Micro-model to Evaluate Alveolar Wall Mechanical Properties from Pressure-Volume Response

Dilaver Singh, Duane S. Cronin, Arthur S. Slutsky

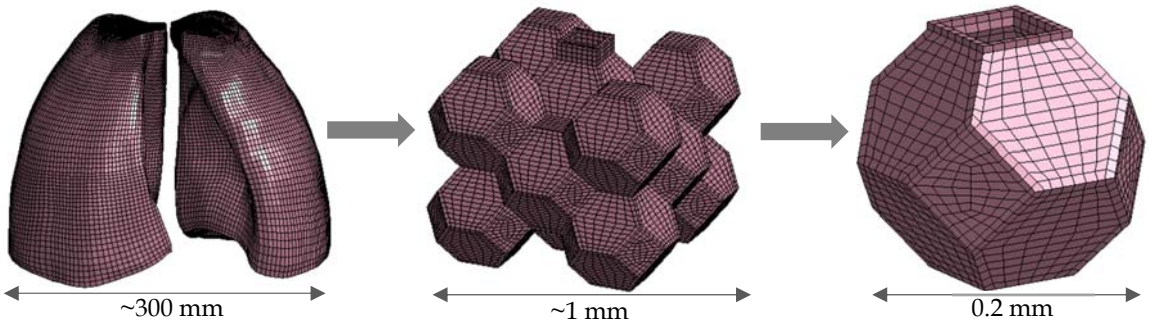
I. INTRODUCTION

The lungs, being responsible for oxygen exchange through respiration, are critical to short- and long-term health. Physical injury to the lungs can manifest in many ways and through a wide range of loading conditions, from ventilator-induced lung injury [1], to blunt impacts [2] and blast exposures [3]. To understand potential injury mechanisms of lung tissue that are relevant to biomechanics, it is first necessary to understand alveolar mechanics. The mechanical properties of human lung tissue at the alveolar scale are not well characterised in the literature, with most of the characterisation done at the bulk tissue scale. Furthermore, existing computational models for injury prediction typically use properties measured on excised tissue samples, rather than *in situ*. In general, the constitutive properties of alveolar tissue are a limitation of previous micro-scale and macro-scale models of the lungs.

Alveolar expansion during respiration is governed by a complex interaction of several factors, including alveolar wall elasticity, surface tension forces in the alveoli, pulmonary surfactant concentration, and pressure differentials driven by contraction of the thoracic diaphragm. Sugihara *et al.* [4] performed uniaxial tension tests on excised samples of alveolar wall tissue, but did not consider pre-strain effects that are present *in situ*. Uniquely, the nature of the lungs allows for the mechanical properties to also be characterised by pressure-volume response. Furthermore, the lungs can be pressurised in saline solution, which eliminates surface tension effects, such that the resistance to expansion of the alveoli is provided solely by the tissue walls. Clements *et al.* [5] performed such an experiment, using saline-filled human lungs, to separate and measure the contributions of tissue elasticity and surface tension on the pressure-volume response of whole lungs and single alveoli. The specific aim of this study was to identify the constitutive properties of lung alveolar wall tissue, using a finite element (FE) model at the alveolar scale, and existing pressure-volume data.

II. METHODS

A model of one alveolus was developed and analysed using a commercial explicit FE code (LS-DYNA, v971, R6.1.1, LSTC). The model consists of a tetrakaidecahedron-shaped alveolus [6] (shaped to facilitate future work in investigating alveolar clusters), with an opening at one face (Fig. 1, right). The alveolus model has an average diameter of 200µm and wall thickness of 12µm, to match human alveoli [7], and is comprised of single integration point hexahedral elements with an average element size of approximately 0.01mm.



Whole Lungs Alveoli Cluster Single Alveolus

Fig. 1. Lung FE models from the whole lung to alveolar scale.

D. S. Cronin (e-mail: dscronin@uwaterloo.ca; tel: 519-888-4567x32682) is a Professor in the Department of Mechanical Engineering and D. Singh is a PhD student in Biomechanics, both at the University of Waterloo. A. S. Slutsky is Vice President, Research, at St Michael's Hospital in Toronto, Canada.

In the first instance of the model presented in this study, surface tension effects were not considered. The tissue was modelled using an Ogden constitutive model, with parameters to fit the stress-strain response measured on excised alveolar wall tissue by Sugihara *et al.* [4]. The pressure inside the alveolus model was increased gradually by applying a uniform stress on the inside surfaces, and the volume change of the model was monitored. If the material properties of the tissue were correct, the pressure-volume response of the model should match the saline-filled pressure-volume curve of one alveolus from Clements *et al*. [5].

III. INITIAL FINDINGS

The pressure-volume response of the alveolus model using the original data from Sugihara *et al*. [4] was more compliant than the curve from Clements *et al.* [4] (Fig. 2, left). An optimisation technique (LS-OPT, LSTC) was applied to identify the Ogden material parameters. The optimisation methodology used a d-optimal sampling scheme and eight iterations, which achieved convergence. The optimised material model (Table I) produced a pressure-volume response in the model that closely matched the experimental curve (Fig. 2, left). The stress-stretch curve of the optimised Ogden model was similar to the initial Ogden fit, although shifted to the left (Fig. 2, right, solid line).

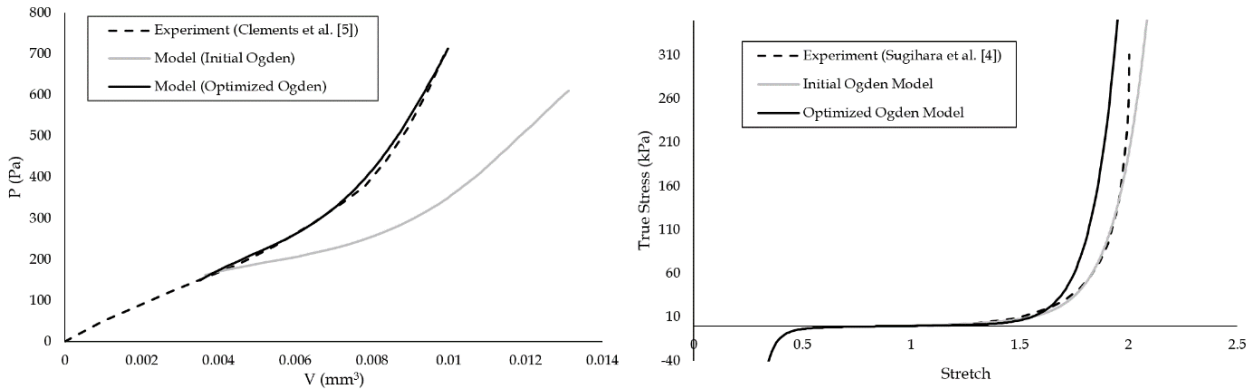


Fig. 2. Pressure-volume (left) and stress-stretch (right) curves for initial and optimised Ogden models.

TABLE I

OGDEN PARAMETERS OF OPTIMISED FIT

Parameter:	Density (kg/m^3)	Poisson's Ratio	μ_1	μ_2	α_1	α_2
Value:	1.050	0.499	0.005	0.949	16.70	2.40

IV. DISCUSSION

The stress-strain curve of the optimised Ogden material model, which produced a biofidelic pressure-volume response in the alveolar model, had a similar shape to the uniaxial tension data from Sugihara *et al*. [4], although shifted to the left by 12% in terms of stretch. Since the experiment used excised samples, which were not pre-strained, the initial stress in the tissue was absent from the measured mechanical properties. The good agreement between the optimised stress-stretch curve, which used an independent data source for the alveolar pressure-volume response, and the experimental stress-stretch curve from [4] demonstrates the importance of initial stress in the tissue.

Based on these results, the contribution of alveolar expansion response from the alveolar wall tissue has been modelled successfully, and is represented by the Ogden material model presented. Future work will incorporate surface tension effects to create an alveolar-scale model of the lung for injury evaluation.

V. REFERENCES

[1] Slutsky, A. S., *et al*., *N Engl J Med*, 2013. [2] Gryth, D., *et al*., *Military Med*, 2007. [3] Stuhmiller, J. H., *Toxicology*, 1997. [4] Sugihara, T., *et al*., *J Appl Physiol*, 1971. [5] Clements, J. A., *et al*., *J Appl Physiol*, 1960. [6] Fung, Y. C., *J Appl Physiol*, 1985. [7] Ochs, M., *et al*., *Am J Respir Crit Care Med*, 2004.