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EFFECT OF MICROSCOPIC PROPERTIES ON THE HOMOGENIZED LINEAR POROELASTIC BEHAVIOR OF LUNG PARENCHYMA

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SUMMARY

In this work, a micro-poro-mechanical model is proposed in 2D with various levels of irregularity and porosity, as a first step toward lung micromechanical modeling. The homogenized behavior of the generated microstructures is computed to evaluate how irregularity and porosity affect the macroscopic poroelastic material parameters.

Key words: *Lung micromechanics, linear poroelasticity, homogenization*

1 INTRODUCTION

IPF is a pulmonary disease that affects lung parenchyma by thickening and stiffening the alveolar wall; this decreases lung compliance and makes it harder for the patient to breathe [1]. To better understand the link between the macroscopic behavior of lung parenchyma and its microscopic mechanical and morphological features, we aim to develop a micromechanical model based on an artificial geometry mimicking the real lung parenchyma microstructure, designed to perform homogenization to obtain a macroscopic poroelastic behavior driven by microstructural phenomena. Such a model could be tuned to depict different pulmonary pathologies, including IPF, and investigate the potential mechanical vicious circle leading to a pathological evolution of the lung [2]. Other computational models have been suggested in the literature, based on microstructures, following nonlinear hyperelastic model [3].

Based on the real lung microstructure, different geometries have been proposed in the literature to mimic the lung microstructure at the alveolar scale, among which TetraKaiDekahedron (TKD) element [4] as it is the simplest sphere-like space-filling shape. In this work, we propose a 2D microstructure whose irregularity can be tuned to model the lung alveoli. A poroelastic linear model is then described with the state variables of strain and added fluid mass density, beside the state equations to obtain the pore pressure and the stress in the macroscopic scale. The effect of geometry on the homogenized behavior of the generated microstructures is evaluated for different levels of irregularity.

2 METHODOLOGY

2.1 Micromechanical model

The focus of this work is lung parenchyma. We aim to generate a microstructure suitable for micromechanical computations and which mimics lung microstructure. Lung in the alveolar scale is made of alveoli which look like polygons with different sizes and number of faces. Based on the images from lung microstructure [5], we have chosen a hexagonal geometry in 2D, as it fills the space. However, in 2D there is no regular space-filling pattern that would lead to isotropic homogenized properties,

while lung parenchyma is supposed isotropic. Therefore, we propose a method to generate irregular 2D microstructures, from perturbed hexagonal microstructure to a random one based on Voronoi tessellation. The key to create such microstructures is seed distribution. If the seeds are regularly placed as in Figure 1a, it will generate a regular hexagonal-based microstructure as in Figure 1b. But, if we add random perturbations to each seed, we obtain a hexagonal-based microstructure with irregularity as in Figure 1c, while randomly distributing seeds results in an irregular microstructure on which elements have different sizes and number of faces. The concept of irregular microstructure base on Voronoi tessellation has been proposed previously [6].

We have defined a parameter DoI (Degree of Irregularity), for the microstructural model, which scales the irregularity level between zero and one. It is based on a threshold defining the acceptable area for each seed, depicted as blue rectangles in Figure 1c. The parameter DoI is defined as below:

$$DoI = \frac{cell\ threshold}{cell\ width}. \quad (1)$$

It is zero when the microstructure is completely regular and equals 1 when the threshold for irregularity reaches the cell width.

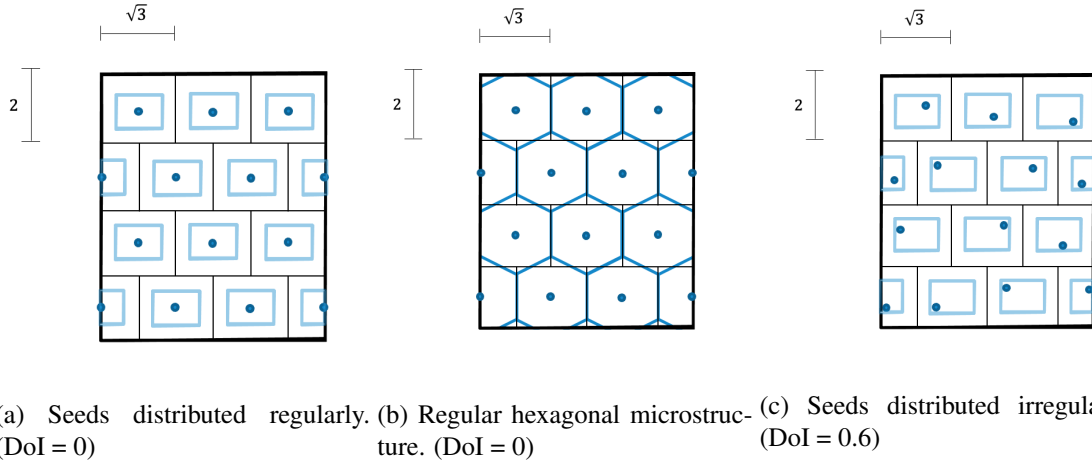


Figure 1: Seeds distribution and irregularity of the microstructure

Representative Volume Elements (RVE) with periodic boundary conditions were elaborated and meshed in GMSH. Walls were generated based on the central seeds location and assembled through Boolean operations. Periodicity was obtained by adding similar seeds pattern around the main central seeds and cropping the mesh just around the central seeds at the end, as proposed in [7]. In this poromechanical model, the tissue is a mixture of solid and fluid. The volume fraction of fluid in the reference configuration is denoted by Φ_{f0} . Alveolar walls were considered linear elastic and described by E_s and ν_s , Young modulus and Poisson ratio respectively, with the following values: $E_s = 5\text{ kPa}$ and $\nu_s = 0.1$.

2.2 Homogenization

The micromechanical model is homogenized to obtain the macroscopic resulting tissue behaviour. To do so we invoke the Hill-Mandel principle, which states that the microscopic and macroscopic energies are equivalent:

$$\frac{1}{2} \langle \underline{\underline{\epsilon}} : \underline{\underline{C}} : \underline{\underline{\epsilon}} \rangle = \frac{1}{2} \underline{\underline{\tilde{\epsilon}}} : \underline{\underline{C}} : \underline{\underline{\tilde{\epsilon}}}, \quad (2)$$

where $\underline{\underline{\tilde{\epsilon}}} = \langle \underline{\underline{\epsilon}} \rangle$. We set $\underline{\underline{\tilde{C}}} = \langle \underline{\underline{C}} \rangle$ as the homogenized elasticity tensor. The macroscopic poroelastic model is described by two state equations and two state variables, namely the strain and the added fluid mass density, and provides the stress and pore pressure. These state equations are:

$$\underline{\underline{\tilde{\sigma}}}(x) = \underline{\underline{\tilde{C}}}(x) : \underline{\underline{\tilde{\epsilon}}}(\underline{\underline{u}}(x)) - \tilde{p}_f \underline{\underline{1}}, \quad (3)$$

where $\underline{\underline{\tilde{\sigma}}} = \langle \underline{\underline{\sigma}} \rangle$ is the homogenized stress over the domain and $\underline{\underline{\tilde{u}}}(\underline{\underline{x}})$ is the perturbation, and:

$$\frac{\tilde{\rho}_{f\pm}}{\tilde{\rho}_{f0}} = \frac{1}{\tilde{\kappa}} \tilde{p}_f + \underline{\underline{\tilde{\epsilon}}} : \underline{\underline{1}}, \quad (4)$$

where \tilde{p}_f is the pore pressure, $\tilde{\rho}_{f0}$ is the fluid mass density in the reference configuration, and $\tilde{\rho}_{f\pm}$ is the added fluid mass density. Applying any macroscopic strain or pore pressure \tilde{p}_f , results in macroscopic stress and change in the volume fraction of solid and as a consequence, added fluid mass density $\tilde{\rho}_{f\pm}$. It is notable that coefficient $\tilde{\kappa}$ tends to infinity for incompressible materials. These equations show that stress is linearly related to pore pressure, while the added fluid mass density depends on the pore pressure and macroscopic strain. Due to the hexagonal microstructure, we expect the homogenized model to be orthotropic so we express $\underline{\underline{\tilde{C}}}$ as:

$$\underline{\underline{\tilde{C}}} = \begin{bmatrix} \frac{1}{\tilde{E}_1} & -\frac{\tilde{\nu}_{12}}{\tilde{E}_1} & 0 \\ -\frac{\tilde{\nu}_{21}}{\tilde{E}_1} & \frac{1}{\tilde{E}_2} & 0 \\ 0 & 0 & \frac{1}{2\tilde{G}_{12}} \end{bmatrix}^{-1} \quad (5)$$

We can compute the evolution of the homogenized parameters with respect to micromechanical features, such as porosity, DoI , alveolar wall elasticity, etc.

3 RESULTS AND CONCLUSIONS

The evolution of homogenized material parameters \tilde{E}_1 , \tilde{E}_2 & $\tilde{\kappa}$ with respect to porosity is investigated for three different values of DoI . As shown in Figure 2 and as expected, \tilde{E}_1 and \tilde{E}_2 decrease with respect to porosity, but get closer when irregularity increases, which means that the behavior gets closer to isotropy.

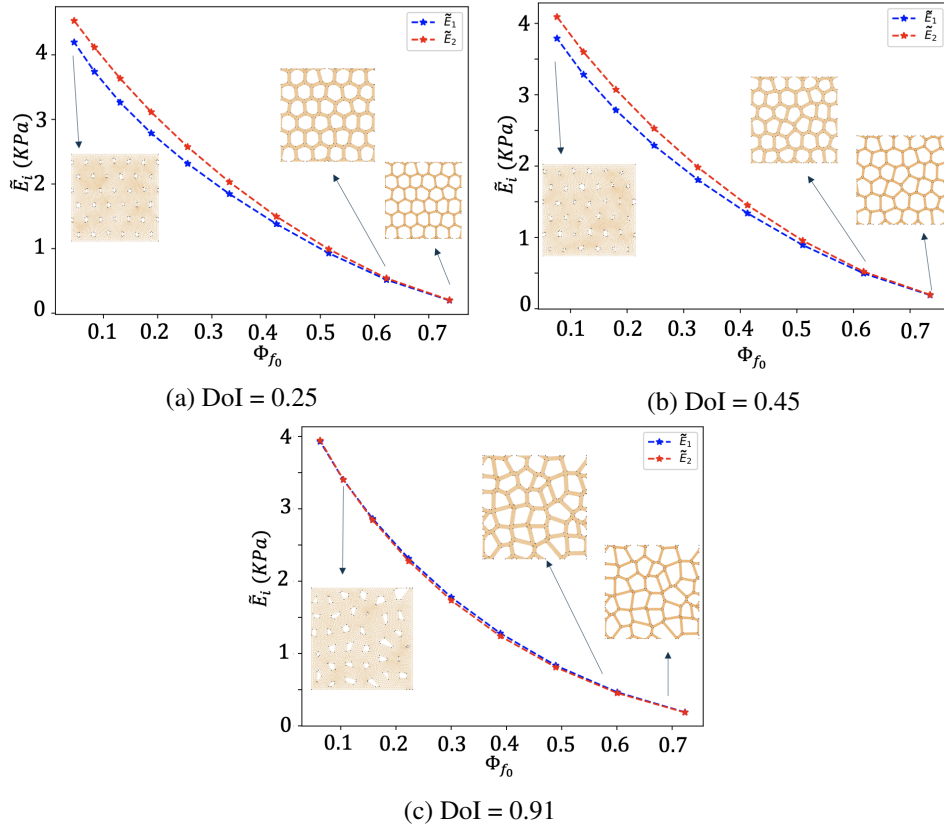


Figure 2: Homogenized Young moduli with respect to microstructure porosity, for various DoI .

As shown in Figure 3, for a regular microstructure, $\tilde{\kappa}$ decreases as the porosity increases. Here the solid material is supposed incompressible, so the mixture tends to be incompressible when the porosity tends to zero ($\tilde{\kappa}$ tends to infinity).

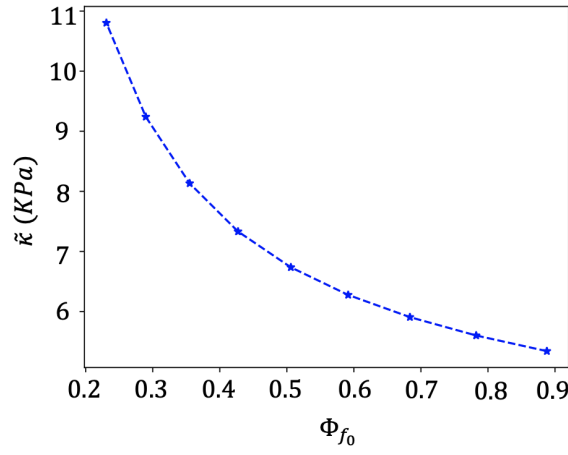


Figure 3: Homogenized bulk modulus with respect to microstructure porosity.

For future work, we are focusing on the nonlinear material behavior. Also, we would be interested to study the nonlinear behavior for a 3D model with TKD elements, besides adding irregularity to the TKD model. This will help improve existing macroscopic poromechanical models proposed for the lung, which could serve as augmented diagnosis tools in personalized modeling pipelines [8].

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