

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

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Kyungpook National University



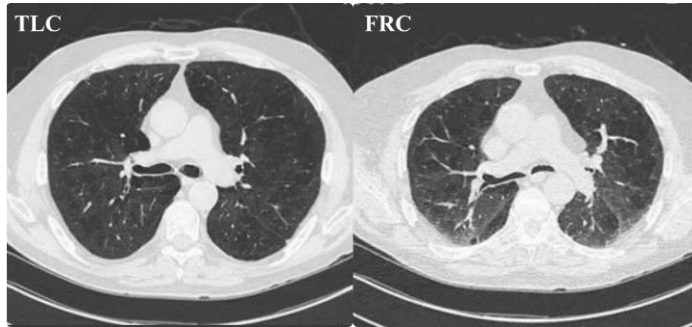
CONTENTS

- **QCT Imaging-Based Structural and Functional Metrics**
- **Airway Structure and Lung Function Differences:**
 - Korean Asians vs. White Americans
 - Healthy Koreans vs. Cement Dust Exposed Koreans
- **Asthma Attack vs. Lung Function Recovery**
- **Aerosol Delivery for Healthy Subjects vs. Asthmatics**
- **1-D Airway Resistance and Compliance Modeling**

Derivation of QCT Imaging-Based Structural and Functional Metrics



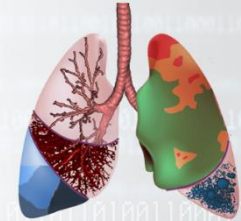
QCT-based Segmental Structural Variables



VIDA®

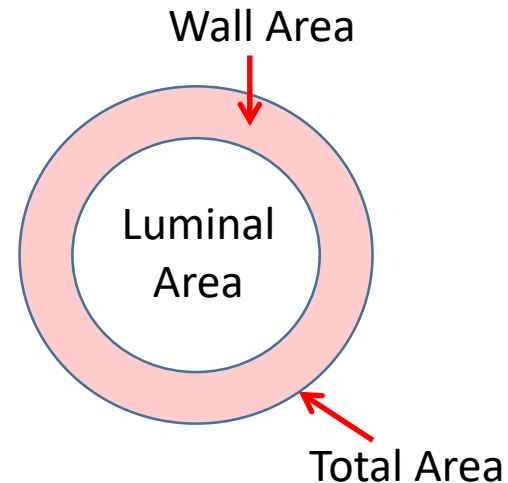
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Transforming Lung Care
in the Age of Intelligence



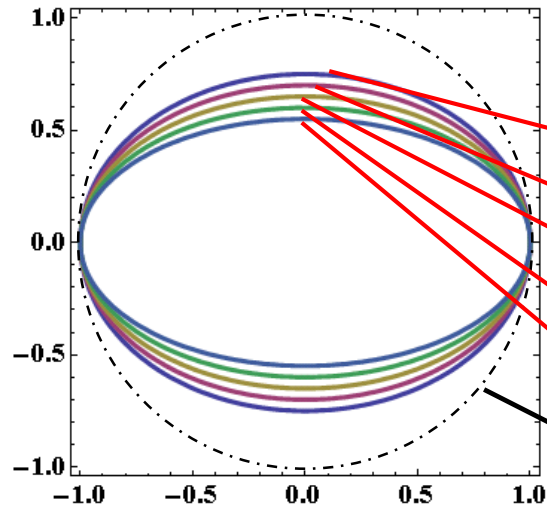
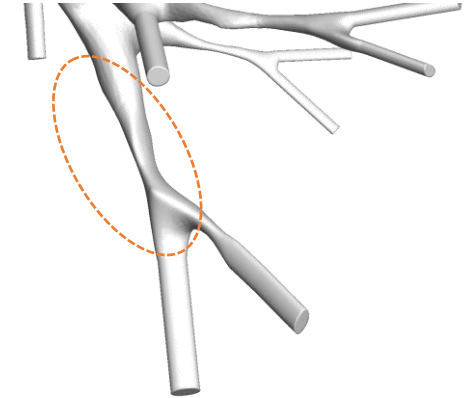
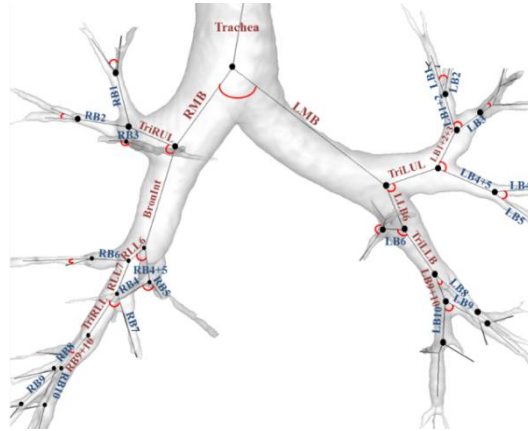
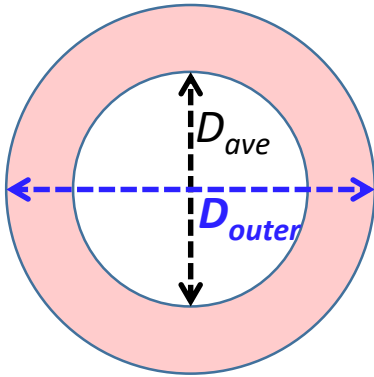
TLC : Total lung capacity
FRC : Functional residual capacity

Pulmonary automatic segmentation program



Segmental STRUCTURAL VARIABLES

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



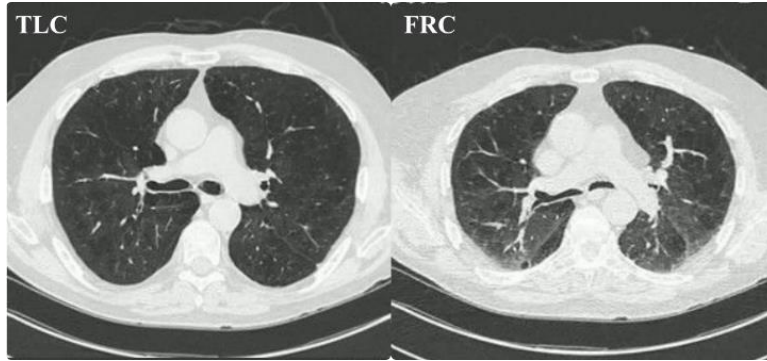
Cr	$\frac{\text{major axis}}{\text{minor axis}}$
0.985	1.333
0.977	1.429
0.966	1.538
0.953	1.667
0.937	1.818

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

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

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

QCT-based Structural and Functional Metrics

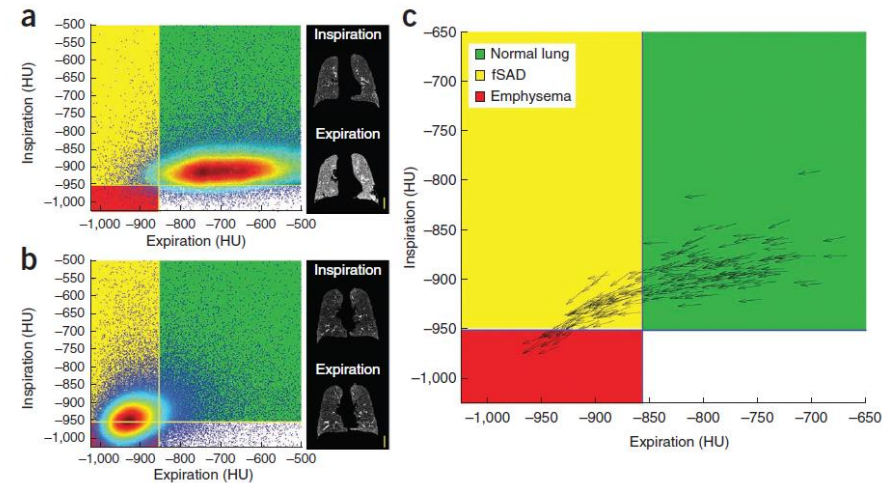
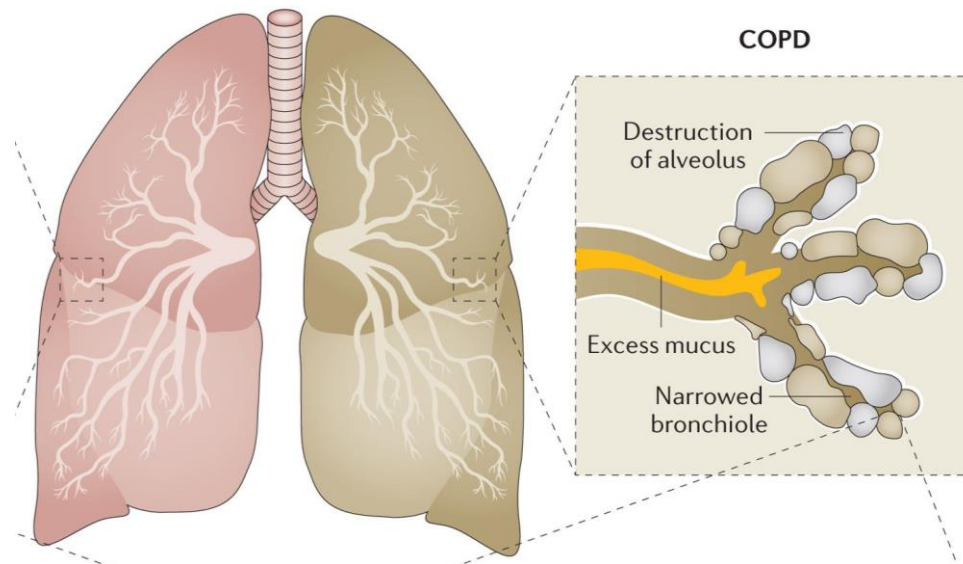


Insight Segmentation
and Registration Toolkit



TLC : Total lung capacity

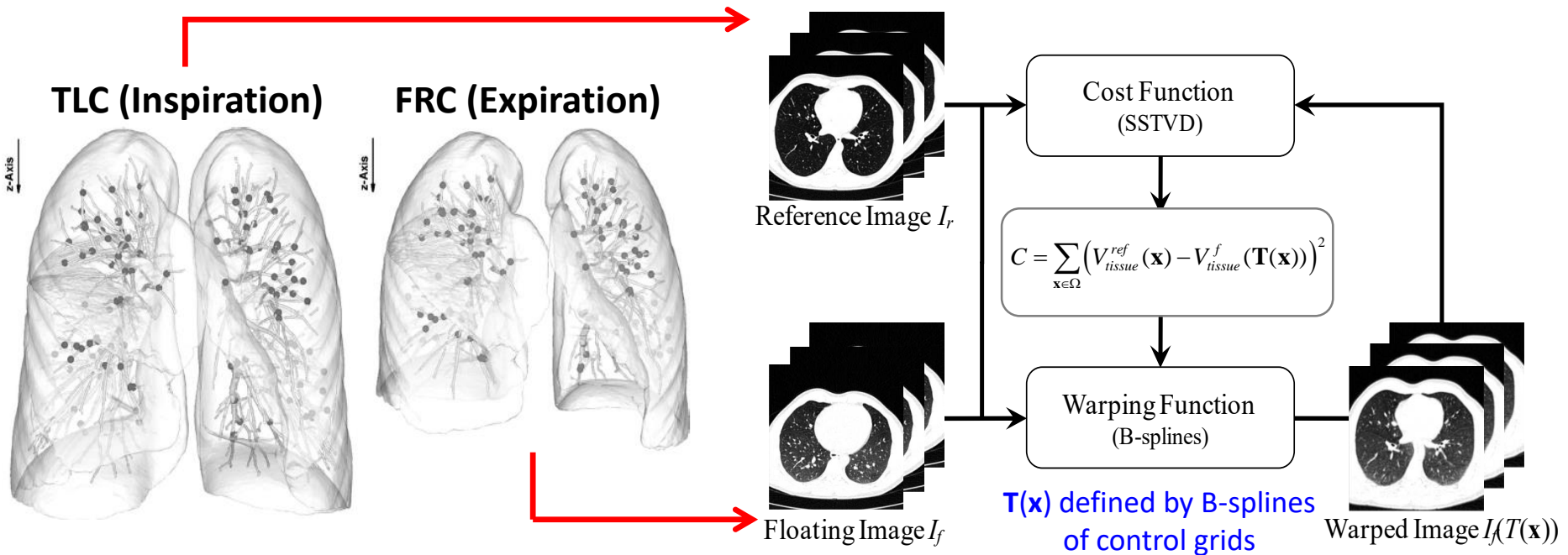
FRC : Functional residual capacity



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*:

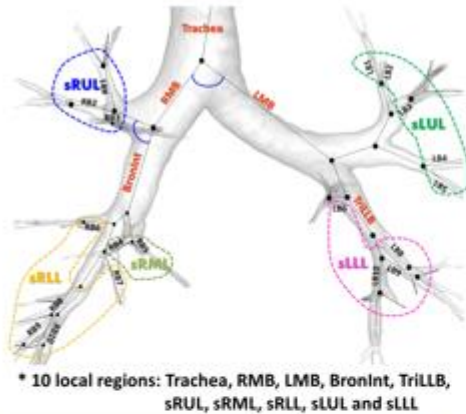
$$ADI = \sqrt{\left(\frac{\lambda_1 - \lambda_2}{\lambda_2}\right)^2 + \left(\frac{\lambda_2 - \lambda_3}{\lambda_3}\right)^2}$$

ADI (Anisotropic deformation index):

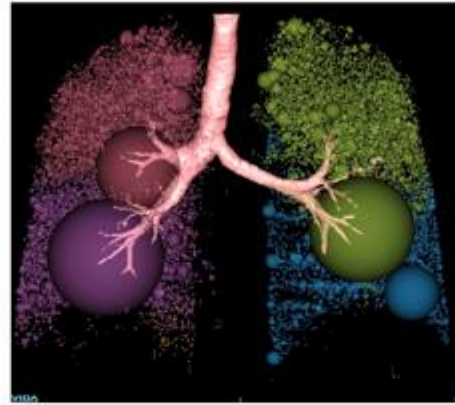
ADI increases, if **one or two directional strains** are greater than others. If it deforms **isotropically** ($\lambda_1 = \lambda_2 = \lambda_3$), ADI is **zero**.

QCT-based Structural and Functional Metrics

a. Inspiration image-based local structures:
 θ , Cr , WT^* , and D_h^*



b. Expiration image-based global and lobar function: AirT%

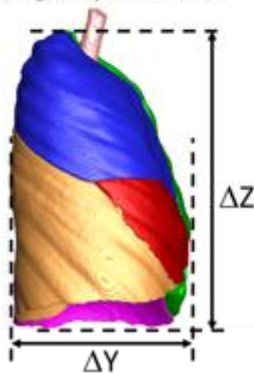


c. Inspiration image-based global and lobar function: Emph%



d. Global structure:

Lung shape = $\Delta Z / \Delta Y$

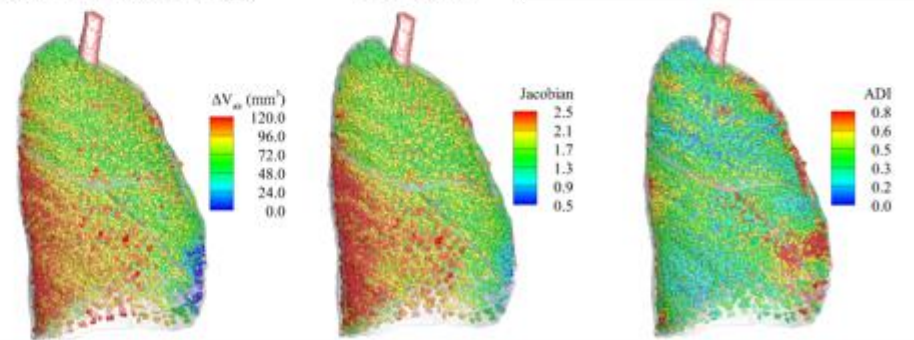


e. Registration-based global and lobar functions:

$U/(M+L)|v$, and ΔV_{air}^F

Jacobian

ADI



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

Airway Structure and Lung Function

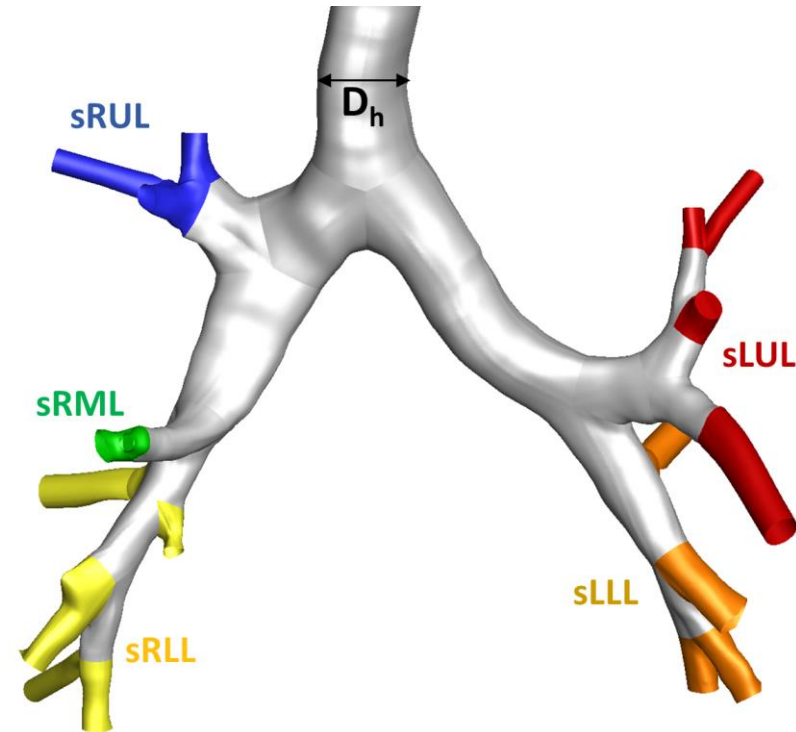
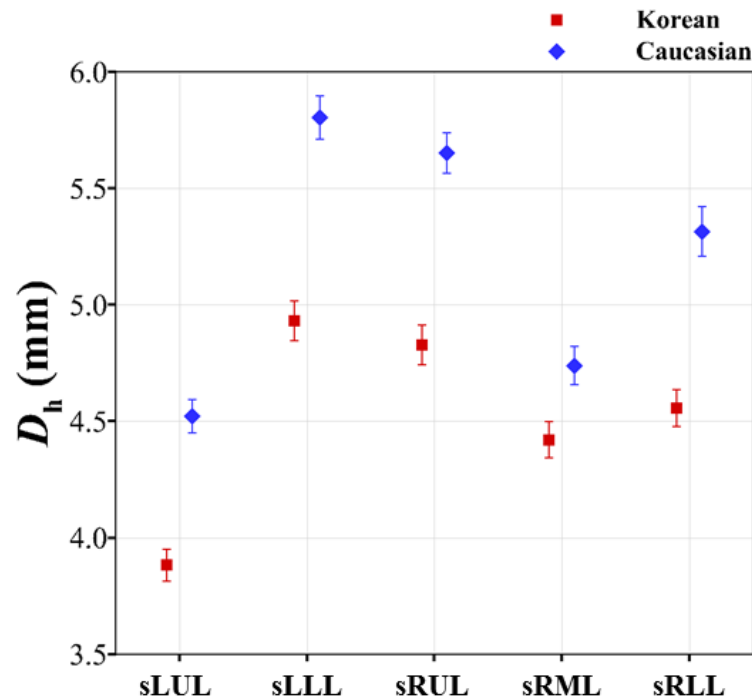
- Koreans vs. Whites
- Healthy vs. Dust Exposed



QCT

RESULTS I

● 64 Koreans vs. 64 Whites

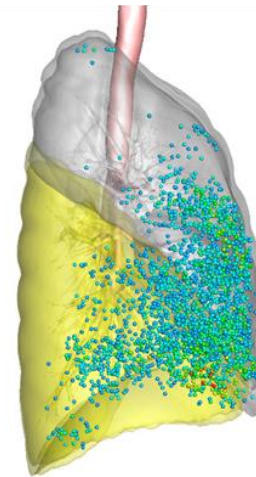
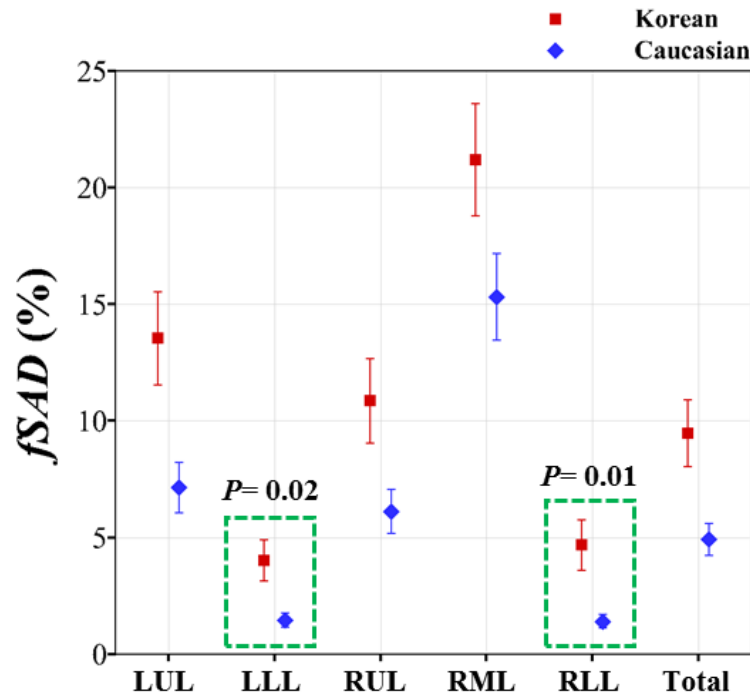


Airway hydraulic diameter (D_h) was smaller in Koreans than that in Caucasians

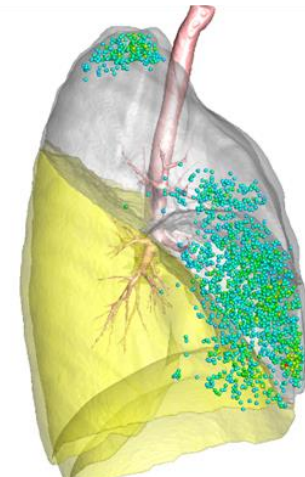
QCT

RESULTS I

● 64 Koreans vs. 64 Caucasians



<Korean>



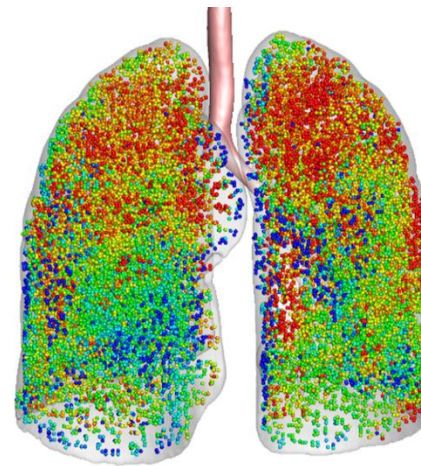
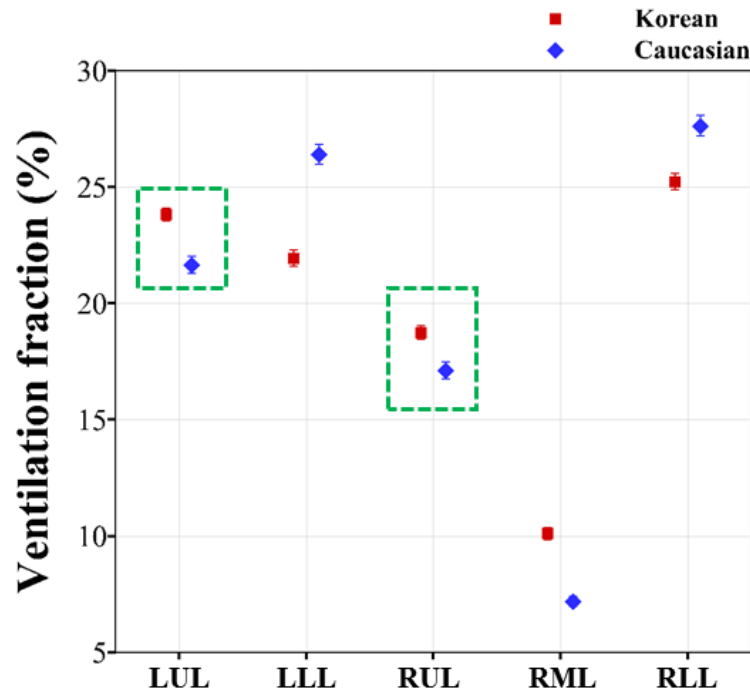
<Caucasian>

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

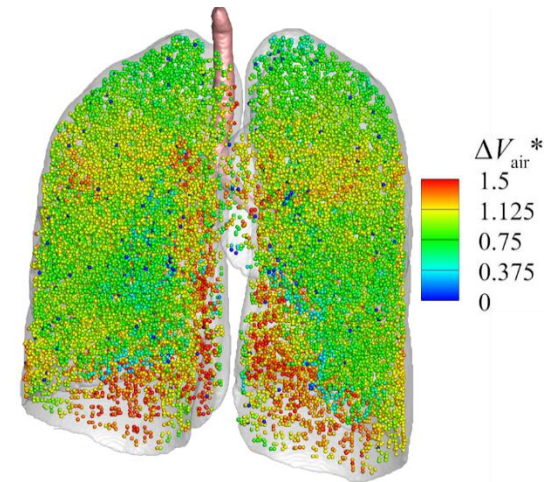
QCT

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.

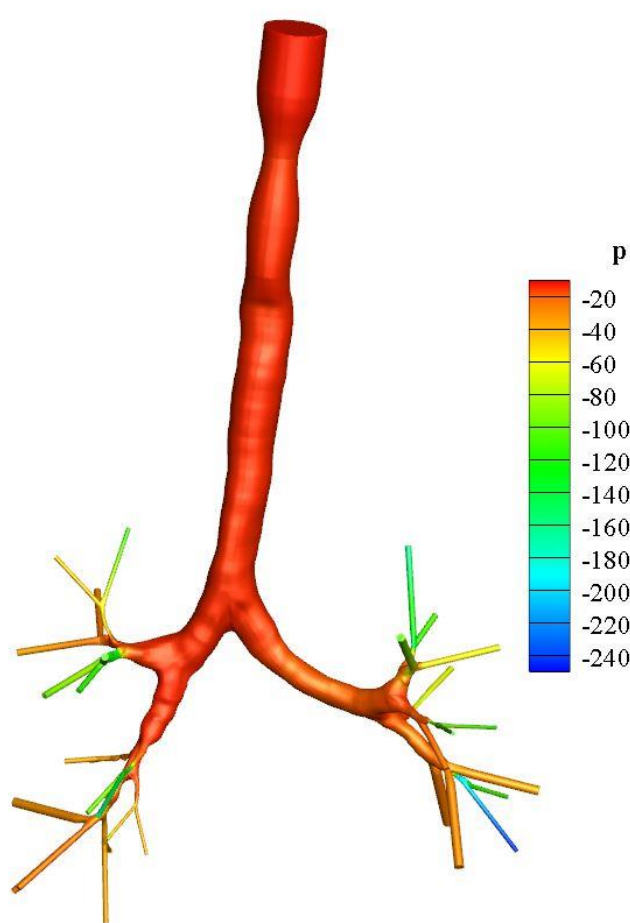
Asthma Attack vs. Lung Function Recovery



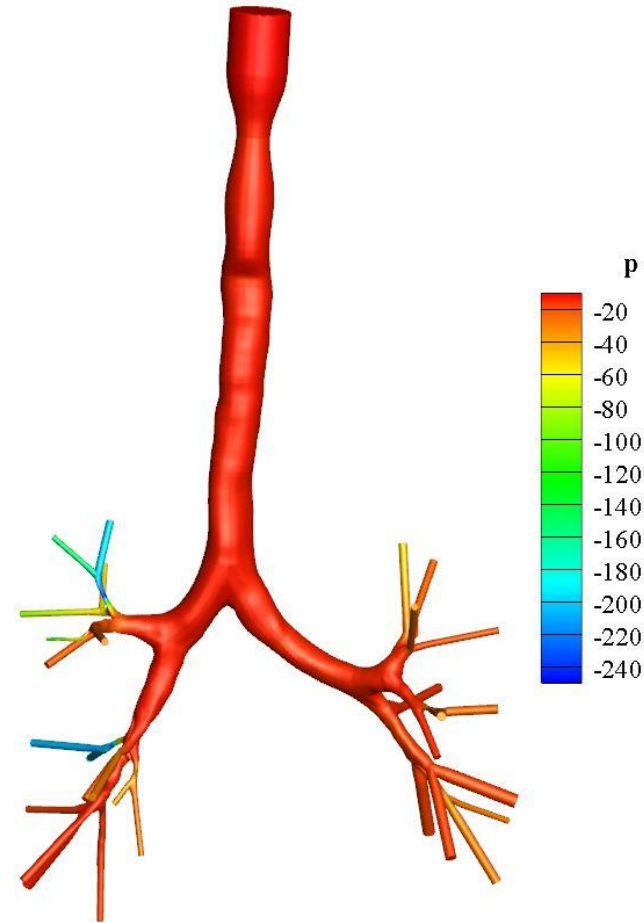
QCT

RESULTS III

- An patient with asthma attack



A patient with asthma attack

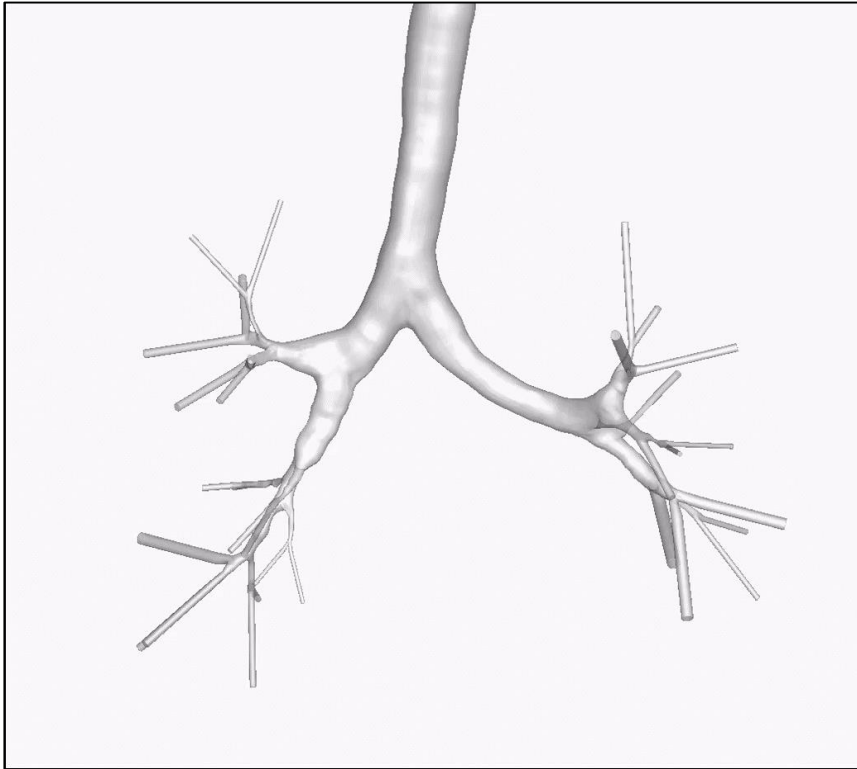


A patient after recovery

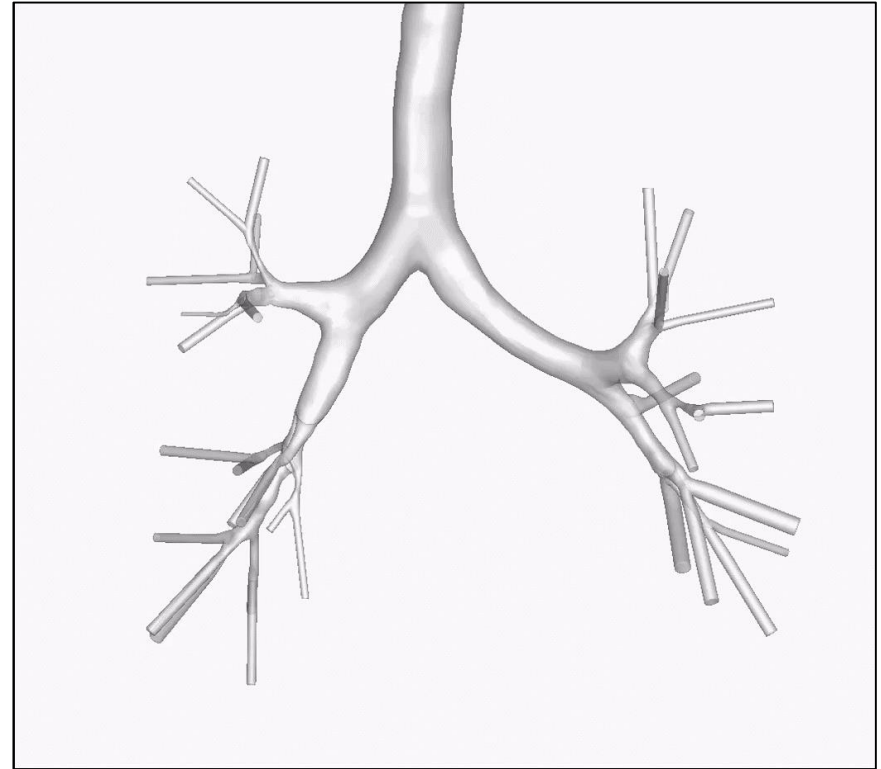
QCT

Particle Simulation

- An patient with asthma attack



A patient with asthma attack



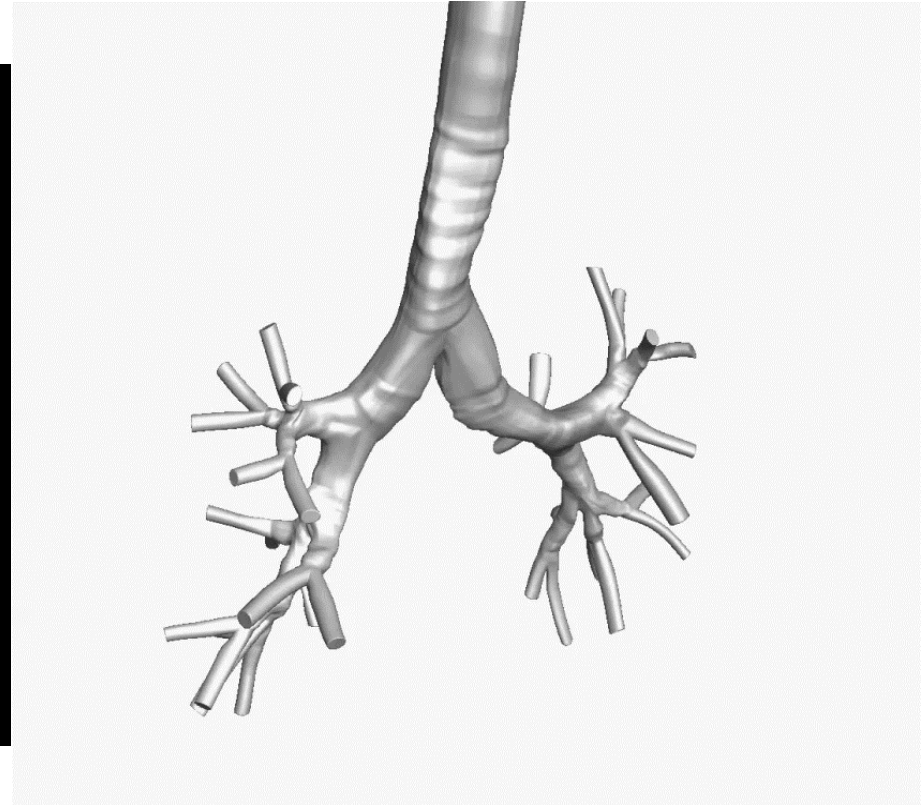
A patient after recovery

Aerosol Delivery for Healthy Subjects vs. Asthmatics



3-D CFD PURPOSE

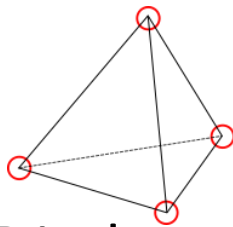
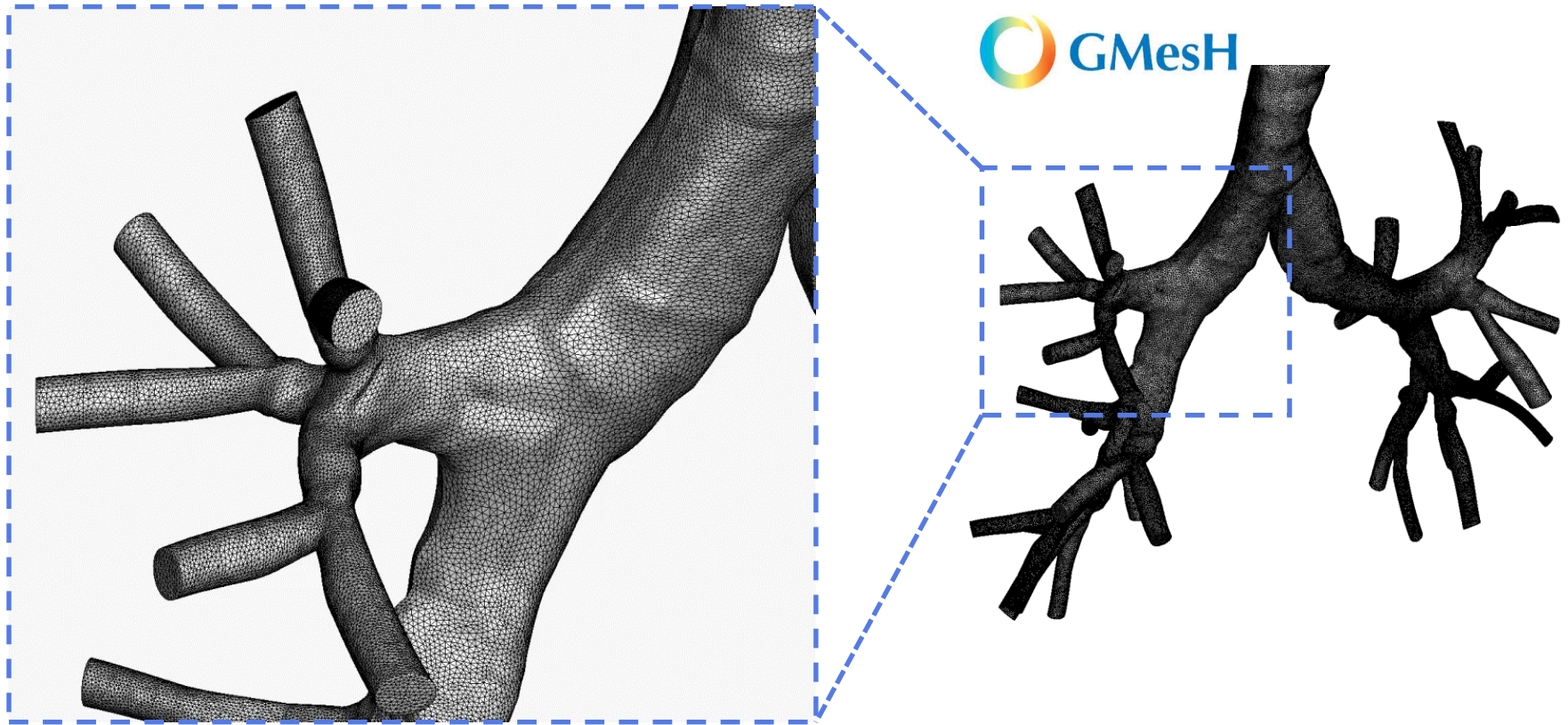
Source: Animated Biomedical



**Using two CT imaging (insp- and expiration),
CFD simulations for normal & severe asthmatic subjects**

3-D CFD METHODS I

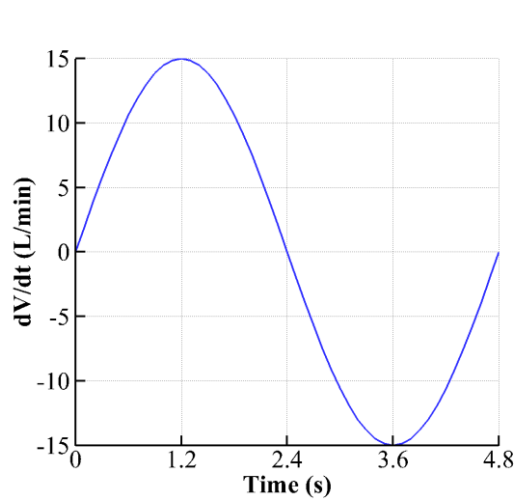
i/n



P1P1 elements

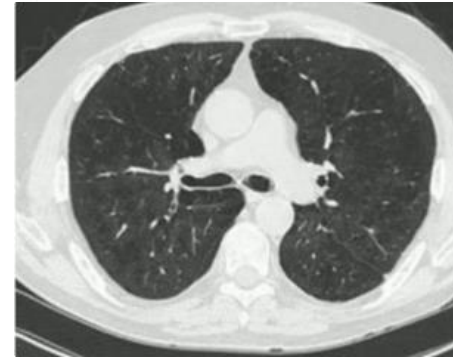
	Normal	Asthmatic
Node	792,207	899,941
Element	4,383,692	4,928,606

3-D CFD METHODS II



$$\frac{dV}{dt}$$

<Inspiratory CT>



<Expiratory CT>

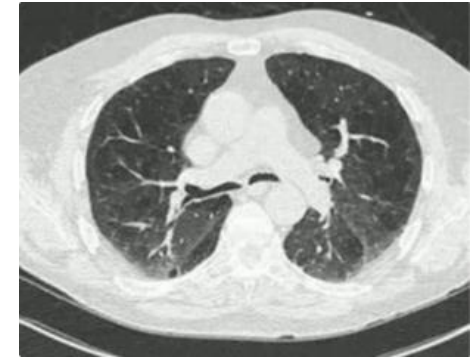


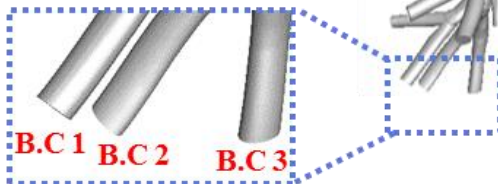
Image registration

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

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

Boundary condition

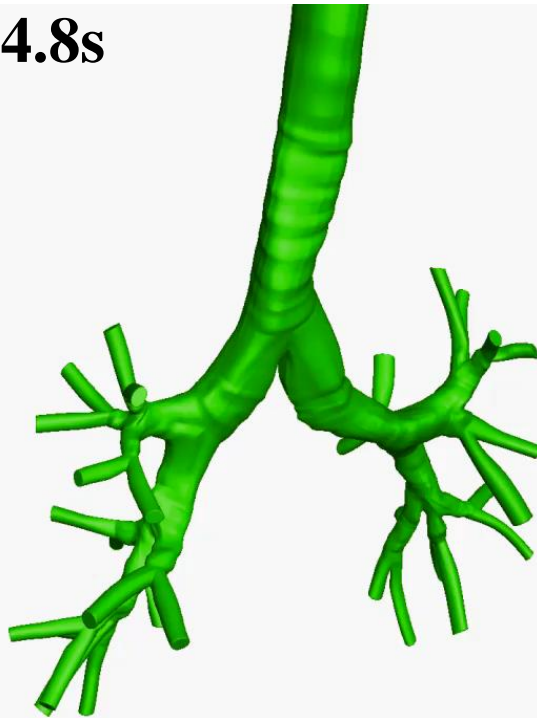
$$\rightarrow \frac{dv}{dt} \approx \frac{dV}{dt} \times \frac{dv}{dV}$$



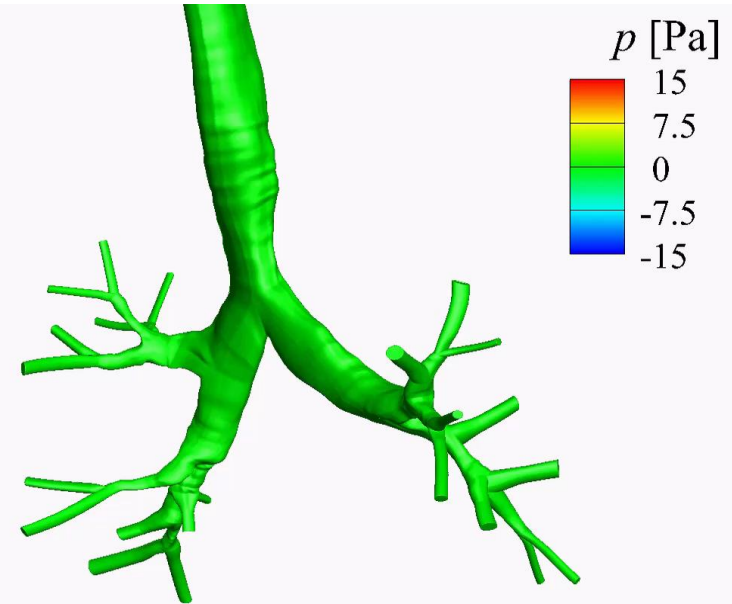
3-D CFD RESULTS I

● Pressure distribution

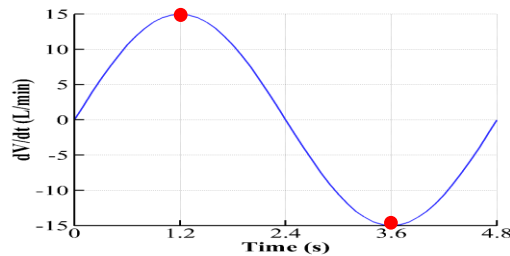
$t=0\sim 4.8\text{s}$



Normal



Asthmatic



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

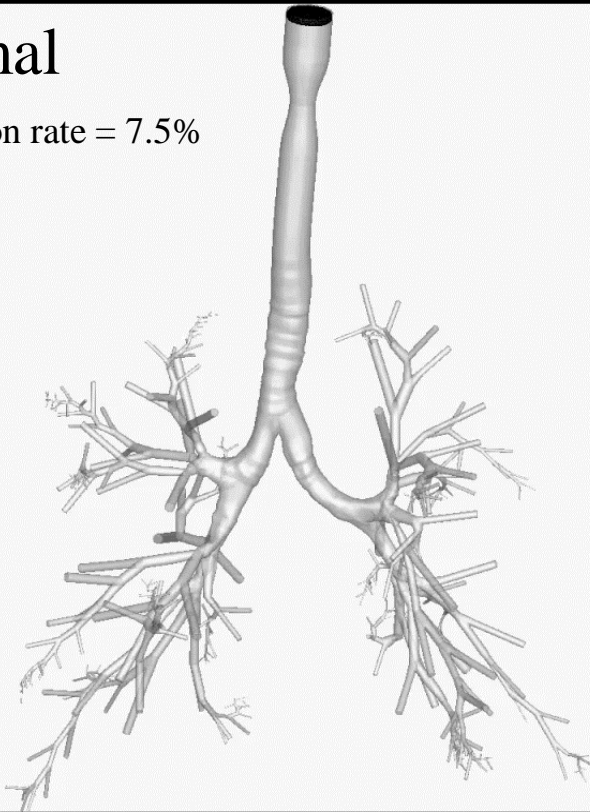
3-D CFD RESULTS II

● Particle simulation

$t=0\sim 1.2$ s

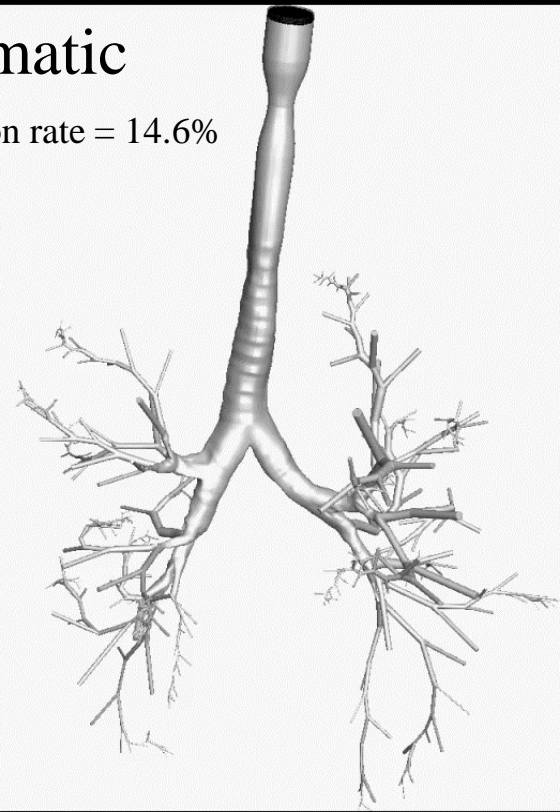
Normal

Deposition rate = 7.5%



Asthmatic

Deposition rate = 14.6%



Particle diameter: $3\ \mu\text{m}$

1-D Airway Resistance and Compliance Modeling



1-D CFD

PURPOSE AND METHODS

● Purpose of study

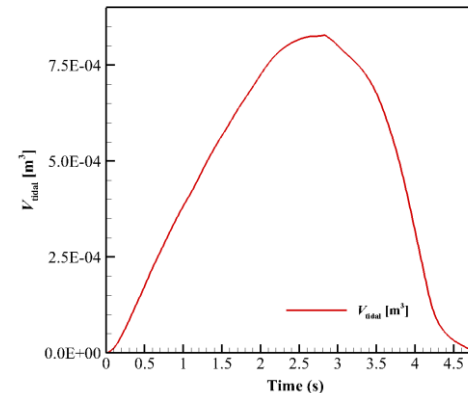
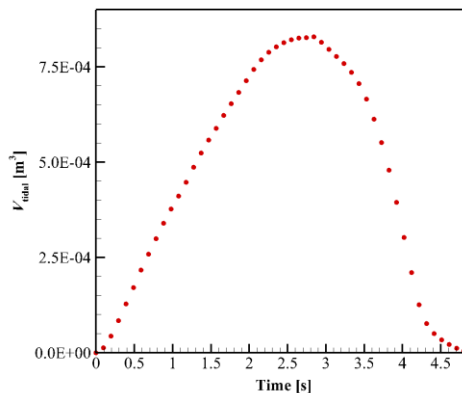
- ✓ 1-D CFD model to analyze **fluid dynamic features** for healthy and asthmatic subjects.
- ✓ Moving 1-D mesh → **Displacement** and diameter

● 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, $V_{\text{tidal}}(t)$

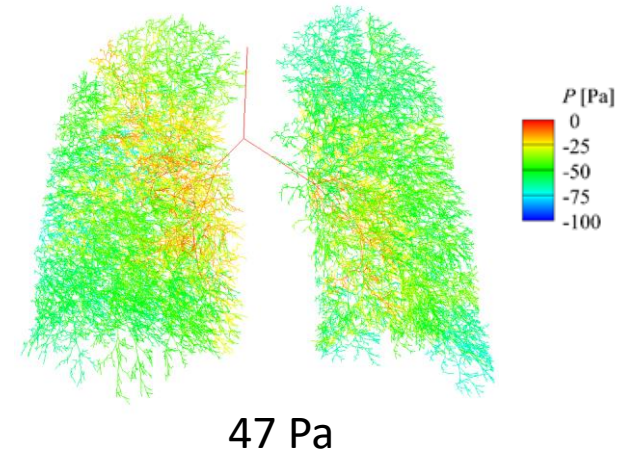
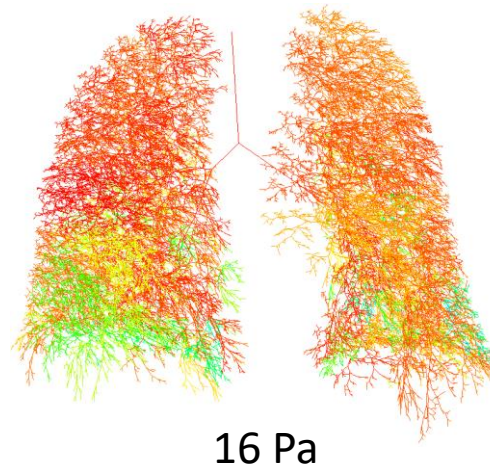


1-D CFD

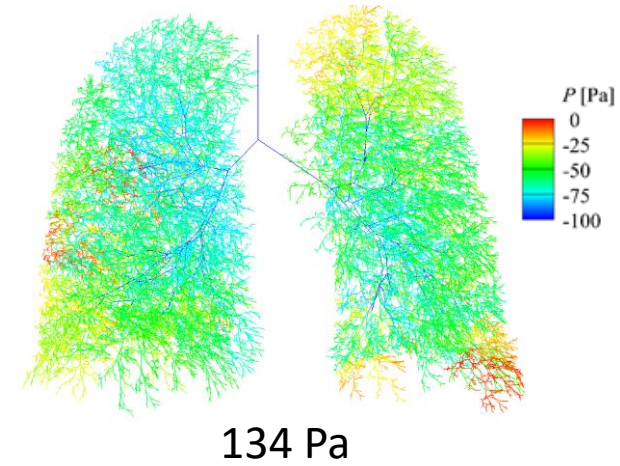
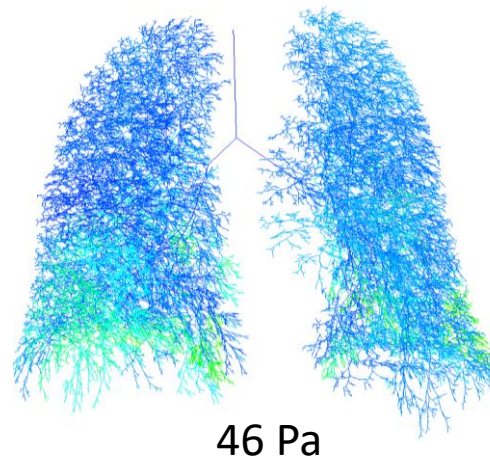
RESULTS II

● Pressure Distributions

Peak inspiration



Peak expiration

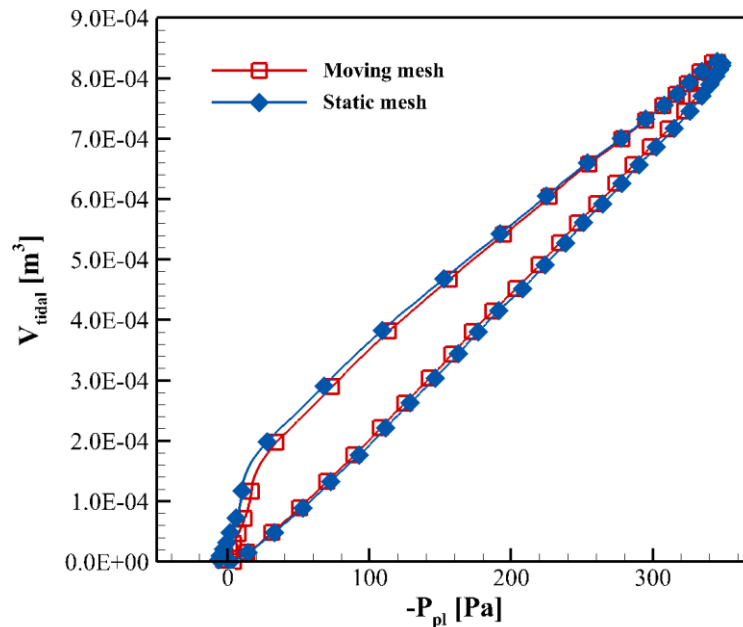


A **healthy** subject

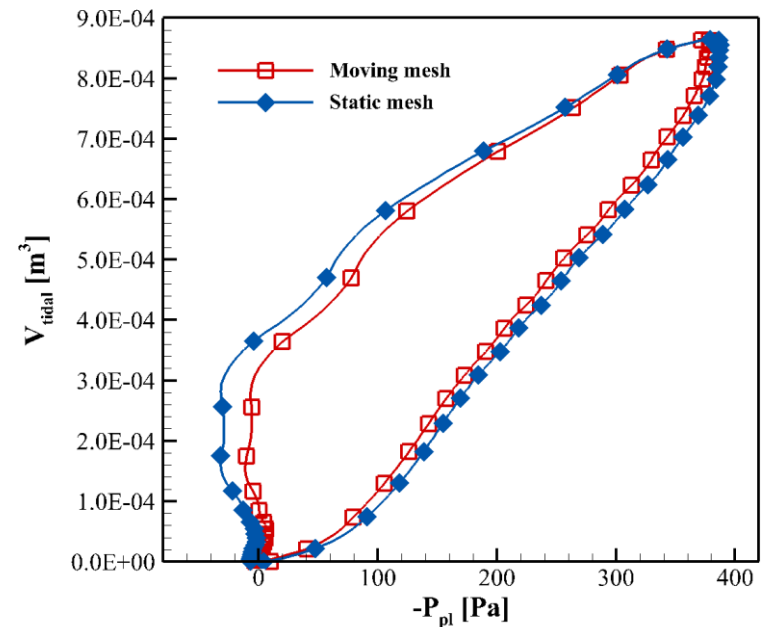
An **asthmatic** subject

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)

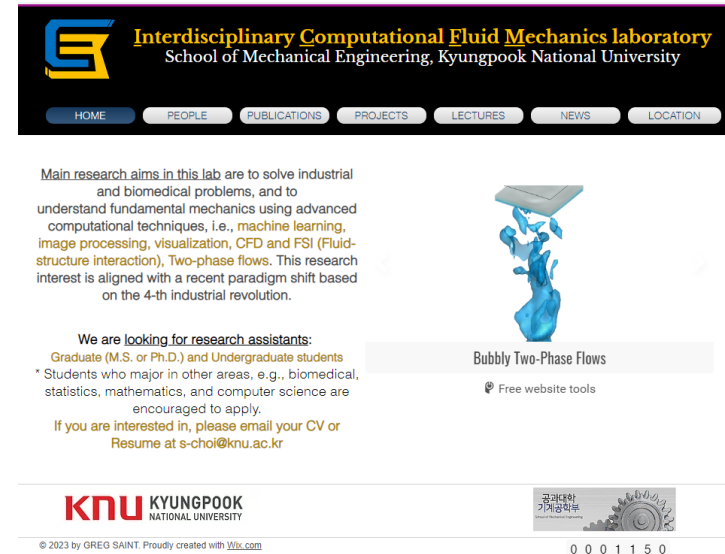
$$\Delta P = RQ, \quad \text{Resistance} = \frac{128\mu L}{\pi d^4} \text{ (Poiseuille); } \frac{128\mu L}{\pi d^4} \left[\frac{2\gamma}{\sqrt{\pi L v}} Q^{0.5} \right] \text{ (Pedely)}$$

ICFM Laboratory



Interdisciplinary Computational Fluid Mechanics

<http://icfm.knu.ac.kr>



The screenshot shows the homepage of the Interdisciplinary Computational Fluid Mechanics Laboratory at Kyungpook National University. The header includes the lab's name and a navigation menu with links for HOME, PEOPLE, PUBLICATIONS, PROJECTS, LECTURES, NEWS, and LOCATION. The main content area features a paragraph about the lab's research aims, a list of research assistants, and a section for research interests. A 3D visualization of a bubbly two-phase flow is shown on the right. The footer includes the KNU logo and contact information.

Interdisciplinary Computational Fluid Mechanics laboratory
School of Mechanical Engineering, Kyungpook National University

HOME PEOPLE PUBLICATIONS PROJECTS LECTURES NEWS LOCATION

Main research aims in this lab are to solve industrial and biomedical problems, and to understand fundamental mechanics using advanced computational techniques, i.e., machine learning, image processing, visualization, CFD and FSI (Fluid-structure interaction), Two-phase flows. This research interest is aligned with a recent paradigm shift based on the 4-th industrial revolution.

We are looking for research assistants:
Graduate (M.S. or Ph.D.) and Undergraduate students
* Students who major in other areas, e.g., biomedical, statistics, mathematics, and computer science are encouraged to apply.
If you are interested in, please email your CV or Resume at s-choi@knu.ac.kr

Bubbly Two-Phase Flows

Free website tools

KNU KYUNGPOOK NATIONAL UNIVERSITY

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0 0 0 1 1 5 0

- ✓ 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

ACKNOWLEDGEMENT



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