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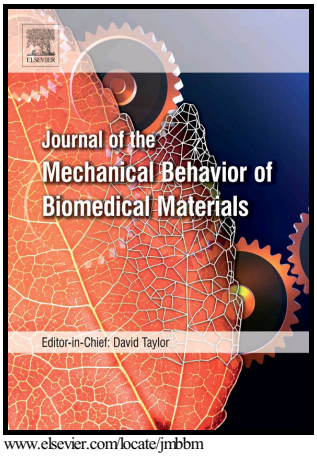

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Experimental characterization and model identification of the nonlinear compressible material behavior of lung parenchyma

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Abstract

The mechanical properties of lung parenchyma are essential both in lung function and biology; consequently, experimental methods are developed to describe the mechanical behavior of lung parenchyma. During breathing and mechanical ventilation, volume change is the physiologically dominating deformation mode of lung parenchyma; nevertheless, most studies examine lung tissue in mainly isochoric tension tests. In this paper, a novel experimental method for the quantification of the compressible material behavior at high volume changes of viable lung parenchyma is proposed. This volume-pressure-change experiment quantifies the pressure and corresponding volume change of lung parenchyma slices. For the characterization of the compressible constitutive properties over the whole physiological pressure range, we combine this newly derived experiment with uniaxial tension tests. The experimental results of both the volume-pressure-change experiments, for which 287 samples were examined, and the uniaxial tension tests, which were performed on 36 specimens, are presented. The resulting measurements are utilized to optimize the material parameters of one suitable hyperelastic strain-energy function describing the nonlinear compressible material behavior of viable lung parenchyma. The derived constitutive model can be used for simulations of lung parenchyma, and will help to quantify the strains and stresses of lung tissue during normal breathing and mechanical ventilation.

Keywords: Experimental methods, Numerical Identification, Nonlinear compressibility, Lung parenchyma, Soft tissue mechanics

1. Introduction

Characterizing the compressible material properties of lung tissue is an essential ingredient allowing the description and prediction of the mechanical behavior and injury of lung parenchyma during normal and artificial breathing. To better understand lung mechanics in health and disease and to improve therapeutic approaches, global and continuum mechanics based models of the whole respiratory system have been developed. [...] Global models, as for example pressure-volume curves of whole lungs, are not able to describe the underlying phenomena in the respiratory system. In contrast, consider continuum models the individual effects and mutual interaction of lung parenchyma, surfactant, airways, and air flow (see e.g., Berger et al. (2015); Roth et al. (2017); Wall et al. (2010)). This separation of the different mechanical phenomena should allow the simulation and even prediction of the progress of several lung diseases, as well as the effects of different interventions. For instance, improper mechanical ventilation can locally overstrain lung tissue and cause ventilator-associated lung injury (VALI) (Consensus-Conference, 1999), particularly in the case of patients suffering from pre-existing lung injuries, such as the acute respiratory distress syndrome (ARDS) (Ware and Matthay, 2000). Continuum mechanics based lung models can provide insights into involved phenomena and support the development of protective ventilation strategies. For these lung models and to better understand the mechanical behavior of lung tissue, an accurate description of the constitutive continuum mechanics model of lung parenchyma is essential. In this paper, the material behavior of the tissue itself without surfactant and airways is characterized, because the mechanical properties of surfactant and airways can be modeled separately (e.g., Roth et al. (2017); Wiechert et al. (2009)) and are mechanically coupled in our lung model (Yoshihara et al., 2017).

The main function of lung parenchyma is the gas exchange; therefore, the exchange-area is maximized through a foam-like structure, composed of bronchioles (i.e., small airways), alveoli (i.e., small cavities forming the blood-gas barrier) and the enclosed air volume. The major load-bearing elements in lung tissue are collagen and elastin fibers, which are aligned along the alveolar walls (Yuan et al., 2000). However, on a macroscopic scale, the alveolar wall orientations and, consequently, the fiber orientations have no preferred direction (Sobin et al., 1988; Toshima et al., 2004). Hence, lung parenchyma, i.e., the homogenized representation of all these constituents and struc-

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