Mechanical Characterization of Lung Tissue

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Introduction

Millions suffer from chronic lung diseases, costing over $150 billion annually, yet pulmonary biomechanics research is still in its infancy. Advancements in computational diagnostic and preventive tools depend on experimental tissue characterization to develop models for clinical insights [1]. Recent experiments highlight airway tissue anisotropy, where fiber engagement along the axial direction exhibits greater stiffness [2]. In this study, we formulate a structurally motivated constitutive model, informed by experimental data, to determine significant variations in collagen fiber and extrafibrillar matrix mechanical behavior of proximal and distal airways.

Methods

Uniaxial tensile tests were performed on multiple samples collected from the trachea, large bronchi, and small bronchi regions of 5 porcine specimens (n>30 per specimen; Figure 1A). The airway wall soft tissue specimens, composed of the mucosa and submucosa layers, were oriented along the circumferential or axial directions. The structural strain-energy function combined matrix and fiber component terms. The matrix was assumed to be the only active component in the circumferential direction and fit to the Neo-Hookean, Ogden, Mooney-Rivlin, or Demiray strain-energy functions. The resulting average matrix parameters for each region informed joined engagement of matrix embedded with fibers for the axial direction. Exponential or polynomial functions were assessed as an appropriate description for the fibers. Agreement between experimental data and the model fit was determined by a Bland-Altman analysis. A one-way ANOVA with a Bonferroni post-hoc analysis was performed to compare model parameters with respect to bronchial regions.

Results

The non-linear stress-strain response was best captured by an Ogden matrix strain-energy term and an exponential fiber strain-energy term (correlation coefficient R^2=0.95); Figure 1B). Assuming incompressibility simplified the models (preliminary analysis found Poisson's ratio of ~0.45). Matrix stiffness (μ) was greater for the small bronchi than the large bronchi. Matrix nonlinearity (α) of the small and large bronchi was greater than the trachea. Additionally, fiber nonlinearity (k_2) continuously decreased for distal regions (Figure 1C).

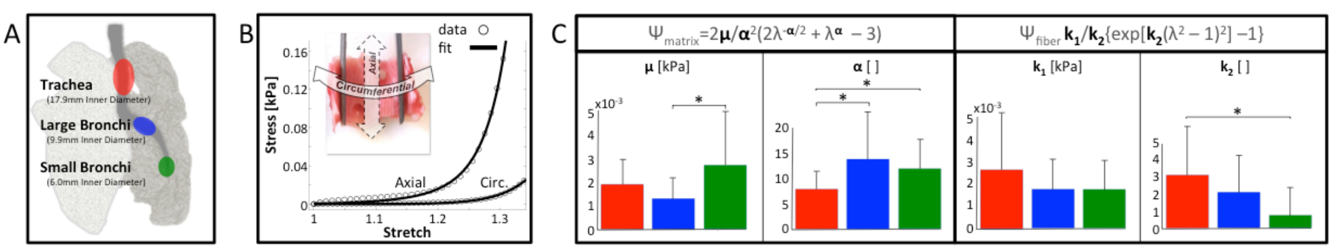

Fig 1: **(A)** Collected sample regions for both circumferential (matrix) and axial (fiber) response. **(B)** Representative circumferential data fit to Ogden strain-energy function; and axial data fit to Odgen combined with exponential strain-energy function. **(C)** Mean parameter values +/- standard error of the mean; significant parameter variation (***p<0.05) is observed between airway regions.

Discussion

These findings emphasize bronchial tree heterogeneity, and demonstrate that previous studies limited to tracheal mechanics do not directly translate to small bronchi and alveolus mechanics, where many lung diseases manifest [3]. Furthermore, the resulting regional variation of mechanical properties may yield insight into the important role of surfactants, which reduce the forces needed for lung expansion, countering stiffer distal airway behavior to facilitate oxygen exchange [4]. In conclusion, the results of this study provide a critical foundation for future finite element simulations of full lung mechanics and diagnostic tools.

[1] Eskandari et al. Journal Theoretical Biology 2016.
[2] Eskandari et al. Experimentally Characterized Mechanical Properties of the Airway Tree. Submitted.
[3] Codd et al. Journal Applied Physiology 1994.
[4] Yang et al. SB3C Proceeding 2017.