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An interdisciplinary study of pulmonary fluid dynamics with medical imaging, machine learning, and high-performance CFD methods

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  - Korean Asians vs. White Americans
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- **Aerosol Delivery for Healthy Subjects vs. Asthmatics**
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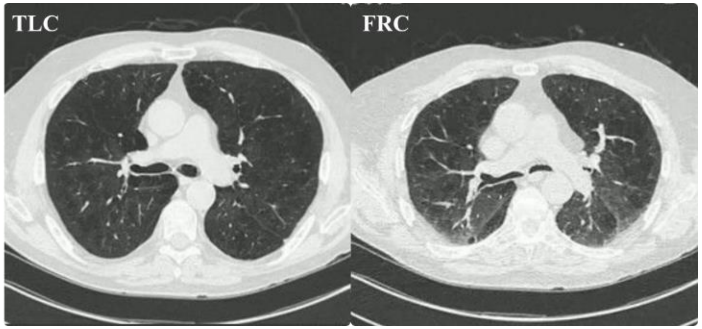
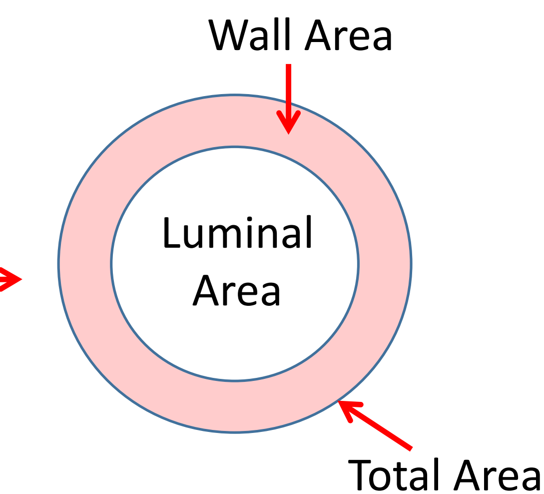
Derivation of QCT Imaging-Based Structural and Functional Metrics

QCT-based Segmental Structural Variables



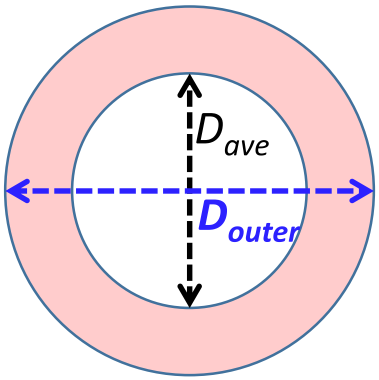
TLC : Total lung capacity
FRC : Functional residual capacity

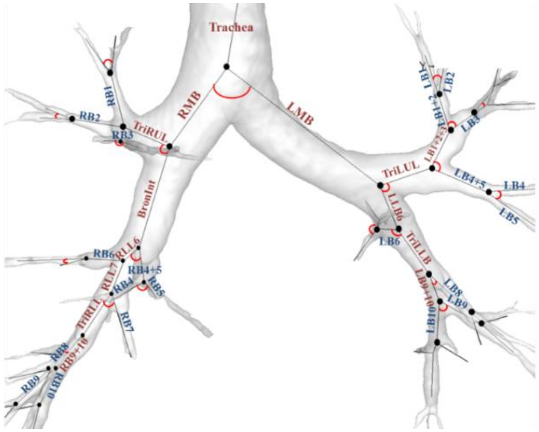
Pulmonary automatic segmentation program

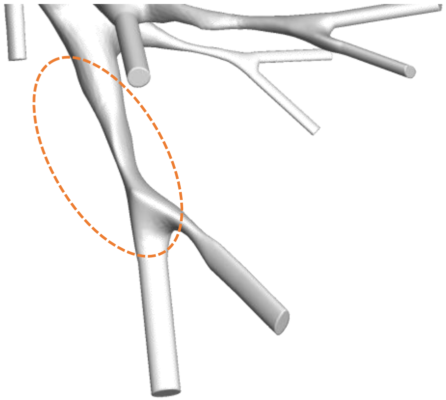


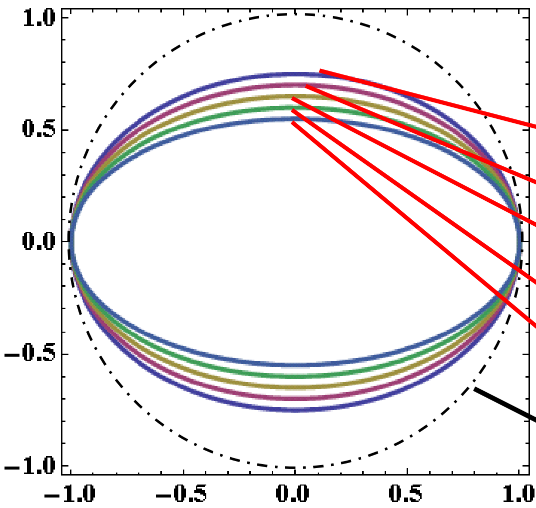
Segmental STRUCTURAL VARIABLES

- **Wall thickness (WT), Bifurcation angle (*θ*), Circularity (*Cr*) and Hydraulic diameter (D_h)**









Cr	major axis / minor axis
0.985	1.333
0.977	1.429
0.966	1.538
0.953	1.667
0.937	1.818

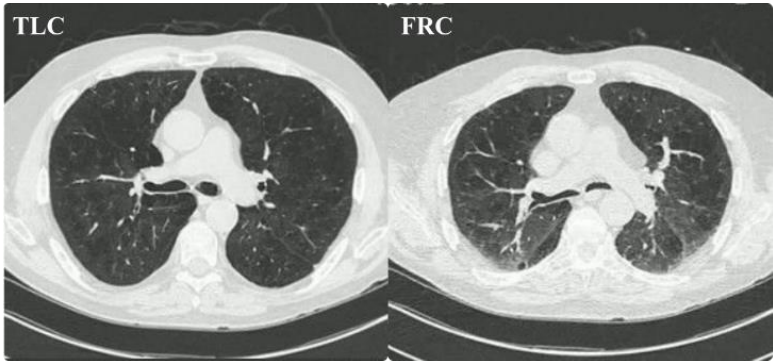
***Cr* = 1**

$$WT = D_{outer} - D_{ave}$$

$$\theta = \cos^{-1}\left(\frac{\mathbf{d}_1 \cdot \mathbf{d}_2}{|\mathbf{d}_1||\mathbf{d}_2|}\right)$$

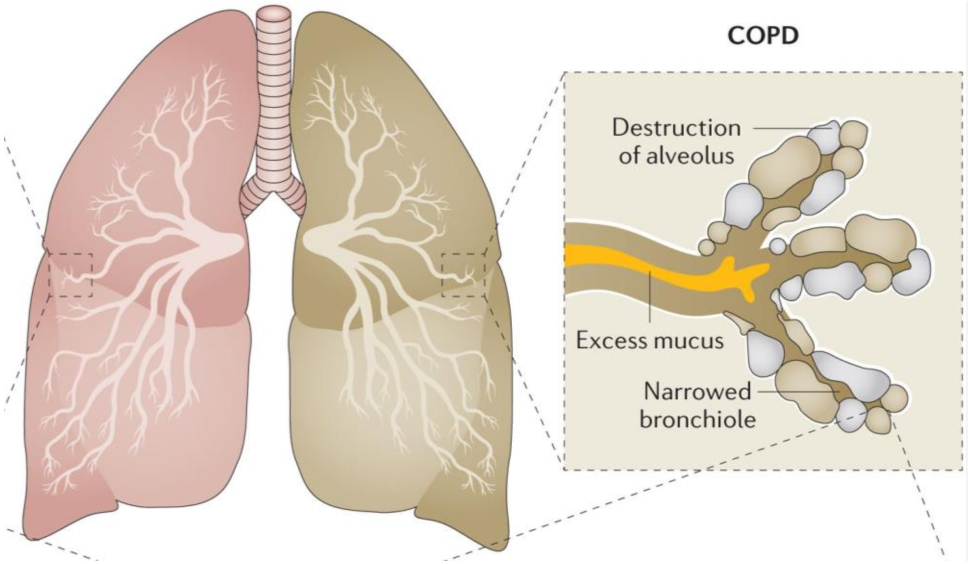
$$Cr = \frac{\pi D_{ave}}{P_e} \qquad D_h = \frac{4 \times LA}{P_e} = \frac{Cr^2}{\pi} P_e$$

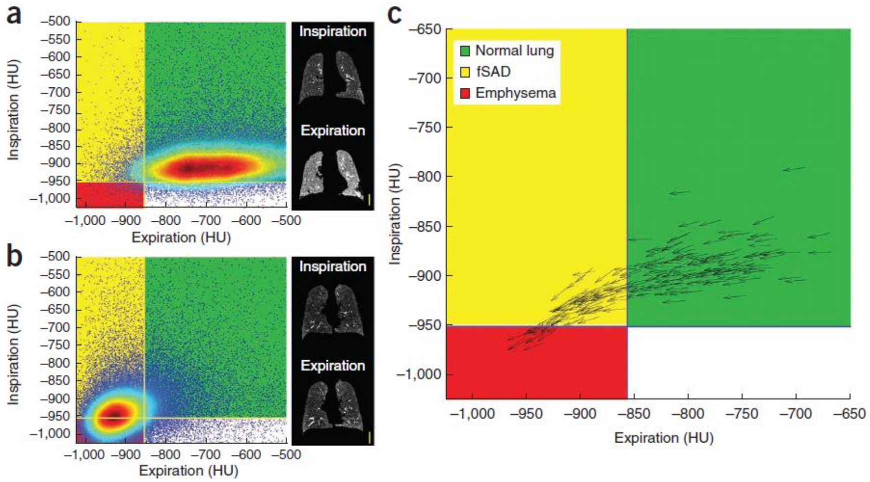
QCT-based Structural and Functional Metrics



TLC : Total lung capacity
FRC : Functional residual capacity

Insight Segmentation and Registration Toolkit

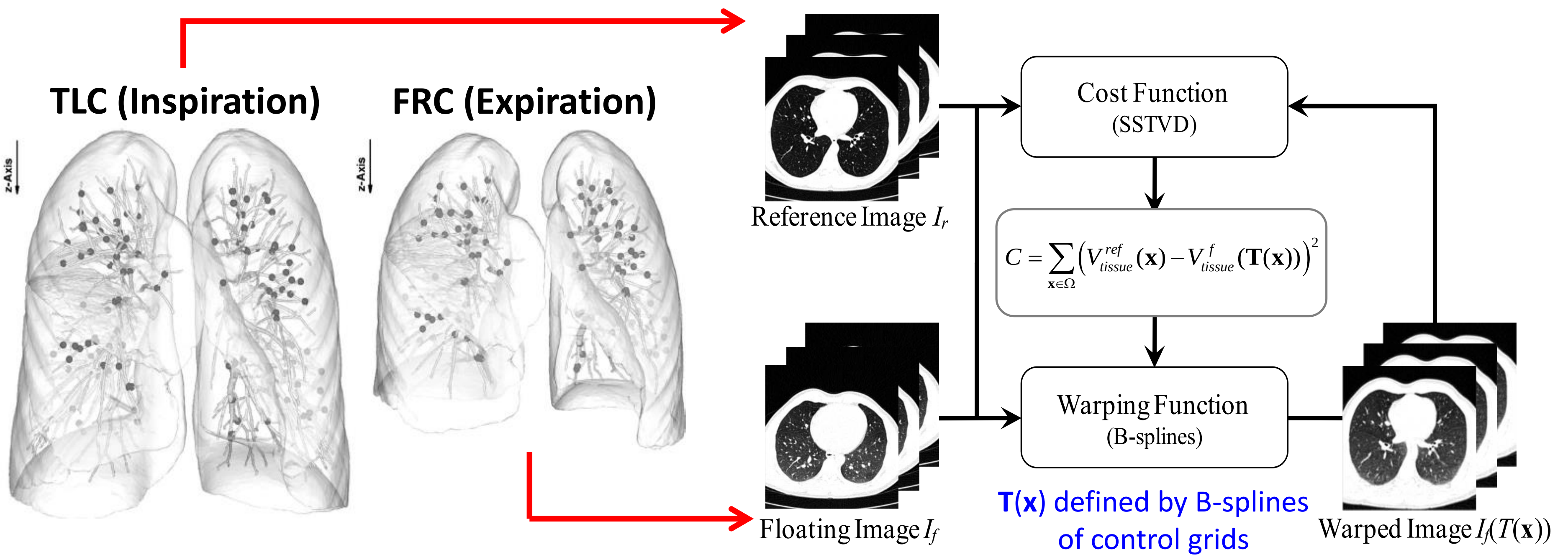




Galban et al. 2012 (Nature Med)

IMAGE REGISTRATION TECHNIQUE

- A **mass preserving image registration*** is employed to match two sets of images.
- Assume that tissue volume remains the same between two inflation levels.



* Yin et al. (2009, *Med Phys*)

SSTVD: sum of squared tissue volume difference

L-BFGS-B: Optimize displacements of control grids

REGISTRATION-DERIVED METRICS

- **Air volume change**:

$$\Delta V_{air}(\mathbf{x}) = V_{air}^{ref}(\mathbf{x}) - V_{air}^{f}(\mathbf{T}(\mathbf{x}))$$

Air volume change:
Local **air volume difference** between TLC (reference) and FRC (floating)

- **Jacobian:**

$$J = \lambda_1 \lambda_2 \lambda_3$$

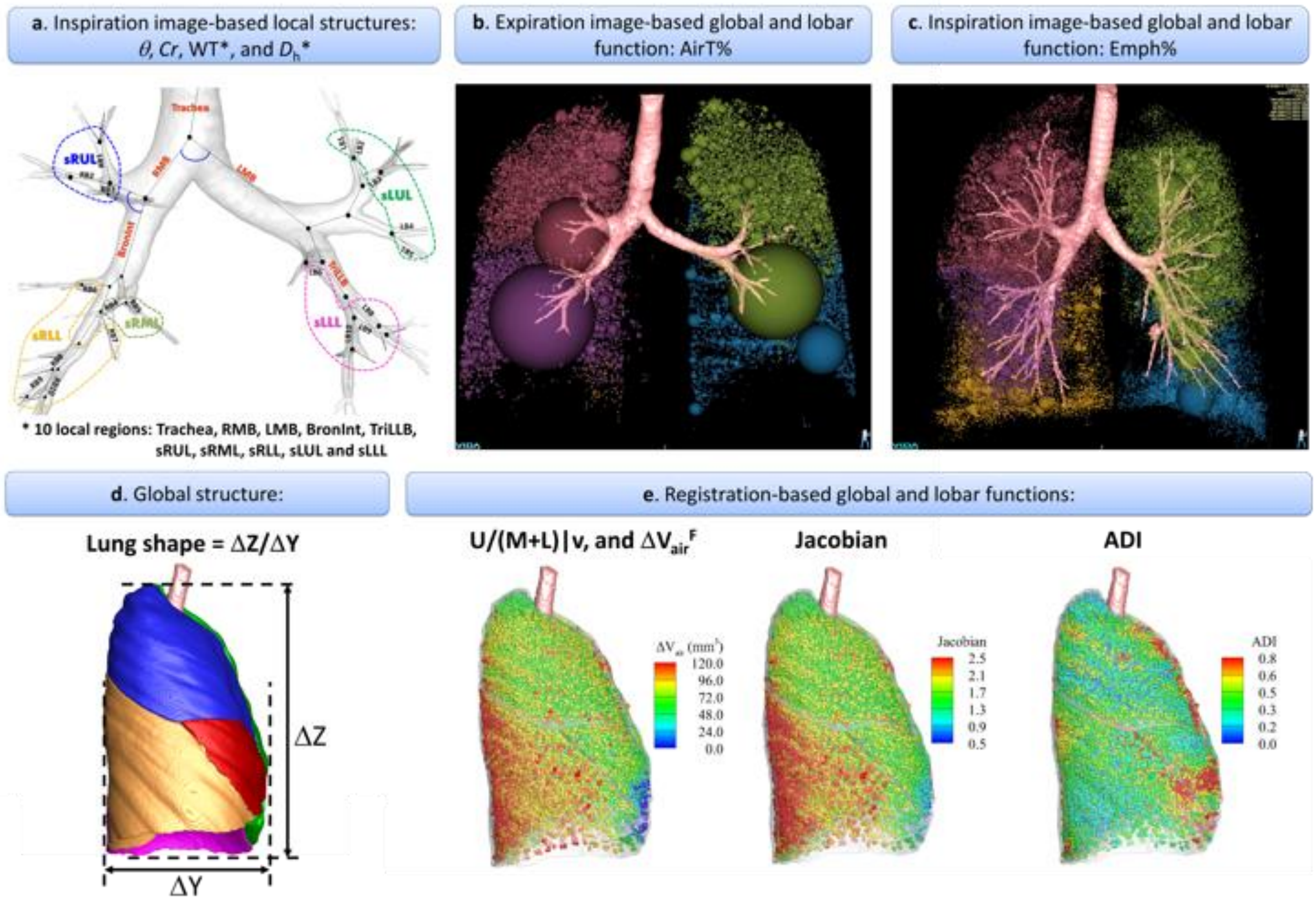
***J* (The determinant of Jacobian)**:
Local **volume ratio** of TLC to FRC **including tissue and air volumes**
(*J*>1 : Expand, *J*=1: same, *J*<1:Contract)

- **Anisotropic Deformation Index*:**

$$ADI = \sqrt{\left(\frac{\lambda_1 - \lambda_2}{\lambda_2}\right)^2 + \left(\frac{\lambda_2 - \lambda_3}{\lambda_3}\right)^2}$$

ADI (Anisotropic deformation index):
ADI increases, if **one or two directional strains** are greater than others. If it deforms **isotropically** ($\lambda_1 = \lambda_2 = \lambda_3$), ADI is **zero**.

QCT-based Structural and Functional Metrics



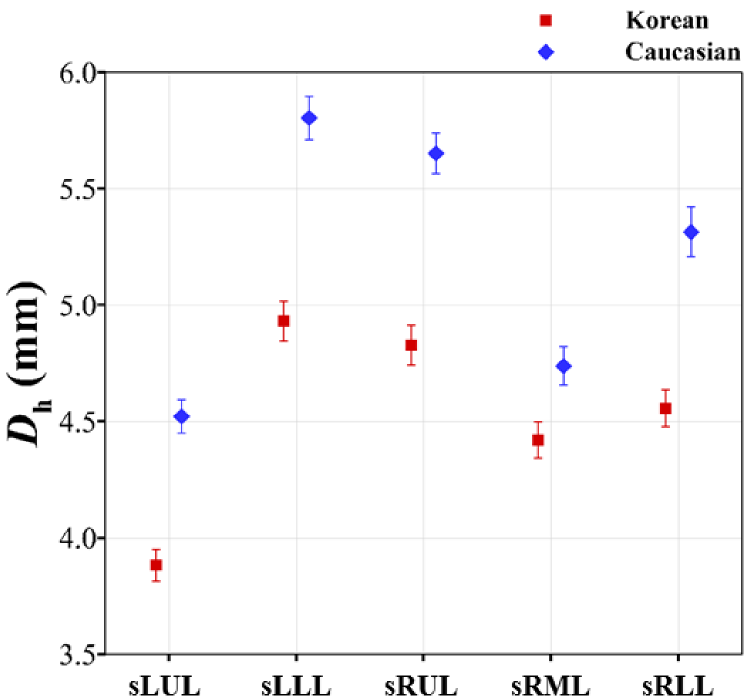
Choi et al. 2017 (J Allergy Clin Immunol), Quantitative computed tomographic imaging-based clustering…

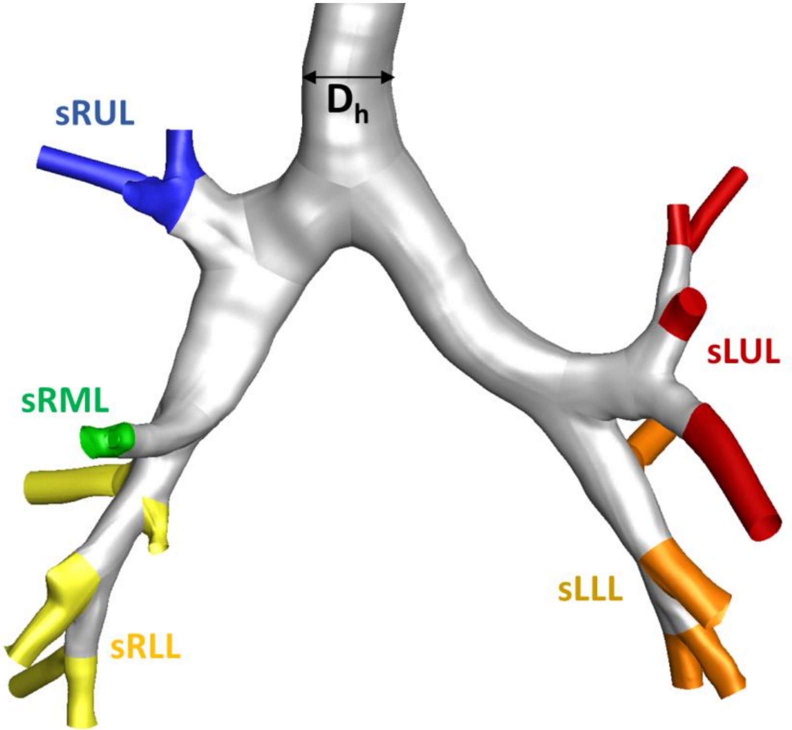
Airway Structure and Lung Function

- Koreans vs. Whites
- Healthy vs. Dust Exposed

QCT RESULTS I

- **64 Koreans vs. 64 Whites**

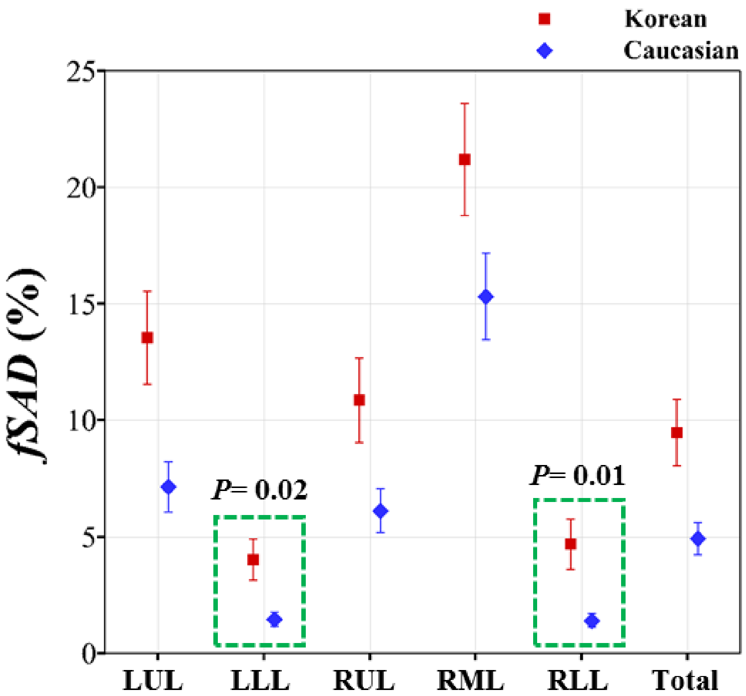


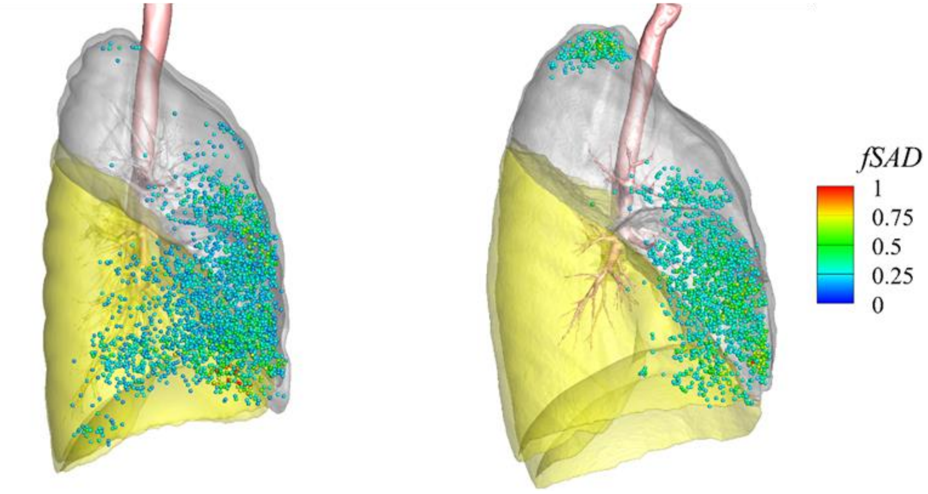


Airway hydraulic diameter (D_h) was smaller in Koreans than that in Caucasians

QCT RESULTS I

- **64 Koreans vs. 64 Caucasians**



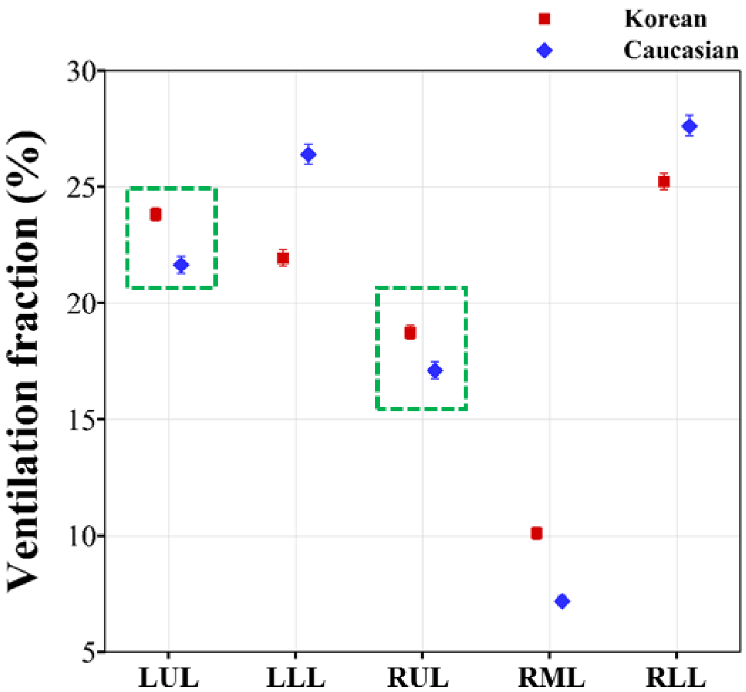


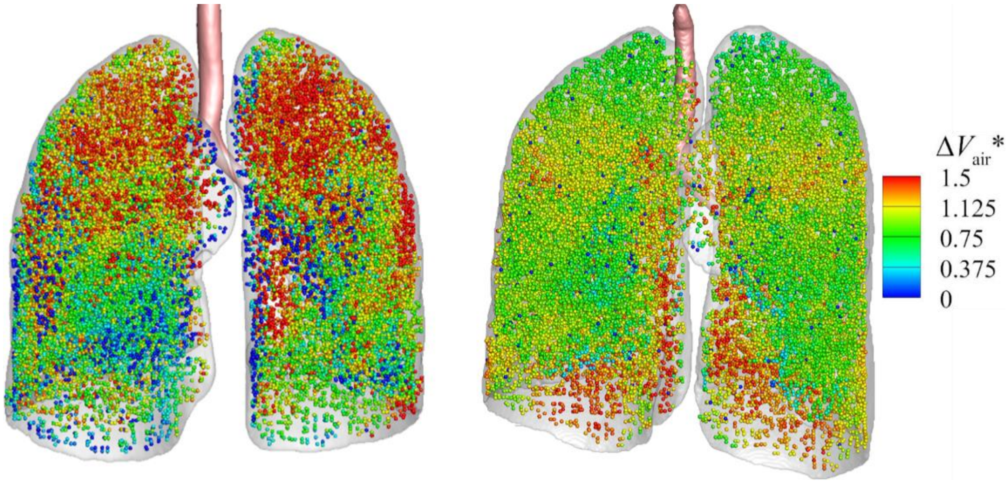
<Korean> <Caucasian>

Percent of functional small airway disease (fSAD%) of Koreans was significantly **larger** than Caucasians **especially in lower lobes.**

QCT RESULTS I

- **64 Koreans vs. 64 Caucasians**





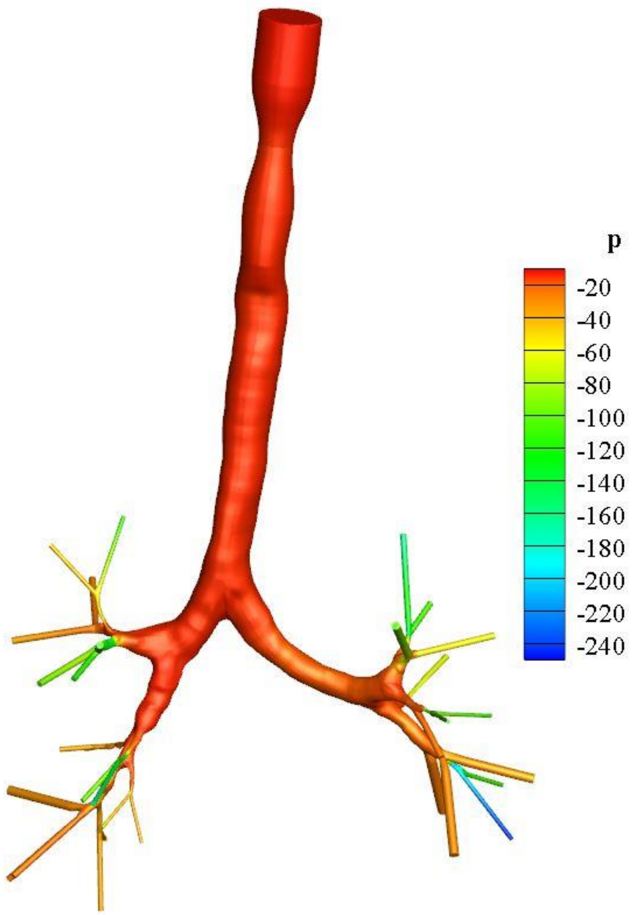
<Korean> <Caucasian>

Ventilation fraction of lower lobes in Korean was smaller than that of Caucasian, consistent with larger fSAD% in the same lobes of Korean.

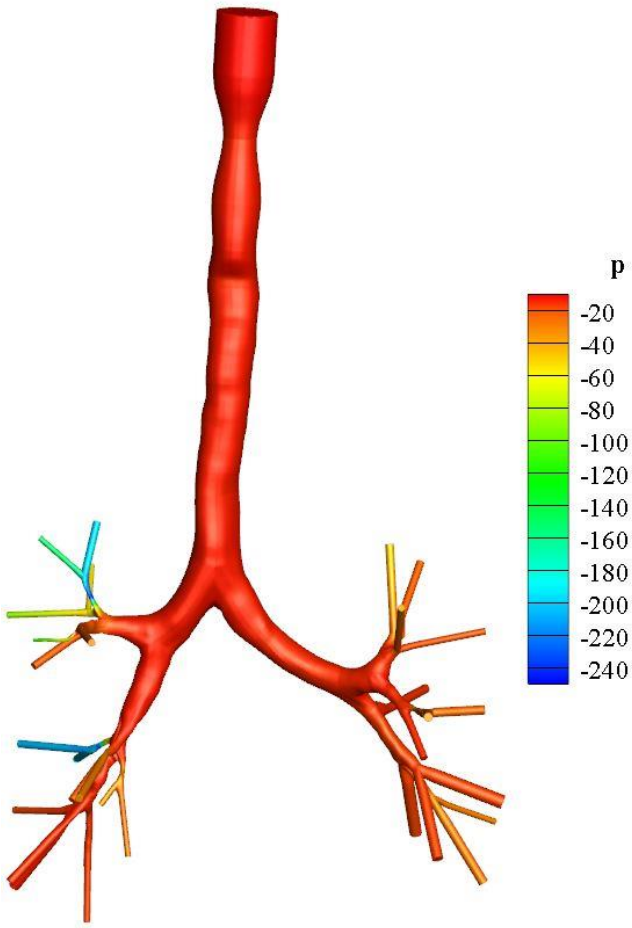
Asthma Attack vs.
Lung Function Recovery

QCT RESULTS III

- **An patient with asthma attack**



A patient with asthma attack

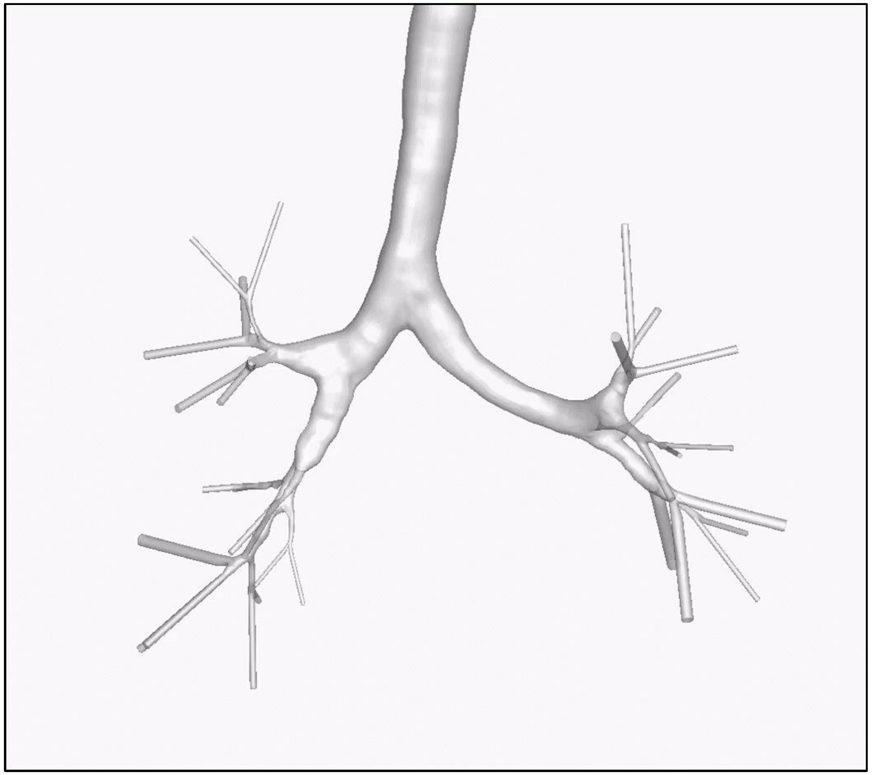


A patient after recovery

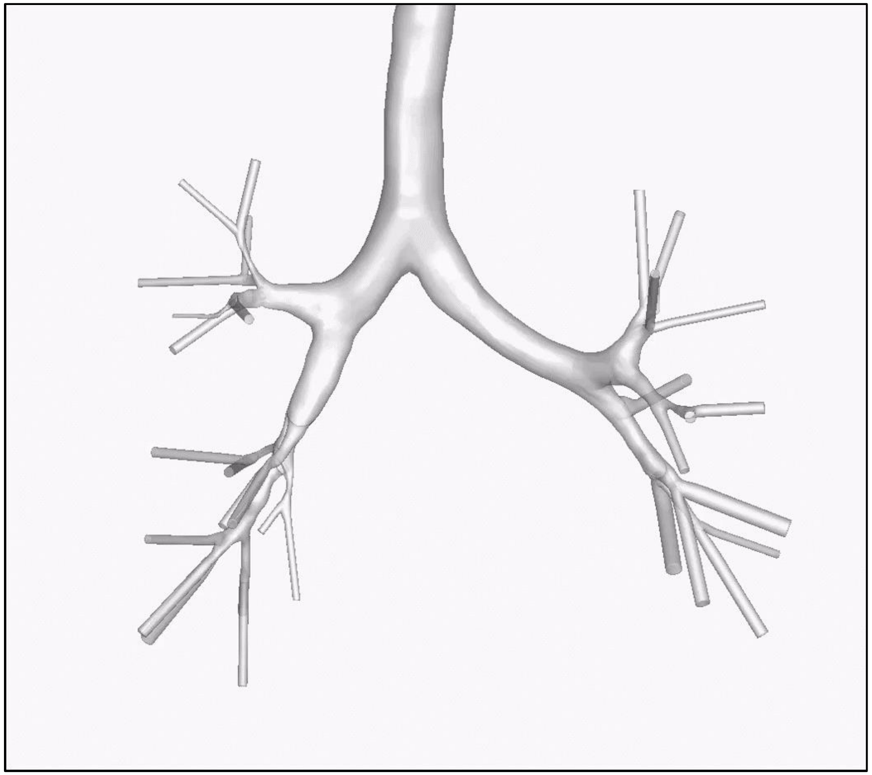
QCT

Particle Simulation

- **An patient with asthma attack**



A patient with asthma attack

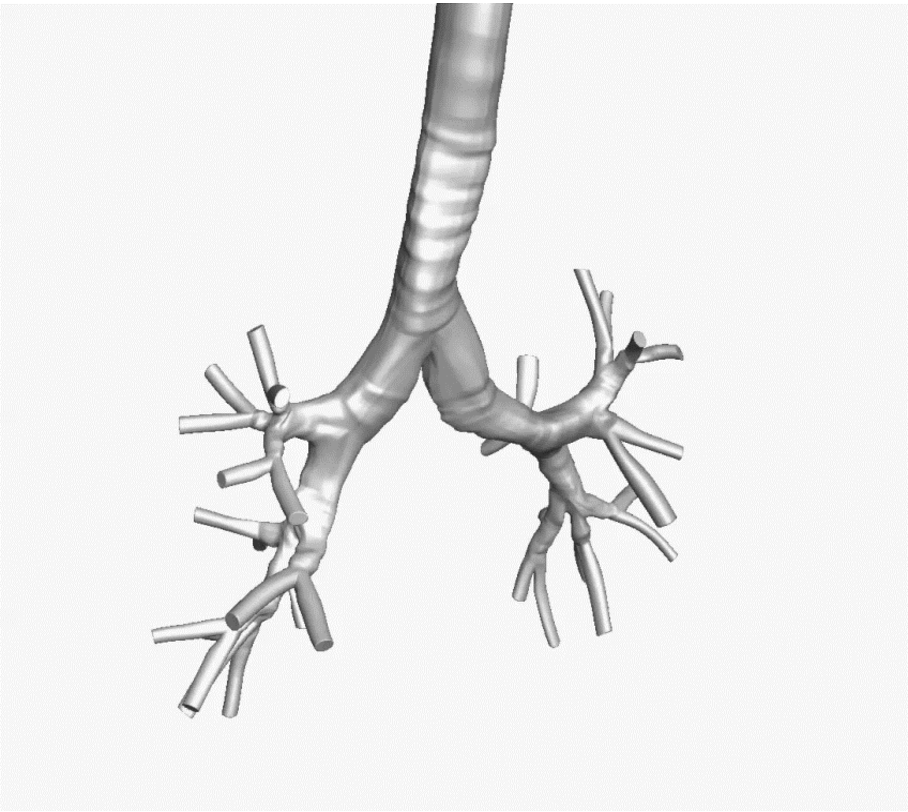


A patient after recovery

Aerosol Delivery for Healthy Subjects vs. Asthmatics

3-D CFD PURPOSE

Source: Animated Biomedical

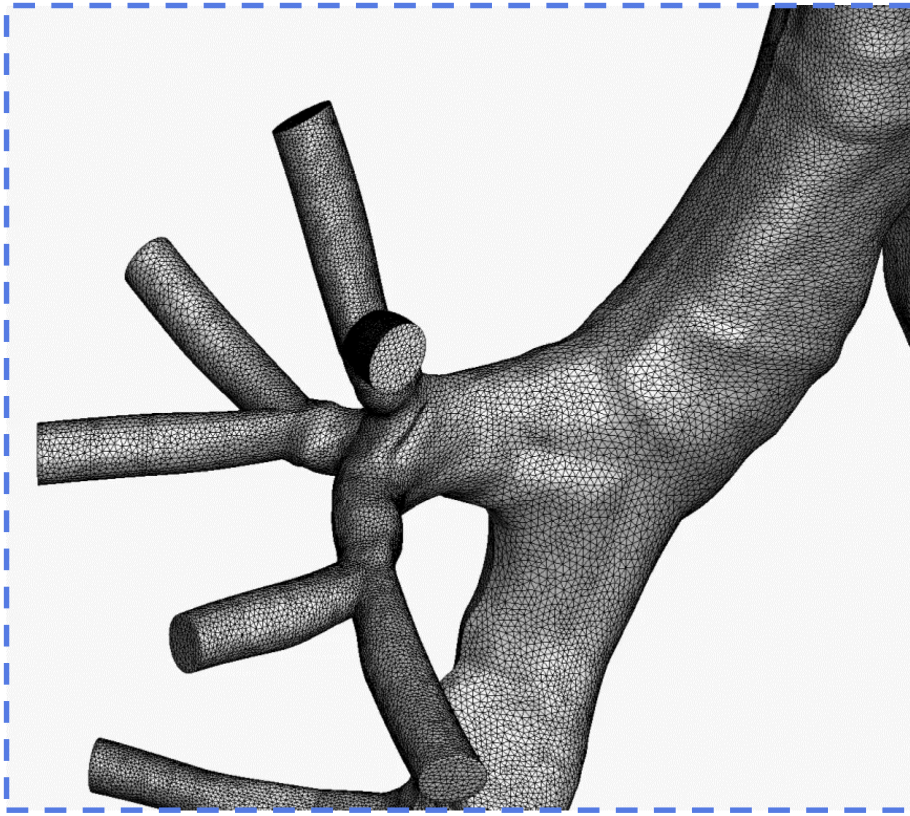


Using two CT imaging (insp- and expiration),

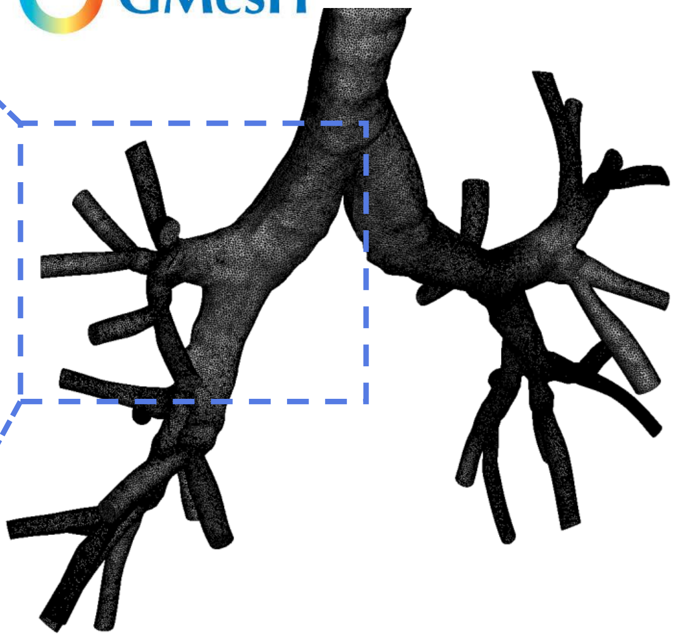
CFD simulations for normal & severe asthmatic subjects

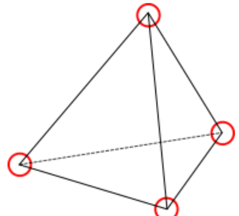
3-D CFD METHODS I

i/n



GMesH

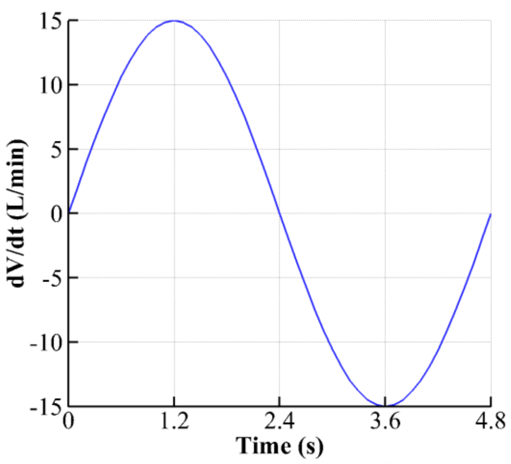


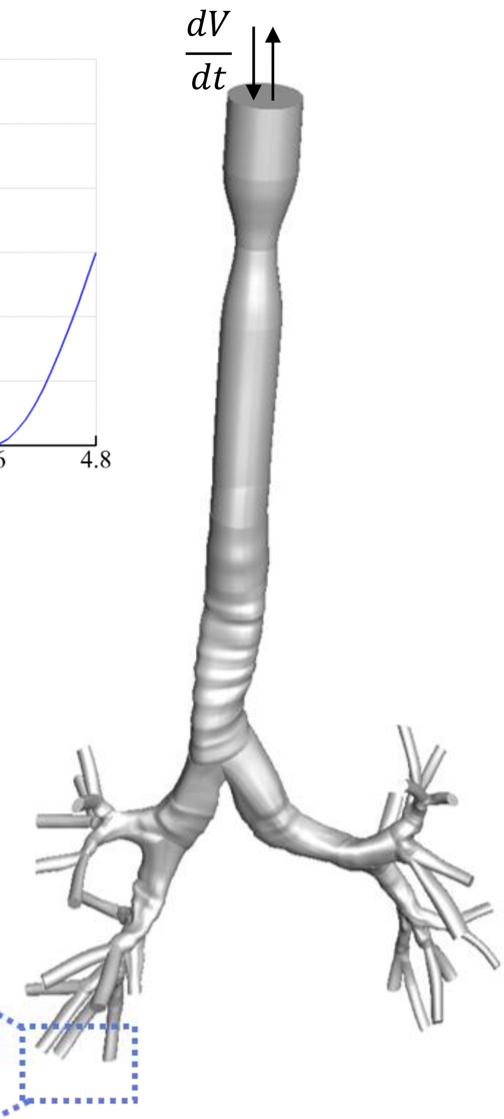


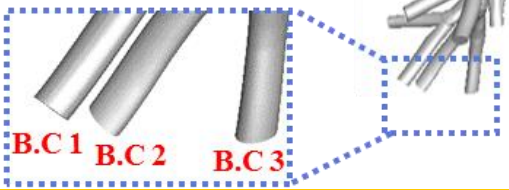
P1P1 elements

	Normal	Asthmatic
Node	792,207	899,941
Element	4,383,692	4,928,606

3-D CFD METHODS II







<Inspiratory CT>

<Expiratory CT>

Image registration

$$\rightarrow \frac{\Delta v}{\Delta V} \approx \frac{dv}{dV}$$

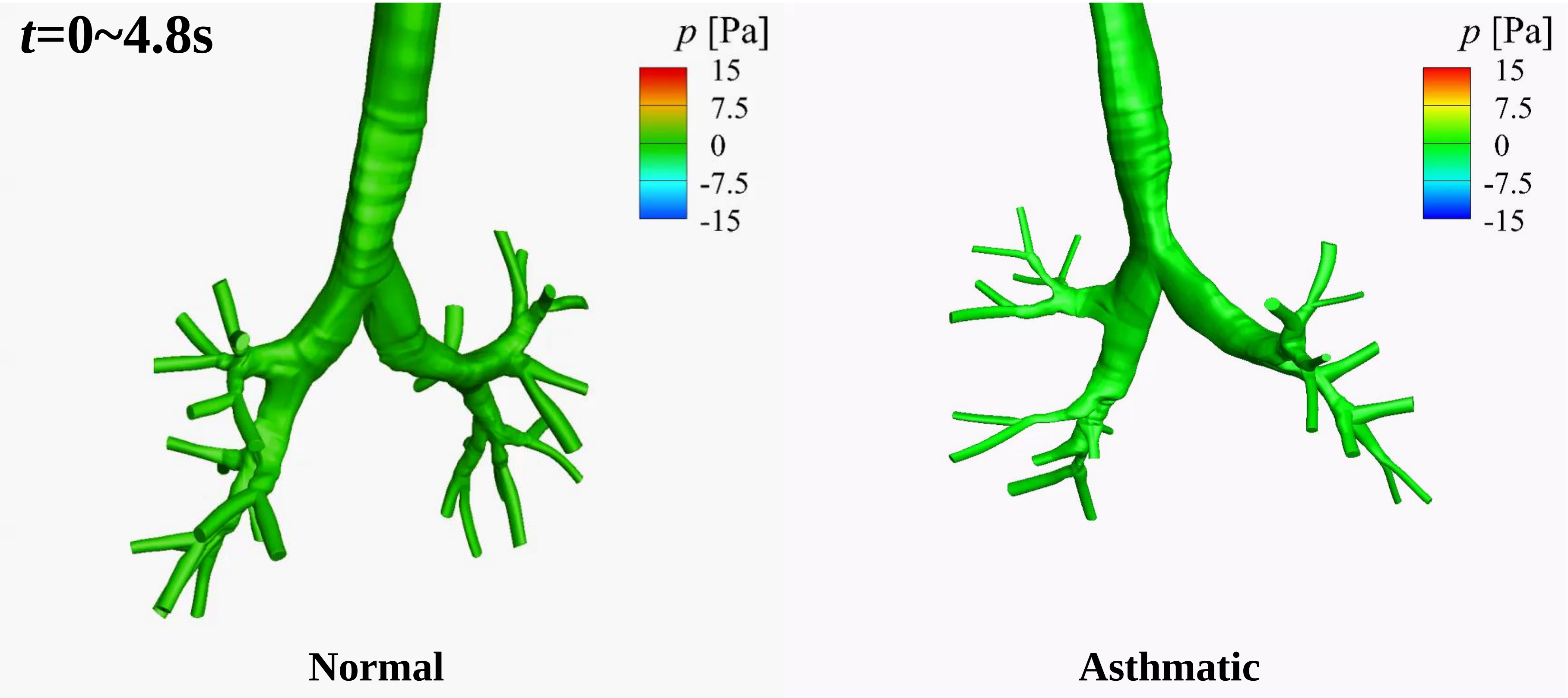
$(V:\ Total\ air\ volume, v:\ Local\ air\ volume)$

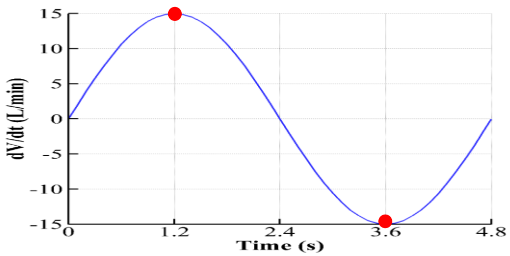
Boundary condition

$$\rightarrow \frac{dv}{dt} \approx \frac{dV}{dt} \times \frac{dv}{dV}$$

3-D CFD RESULTS I

- **Pressure distribution**



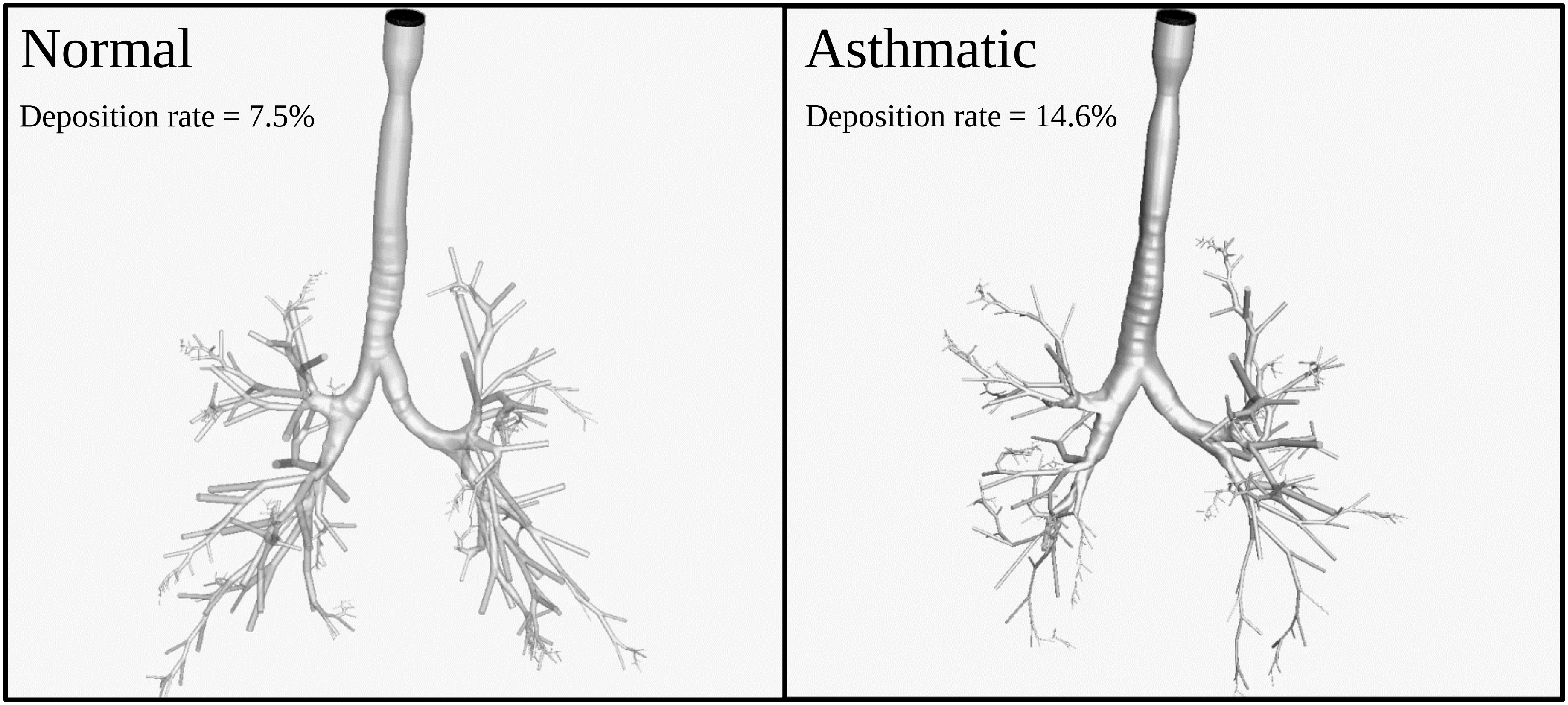


TriRLL	Normal	Asthmatic	Asthmatic/Normal (%)
1.2s	-4.87 Pa	-29.23 Pa	600
3.6s	6.4 Pa	11.12 Pa	174

3-D CFD RESULTS II

- **Particle simulation**

***t*=0~1.2 s**



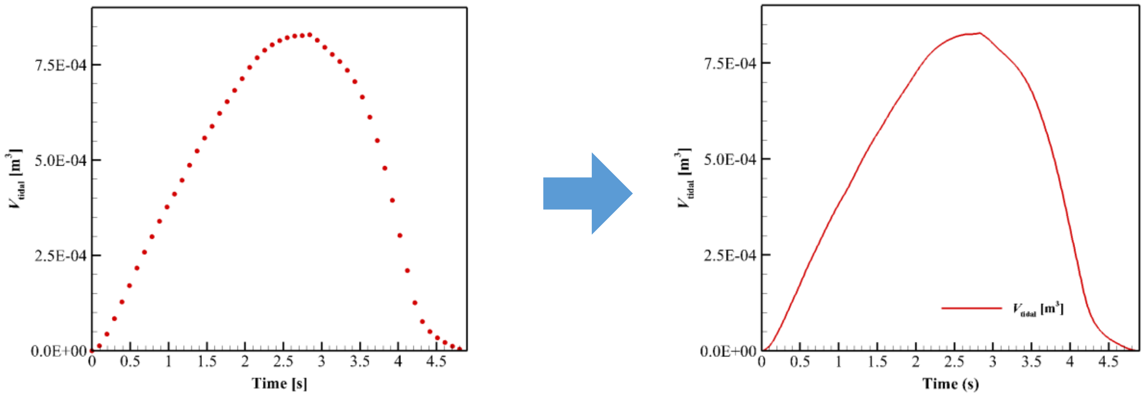
Particle diameter: 3 μm

1-D Airway Resistance and Compliance Modeling

1-D CFD PURPOSE AND METHODS

- **Purpose of study**
  - ✓ 1-D CFD model to analyze fluid dynamic features for healthy and asthmatic subjects.
  - ✓ Moving 1-D mesh → Displacement and diameter
- **CT scan images**
  - ✓ 5 healthy vs. 5 asthmatic subjects
  - ✓ Dynamic CT (4-D CT) & 2 static CTs at inspiration and expiration
- **Procedure of generating moving 1-D mesh**

(1) Time – volume spline, ***V_{tidal}(t)***

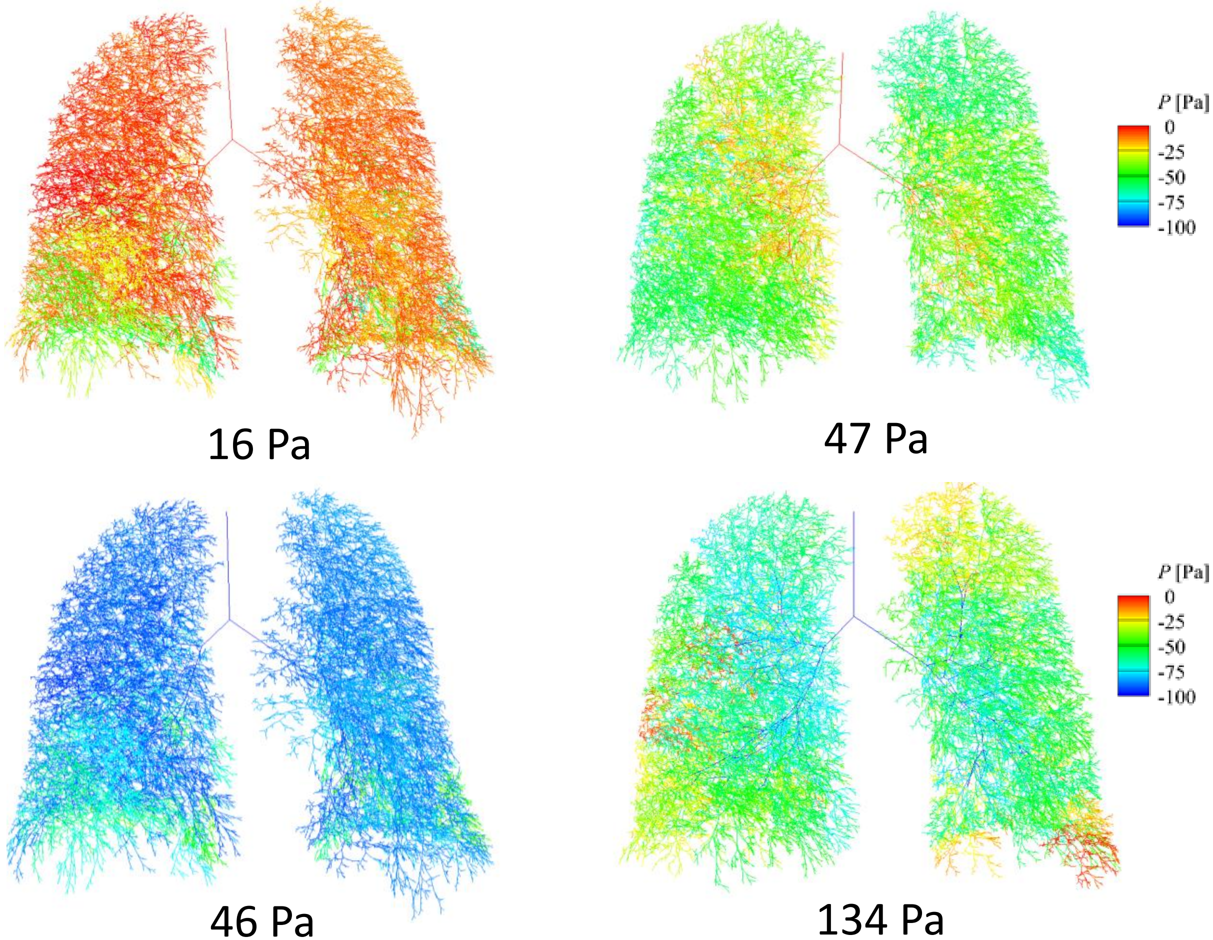


1-D CFD RESULTS II

- **Pressure Distributions**

Peak inspiration

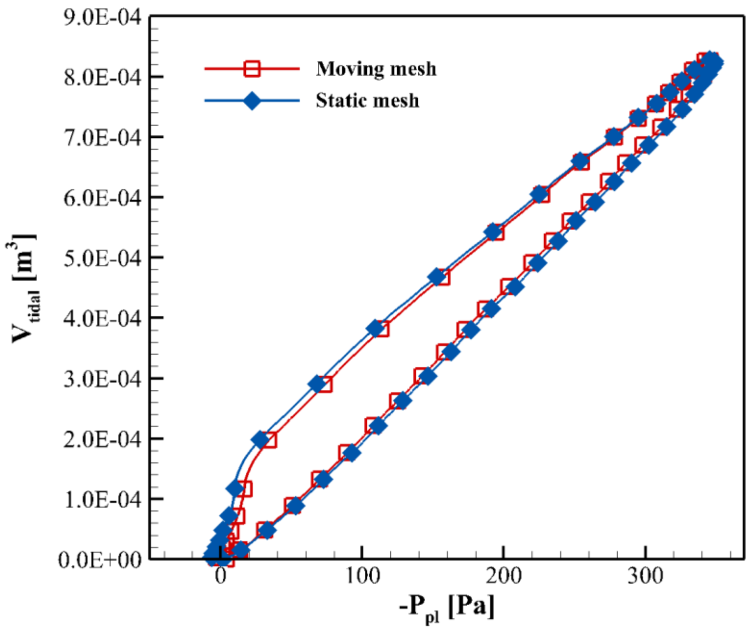
Peak expiration



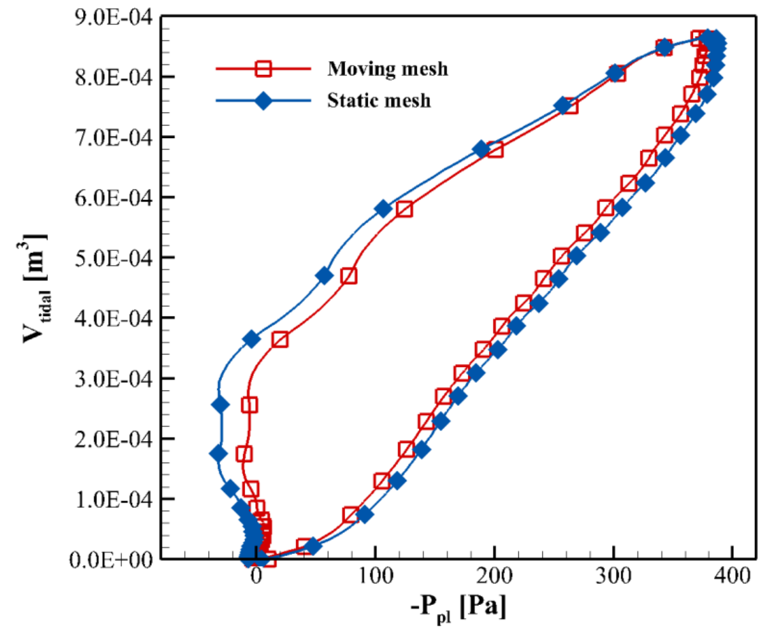
A healthy subject **An asthmatic subject**

1-D CFD RESULTS III

- **Hysteresis curve of P_{pl} vs. V_{tidal}**



< A healthy subject >



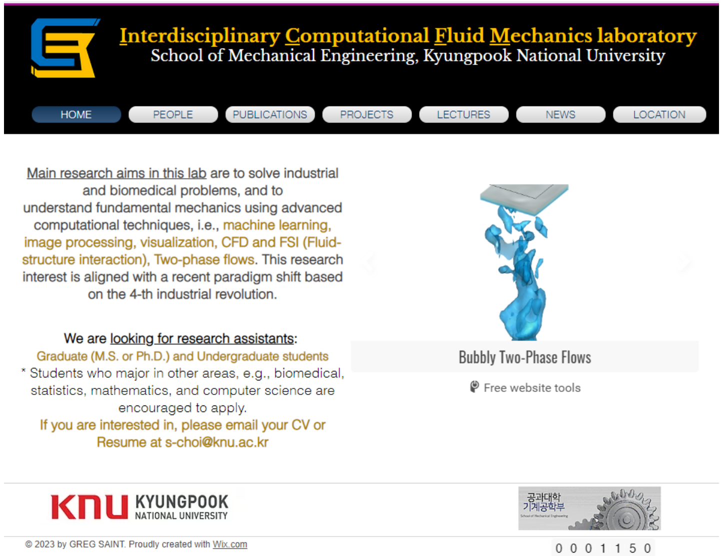
< An asthmatic subject >

Mean effective pressure = 51 Pa, 158 Pa (static); 47 Pa, 134 Pa (moving)

$$\Delta P = \boldsymbol{R}Q, \qquad \boldsymbol{Resistance} = \frac{128\mu \boldsymbol{L}}{\pi \boldsymbol{d}^4} \text{ (Poiseuille)}; \ \frac{128\mu \boldsymbol{L}}{\pi \boldsymbol{d}^4}\left[\frac{2\gamma}{\sqrt{\pi L \nu}} Q^{0.5}\right] \text{ (Pedely)}$$

ICFM Laboratory

http://icfm.knu.ac.kr



Interdisciplinary Computational Fluid Mechanics

- ✓ **Image analysis, Registration and Cluster analysis using Quantitative Computed Tomography (QCT) images**
- ✓ **Pulmonary Air Flows and Particle delivery with advanced 3-D CFD techniques**
- ✓ **1-D Airway Resistance and Lung Compliance Dynamic Modeling**
- ✓ **Two-phase Flows with FEM, OpenFOAM, and ANSYS**

ACKNOWLEGEMENT

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SPIROMICS
SUBPOPULATIONS AND INTERMEDIATE OUTCOME MEASURES IN COPD STUDY

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Kangwon National University Hospital

THE UNIVERSITY OF IOWA

SARP