A 3D hyperelastic lung model coupled to a 0D representation of the bronchial tree

Romain LOPEZ--SURJUS, Inria - Laboratoire Jacques-Louis Lions - Paris
Céline GRANDMONT, Inria - Laboratoire Jacques-Louis Lions - Paris
Frédérique NOËL, Inria - Laboratoire Jacques-Louis Lions - Paris
Fabien VERGNET, Inria - Laboratoire Jacques-Louis Lions - Paris

Mathematical modeling of the respiratory system provides a structured framework for analyzing various processes involved in breathing. This approach may be particularly relevant to improve diagnosis in the context of lungs pathologies such as asthma, COPD, fibrosis or emphysema where spontaneous ventilation is impaired. In these situations, patients are admitted to intensive care units where artificial ventilation assists them with their breathing effort by injecting air through the trachea, leading to possible lung injuries. To describe the ventilation process and understand how the lungs react to these large pressure variations, we propose a dynamic continuum mechanics model describing the lung deformations as those of a hyperelastic material. We consider the non-linear constitutive law developped in [1] in the steady state setting and generalize it to an unsteady setting. Furthermore, we couple it to a 0D representation of the bronchial tree, viewed as a resistive diadic tree as in [2]. We choose to preserve the equivalent resistance of the tree while reducing the total number of generations, in an effort to lower computational cost. Several terminal subdomains are then defined, representing the region of influence of a path through the bronchial tree. This coupling between the air flow through the bronchial generations and the lung parenchyma deformations adds a pressure gradient in the elastic equations representing the action of the air flow on the elastic media. This additional term can be written as a non-local non-linear dissipative term which depends only on the parenchyma deformations. The resulting equations can be viewed as a poromechanical model describing the air-parenchyma interaction and satisfying energy estimates. To discretize in time the resulting system, we consider a Generalized-α scheme with a finite element approximation for the space discretization. Due to the non-local term, the associated finite element matrix is a dense matrix obtained by the product of two time-dependent matrices, greatly increasing computation and memory costs, especially as the system is solved by a Newton algorithm. To overcome this limitation, we propose different numerical strategies as well as a local approximation of the resistive term. Various breathing scenarios are simulated for a 3D realistic lung geometry considering some boundary conditions modeling the impact of surrounding elements such as the rib cage or the abdomen. The proposed coupled models shall be further used in pathological situations in particular to explore possible lung injuries for patients under artificial ventilation.

[1] C. Patte, M. Genet, D. Chapelle. *A quasi-static poromechanical model of the lungs*. Biomechanics and Modeling in Mechanobiology, **21**, 2022. doi :10.1007/s10237-021-01547-0.

[2] N. Pozin, S. Montesantos, I. Katz, M. Pichelin, I. Vignon-Clementel, C. Grandmont. *A tree-parenchyma coupled model for lung ventilation simulation.* International journal for numerical methods in biomedical engineering, **33(11)**, e2873, 2017.

Contact : `romain.lopez-surjus@inria.fr`