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Multi-Scale Analysis of Coupled Lung Tissue Dynamics

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ABSTRACT

Mechanical ventilation of patients suffering from lung failure (ARDS/ALI) is a vital supportive therapy. Improper methods of ventilation, however, can cause mechanical overstraining of parenchymal tissue resulting in additional and frequently lethal inflammatory injuries. This complication is commonly called ventilator-induced lung injury (VILI) and occurs mainly at the alveolar level of the lung. We are interested in finding protective ventilation strategies and thereby contributing to decrease the dramatically high mortality rates of ARDS/ALI patients.

The lung is a highly heterogeneous structure comprising multiple spatial length scales. A direct numerical simulation of the respiratory system resolving the alveolar level is neither possible nor reasonable. Therefore a computational multi-scale approach is developed allowing the derivation of local boundary conditions for representative volumes of the microstructure as well as homogenized properties for global simulations of the lung. The multi-scale analysis is based on a detailed mechanical model of the underlying microstructure as described in [1].

A representative volume element (RVE) of the human lung is defined as an assemblage of pulmonary alveoli represented by tetrakaidecahedral cells. Connections of alveoli within a ventilatory unit are established with the help of a novel labyrinthine algorithm introduced in [2]. Preservation of overall minimal mean pathlength is a priori guaranteed by introducing affiliation rules specific to the chosen geometry.

A hyperelastic constitutive model is employed for the mathematical description of alveolar soft tissue behavior following [3]. The strain-energy density function accounts for an isotropic ground substance including elastin fibers and collagen fiber families with distributed fiber orientations. Each function fulfills the principles of objectivity and material symmetry as well as the requirements of polyconvexity and a stress-free reference state. Tension tests on lung slices combined with an inverse analysis are used to identify material parameters of single alveolar walls as presented in [4].

Interfacial phenomena stemming from surface-active agents (the so-called surfactant) covering pulmonary alveoli are also incorporated into the micromechanical model. Structural and interfacial mechanics are coupled at the surface of the alveolar wall without explicitly modeling the very thin continuous liquid lining. The highly nonlinear and dynamic nature of surfactant is taken into account with

the help of an adsorption-limited model [5] relating surface stresses to the interfacial concentration of surfactant molecules.

Based on this three-dimensional coupled model for pulmonary alveoli a dynamic computational multi-scale approach is established. A nested solution technique as proposed e.g. in [6] enables the information transfer between global and local scales that are solved simultaneously. Boundary conditions of the RVE are defined by the current macroscopic deformation state. Consequently problems arising in single-scale simulations of alveoli as determining alveolar pressures or considering the influence of adjacent ventilatory units are circumvented. After having solved the current microscale boundary value problem, macroscopic quantities of interest can be determined by volume averaging of the corresponding local counterparts. Therefore no constitutive assumptions on the macroscale are necessary in contrast to classical sequential homogenization methods.

The applied multi-scale approach is applicable for large deformations, rotations and arbitrary microstructural behavior. An extension to even further scales like e.g. lower airways or cells is also conceivable. Thus the presented model provides a framework for investigating the effects of mechanical ventilation on all interesting length scales.

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