A 3D-tissue/0D-airway coupling approach in respiratory mechanics

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Introduction

Ventilator-Associated Lung Injuries (VALI)

- Severe complication of mechanical ventilation
- Risk factor: pre-existing heterogeneous lung damage (e.g., ALI, ARDS, Asthma, COPD)
- Local overstraining of lung tissue → inflammation, damage
- Probability of survival: 20% after 21 days of mechanical ventilation for chronically diseased lung patients [1]
- Optimal ventilation protocol unclear

Objective and Methods

Objective

- Promote understanding of respiratory mechanics in general
- Connect local parenchyma deformation and airflow in specific regions of the lung
- Improve ventilation protocols for chronically diseased lung patients

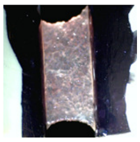
Methods

- Combine biological and mechanical insights from fully resolved three-dimensional parenchyma with reduced-dimensional airway models

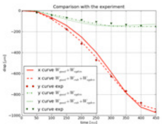
3D Parenchyma Model

In-vitro

- Experimental determination of material properties using precision-cut lung slices [2]



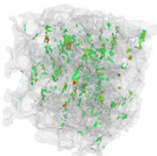
- Fitting of model parameters using an inverse approach [3]



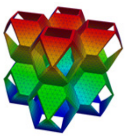
- Future investigation on tissue-based diseases e.g. fibrosis

In-silico

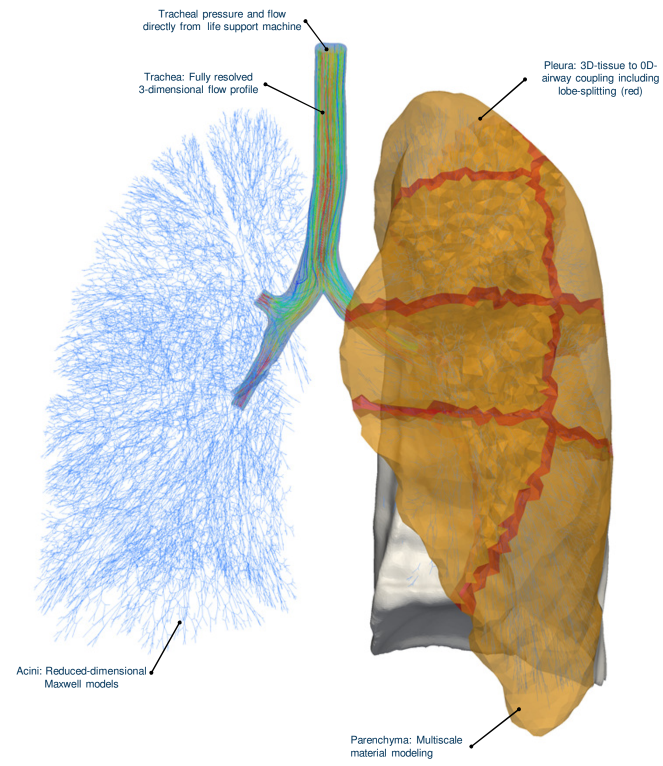
- Micro-scale geometry scanning using the Swiss Light source



- Simulation of stresses and strains on cellular level to find locations of tissue damage [4]
- Calibration of artificial micro-scale geometries for efficient multi-scale simulations of natural breathing [5]

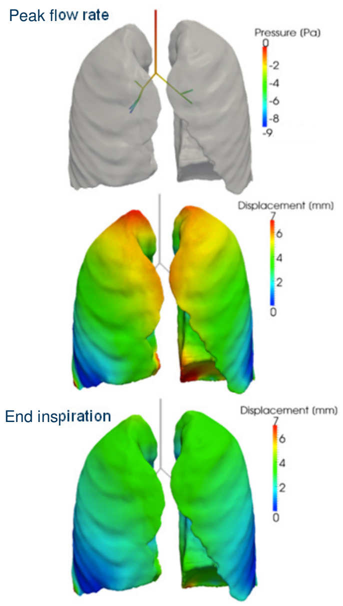


The Lung from the engineering point of view



3D/0D: Preliminary Results

First simulations based on 3-generation 0D airway model
→ Each outlet associated with one lobe



→ Proof of concept: Successful coupling of 0D airway and 3D parenchyma models
→ Advantage compared to 0D/0D model: Availability of 3D stresses and strains

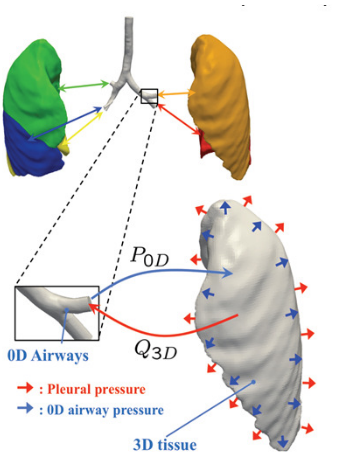
3D-Tissue/ 0D-Airway Coupling

Idea

- Replacement of interdependent 0D acinar models from [6] with 3D continuum parenchyma model
- Association of parenchyma regions with airway tree outlets
- Coupling of 3D volumetric tissue deformation and 0D fluid dynamics

Method

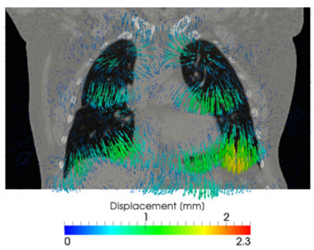
At time step t_n
while $\epsilon_Q > Tol_Q$ or $\epsilon_P > Tol_P$ **do**
  Apply pleural pressure on 3D tissue
  Apply 0D pressure on 3D tissue
  Evaluate 3D volume $V^k_{3D_n}$
  Evaluate 3D flow rate $Q^k_{3D_n} = \frac{V^k_{3D_n} - V_{3D_{n-1}}}{\Delta t}$
  Apply $Q^k_{3D_n}$ on to 0D airway
  Evaluate $\epsilon_Q = |Q_{3D} - Q_{0D}|$
  Evaluate $\epsilon_P = |P_{3D} - P_{0D}|$
end while



Ongoing Work – 4D-CT Data

Respiratory Motion

- Inspiration and expiration mainly driven by diaphragm (in resting condition) and by ribcage
- Very local and nonlinear movement that drives respiration and has to be considered in our simulations
- Time series of 3D-CT data over full breathing cycle provides patient-specific information



- Suitable 3D image registration algorithm provides local deformation fields between certain points of the breathing cycle
- Deformation fields are used as driving force in our simulations

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