Finite Element Simulation and Visualisation of Hyperpolarised Gas Diffusivity Distributions in Models of Lung Airways

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Introduction

MR diffusion experiments using hyperpolarized noble gases are sensitive to lung microstructure. Computer simulations in simplified models of acinar airway geometry have been used [1-4] to investigate ^{3}He diffusion in lungs. The applicability of those models is limited by their non-realistic nature as a consequence of the geometric assumptions and simplifications necessary to implement the computer simulations. An alternative has been the use of 2D models obtained from lung histological sections [5] for Monte Carlo simulations.

In this work, we use histological sections to generate computer models of acinar airways. Using these models, finite element computer simulations of ^{3}He and ^{129}Xe gas diffusion in the lungs are implemented. The results of these simulations are presented here through maps of microscopic magnetization and diffusivity distributions. This approach to the simulation and visualization of the results helps provide a better understanding of the different length scales and diffusion regimes [6] present in lung diffusion MR experiments.

Methods

Geometric models were developed from lung histology sections stained with hematoxylin and eosin (H&E) as described in [7], for better contrast between lung parenchyma and airspace. The image processing tools used to convert the histology images into a set of geometrical objects for use in the simulations were implemented in Matlab. These tools included: intensity (i.e. lighting) non-uniformity correction, threshold selection for conversion to binary images and detection of closed contours for extraction and labelling of airways (Fig. 1). Computer simulations were performed by solving the Bloch-Torrey equation using finite element methods (FEM) for a bipolar gradient waveform [6] using Comsol Multiphysics and Matlab. A broad range of diffusion times (0.5-6 ms) and gradient strengths (G = 0-40 mT/m) was investigated for mixtures of ^{3}He and ^{129}Xe in air.

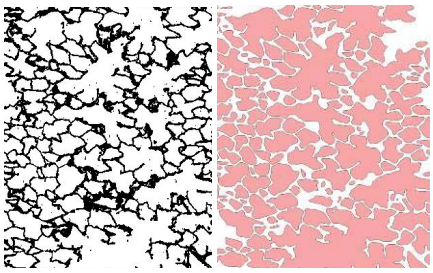

Figure 1. Realistic geometric model of acinar airways obtained from histology sections. A: Binary image. B: Airway objects extracted from the closed contours in the binary image.

Results and Discussion

FEM simulations using the realistic airway models allowed the generation of maps of the microscopic distributions of signal and diffusivities (Figs. 2 and 3) within lung acinar structures. Figs. 2A and 2C show that the diffusivity of ^{3}He is affected by both the size of airway and the presence of branches. In Fig. 2B, it can be seen that for large gradients, the onset of the localized diffusion regime significantly modifies the diffusivity distribution with regions of larger apparent diffusivity (ADC) in the regions (arrow) farthest from the boundaries.

Fig. 3 shows how the reduced diffusivity of ^{129}Xe with respect to ^{3}He, results in different ADC distributions. For ^{3}He (Fig. 3A) the distribution over the largest airway is nearly uniform due to motional averaging, since during the diffusion time (2 ms) its atoms can travel across the whole airway. For ^{129}Xe, the ADC distribution is non-uniform, with diffusion of ^{129}Xe atom within alveoli being highly restricted, while atoms outside the alveoli experience much less restriction. The reduced diffusivity of ^{129}Xe limits the mixing between atoms in the intra and extra-alveolar spaces; this suggest that ^{129}Xe diffusion behaviour may be described using a simple two-compartment analytical model.

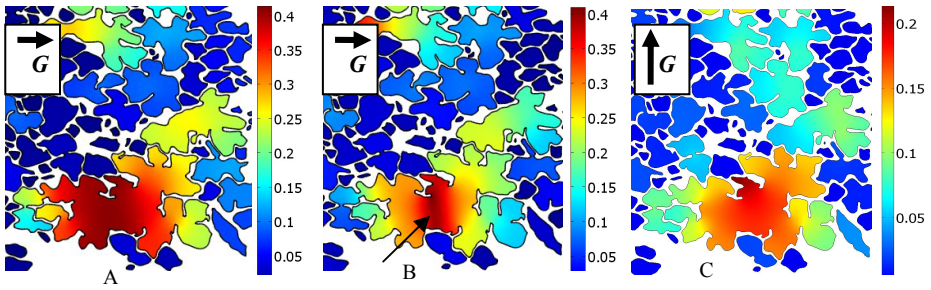

Figure 2. Diffusivity distributions (cm^2/s) of ^{3}He (D_0=0.88 cm^2/s, in air) for different gradient strengths and directions (diffusion time 1.8 ms). A: G=10 mT/m along horizontal direction. B: G=30 mT/m, horizontal direction. C: G=30 mT/m, vertical direction.

These results also suggest that ^{129}Xe MRI may be more sensitive to alveolar structure than ^{3}He, while been less sensitive to branching and localized diffusion effects.

Conclusions and Future Work

The image processing algorithms developed in this work allowed automatic generation of realistic models of acinar airways from images of lung histology sections. The visualization of microscopic diffusivity distribution obtained from FEM diffusion simulations makes it possible to gain physical insight into the nature of gas diffusion in lung airways, in particular the diffusion regimes relevant for different pulse sequence parameters and gas mixtures used in hyperpolarised gas MR. In future work, the methods developed here will be extended to create 3D realistic airway models, using 2D histological sections as the starting point for model generation.

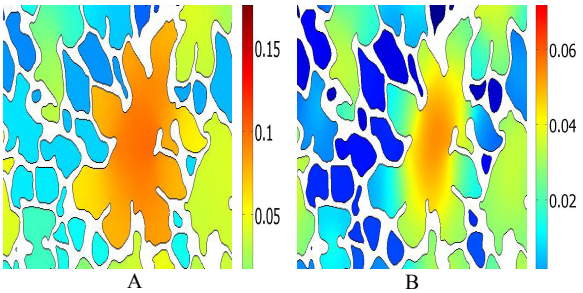

Figure 3. Diffusivity distributions (cm^2/s) of A) ^{3}He (D_0=0.88 cm^2/s, in air) and B) ^{129}Xe (D_0= 0.14 cm^2/s, in air) with a diffusion time Δ= 2 ms and b= 1.64 s/cm^2. The gradient was directed along the vertical direction.

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