AUCKLAND BIOENGINEERING INSTITUTE
THE UNIVERSITY OF AUCKLAND NEW ZEALAND
Te Whare Wānanga o Tāmaki Makaurau

Developing Subject-Specific Lung Tissue Mechanics Models

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Background

- Changes in density and heterogeneity of lung soft tissue often accompany physiological changes.
- These changes may be expected, such as those due to aging, or may be an indicator of disease.
- Physiological and disease related changes lead to altered mechanical behaviour of the lung.
- A biophysical model for lung tissue mechanics would allow us to link structure on CT imaging to measurements of integrated lung function via standard clinical pulmonary function tests (PFTs).

Objectives

- To derive subject-specific models of the stress-strain relationship in the lung tissue that replicate the pressure-volume behaviour of the whole (individual) lung, simultaneous with the regional deformation of the lung tissue as visualized on CT.
- To tailor this approach to different diseases or states of the lung, such as:
  - The older lung (decreased elastic recoil).
  - Lungs of obese patients (reduced lung volume).
  - Emphysema (reduction in elastic recoil, increased heterogeneity).
  - Acute Respiratory Distress Syndrome (ARDS) (stiffer tissue).

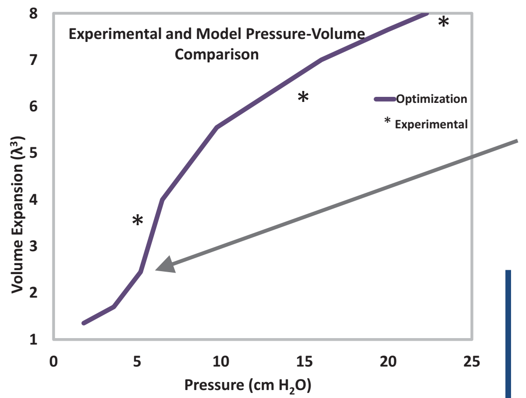

Figure 1: Pressure – volume comparison of the model vs. experimental data for one subject.

Image-Based Modelling

- Pressure-volume data from porcine measurements and experimental shear-stress data from human lung parenchyma[1] were used to generate an optimised energy density function.
- 5 pigs were used. The study protocol was approved by the University of Iowa Institutional Review Board and Animal Ethics Committee. Experiments were conducted at I-CLIC (Iowa Comprehensive Lung Imaging Center).
- The animals were intubated and mechanically ventilated with oxygen[2].
- The pigs' lungs were inflated to pressures of $7cmH_20$, $15cmH_20$, and $25cmH_20$.
- Volumetric CT scans were taken of the animals in the prone position at each of the inflation pressures, and the lung volumes reconstructed.

Mechanics Modelling

- A double-optimization problem was set up in MATLAB to generate coefficients for the SEDF using experimental data.
- Tissue deformation due to gravity was simulated for prone pig lungs using the optimized energy density function.
- The mechanics results were compared to the density distributions of the images as validation.

Optimisation

- The optimisation generates coefficients for a polynomial energy density function:

$$W = a_1 I_1 + a_2\left(I_1^2 - 2I_2\right) + a_3\left(I_1^3 - 3I_1I_2 + 3I_3\right) + a_4\left(I_1^4 - 4I_1^2 I_2 + 2I_2^2 + 4I_1I_3\right) + b_1 I_2 + b_2\left(I_2^2 - 2I_1I_3\right) + c_1 I_3 + c_2\left(I_1I_2 - 3I_3\right) + c_3\left(I_1^2 I_2 - 2I_2^2 - I_1I_3\right)$$

- Figure 1 shows the pressure-volume relationship of the optimised function.
- The knee at lower volumes represents airway closure in this phenomenological model, which is not well represented by exponential forms of the strain energy density function.
- The coefficients acquired from the optimisation were used in the lung tissue mechanics model.

Results

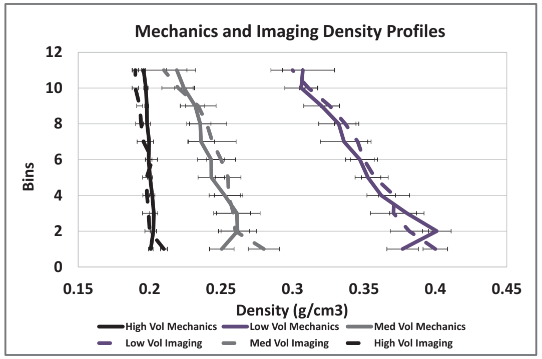

Figure 2: Mean mechanics and imaging density profiles for the dorso-ventral (gravitational) axis, for one representative subject. Porcine subjects were imaged in the prone position.

Volume	$\Delta\rho_{mean}$ expt-model ±S.D. (g/cm^3)	Δpressure expt-model ±S.D. (cmH_2O)	Δlinegradient expt-model (min.p-value)
low	0.0106 ±0.0114	0.2 ±0.56	p>0.1773
med	0.0058 ±0.0093	1.2 ±0.54	p>0.1692
high	0.0019 ±0.0014	≈0 ±0.41	p>0.1701

Table 1: Mean density, pressure, and overall density gradient difference for each inflation volume.

- Figure 2 above illustrates the results from the mechanics model and densitometry performed on the CT imaging, for one representative subject.
- Table 1 shows model accuracy for density and pressure, summarized for each inflation volume. T-tests were performed for the density profile gradients. P-values > 0.05 showed that the differences between model and experimental results were not statistically significant.
- A sensitivity analysis was performed for the SEDF coefficients using a uniaxial extension model.

Alveolar Micromechanical Model

- A space-filling truncated octahedral alveolar model was built in SolidWorks, representing a cube of excised lung parenchymal tissue (Figure 3).
- Data from mammalian stress-strain lung tissue material tests[3] were used to parameterise the model.
- It is intended that this model provide uniaxial or shear modulus data that can be used in the double optimization process, since human experimental data is generally unavailable for cases such as the older lung, lungs of obese patients, emphysema sufferers, those with ARDS, infant lungs, and patients with surfactant-production deficiency.

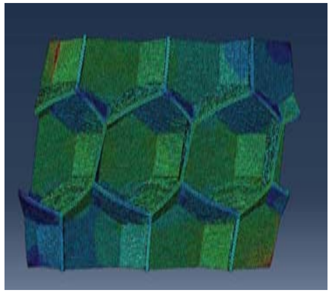

Figure 3: Micromechanical geometry of a block of alveoli, subject to shear testing.

References

[1]Lai-Fook, Stephen J., Hyatt, Robert E.; Effects of age on elastic moduli of human lungs; J Appl Physiology, 89: 163-168, 2000.
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[3]Rausch, S. M. K., et al. "Material model of lung parenchyma based on living precision-cut lung slice testing." Journal of the mechanical behavior of biomedical materials 4.4 (2011): 583-592.

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