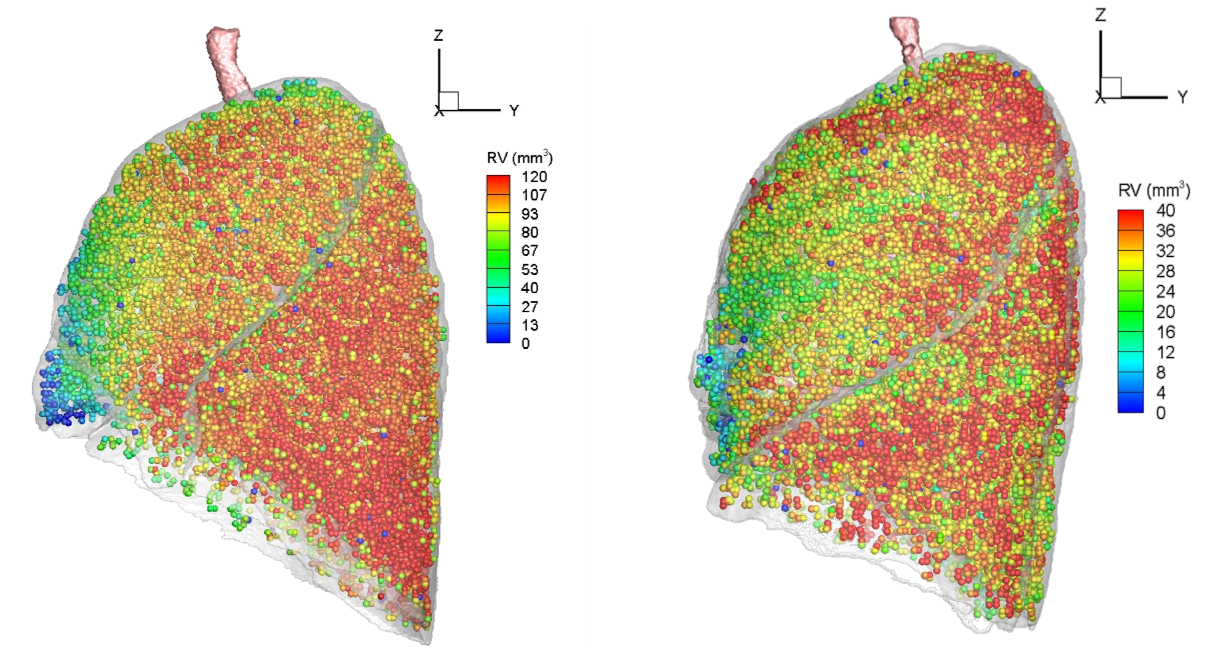


Figure 1. Comparison of bifurcation angles between normal and asthmatics

Ventilation fraction

- To obtain boundary conditions based on ventilation fraction, image registration based on mass-preserving method (Yin *et al.* 2009) is performed.
- Ventilation of asthmatic lung shows irregular distributions than normal subject.
- This difference is reflected to boundary conditions of 3 D ending branches obtained from CT image.



(a) A normal subject (b) An asthmatic subject

Figure 2. Ventilation distribution in terminal bronchioles

CT based geometry

Boundary conditions

CFD and Particle simulation

Flow structure

- A large eddy simulation technique is adopted to capture turbulent-transitional-laminar flows in the central airways.
- The region of high velocity is observed according to the constricted airways, resulting in high pressure drop especially LLL and RUL.

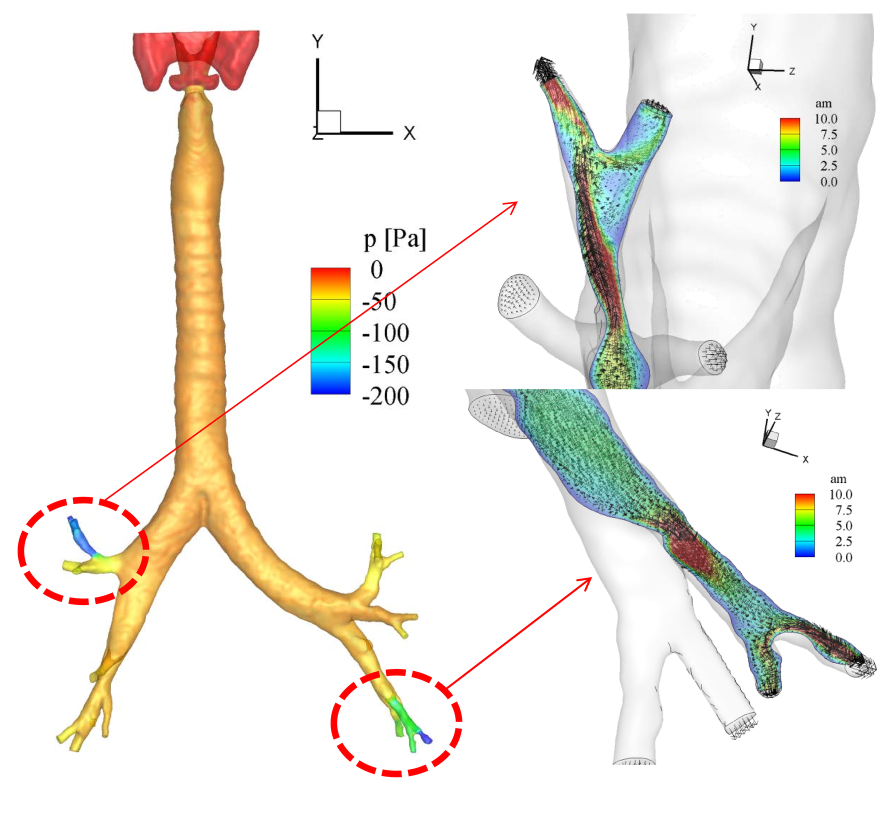


Figure 3. Pressure on the entire geometry and velocity profiles on constricted airways

Particle deposition

- The region of constricted airways is consistent with the spots of high particle deposition.
- We can deduce that the spots could be main sources affecting asthma infected by bacteria.
- This information can also help determining the size of pharmaceutical aerosols.

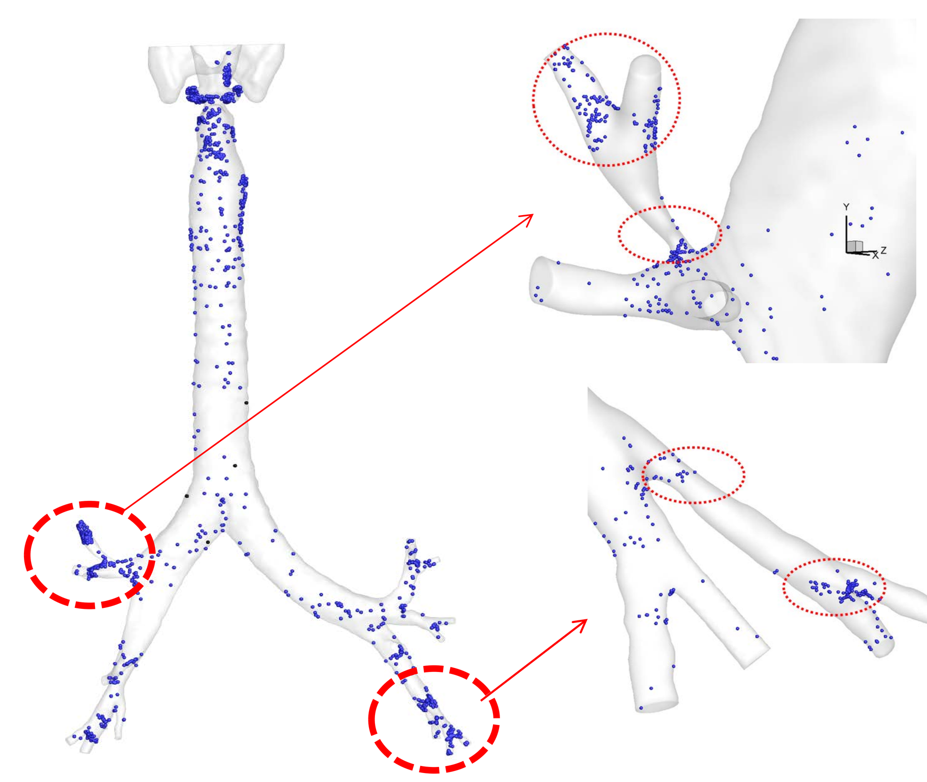
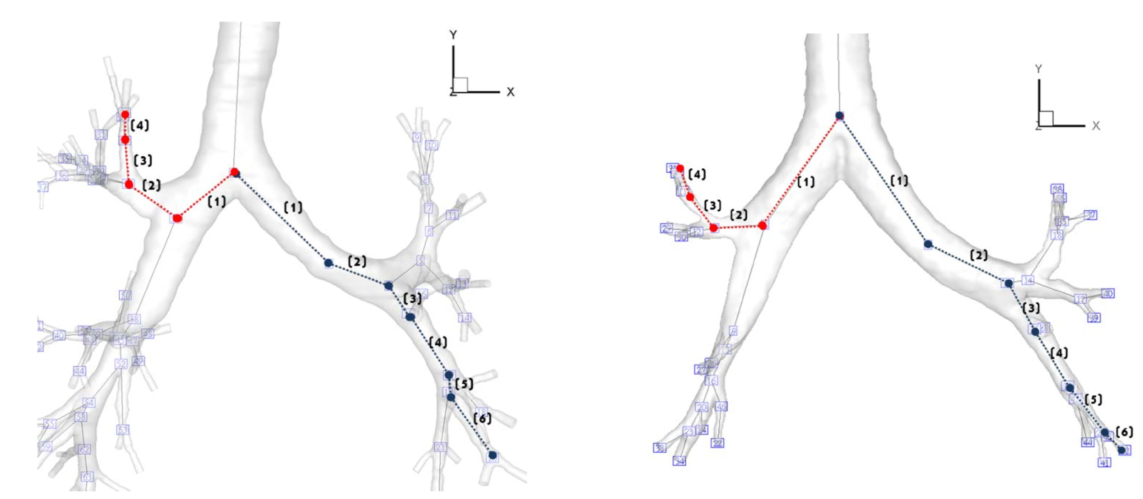


Figure 4. Particle depositions on the entire geometry and constricted airways

Pressure drop (Δp) and Resistance (Q/Δp)

- According to the central 1D tree, pressure drop and resistance are calculated quantitatively.
- Significant pressure drop (~ 200 Pa) and airway resistance (~7420 Pa/(m^3/s)) are observed in the asthmatic subject.



(a) A normal subject (Choi *et al.* 2009) (b) An asthmatic subject (In this study)

Figure 5. Schematics of 1D lines in a normal and an asthmatic

Table 1. Pressure drop and resistance according to the 1 D line

(a) Pressure drop

Gen.	RUL		LLL	
	Asthmatic	Normal	Asthmatic	Normal
(1)	0.929	0.170	2.357	1.875
(2)	27	1.037	0.631	-0.065
(3)	131	0.422	2.149	0.157
(4)	31.9	0.261	4.079	1.618
(5)			62.393	0.257
(6)			127.931	4.951
Total	191	1.89	199.5	8.79

(a) Resistance

Gen.	RUL		LLL	
	Asthmatic	Normal	Asthmatic	Normal
(1)	5.34	0.98	14.01	11.11
(2)	406.15	23.93	3.75	-0.39
(3)	4494.17	41.58	22.82	1.32
(4)	1666.46	60.15	59.40	17.00
(5)			1805.62	3.28
(6)			5514.15	147.12
Total	6572.12	126.64	7419.75	179.44