Hyperpolarized gas MR diffusion simulations and experiments in realistic 3D models and phantoms of human acinar airways

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Target Audience: diffusion MR, hyperpolarized gas MR and lung MR researchers.

Introduction: Theoretical models of gas diffusion can be used to obtain quantitative information about lung microstructure (e.g. airway dimensions) from hyperpolarized gas MR images [1]. The accuracy and applicability of current models is limited by their reliance on simplified geometries (i.e. non-connected infinite alveolated cylinders) that do not necessarily best reflect the complexity of acinar airways [2]. Assessment of the validity of these theoretical models has only been possible by indirect comparison to histological measurements [1] or MR diffusion experiments in phantoms with simple geometries [2].

Purpose: Development of a new framework for computational modelling and MR measurement of hyperpolarized gas diffusion using realistic 3D geometric models and phantoms of acinar airways generated from micro-CT imaging ex-vivo with the goal of better understanding and modelling the in-vivo diffusion signal.

Fig 1. 3D rendering of microCT data of lung tissue sample corresponding to in-vivo image voxel size (7x7x7 mm)

Methods

Models: 3D micro-CT images (16μm resolution) of excised samples of human lungs (Fig. 1) [3] were segmented to produce 3D models of the acinar airways ranging from a few branches up to a complete acinus. The image processing workflow (Fig. 2) used to generate the models was implemented in Matlab and Simpleware. Models with different numbers of airway generations were obtained by region growing into the airspace that is distal to a manually selected seed within an airway (e.g. in a respiratory bronchiole for a whole acinus model).

Diffusion Simulations: Volume meshes (Fig. 3A) were generated in Simpleware and exported to Comsol Multiphysics for Finite Element (FE) simulations, which were implemented by solving the Bloch-Torrey equation [2] for the ranges of pulsed diffusion weighting gradients (G= 0-40 mT/m) and diffusion times (Δ= 1ms – 1s) relevant to in-vivo human lung gas diffusion MRI.

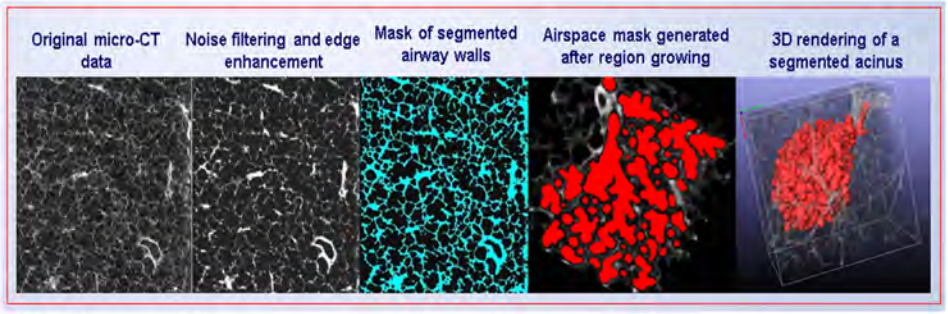

Fig 2. Summary of the image processing workflow used to generate the airways models.

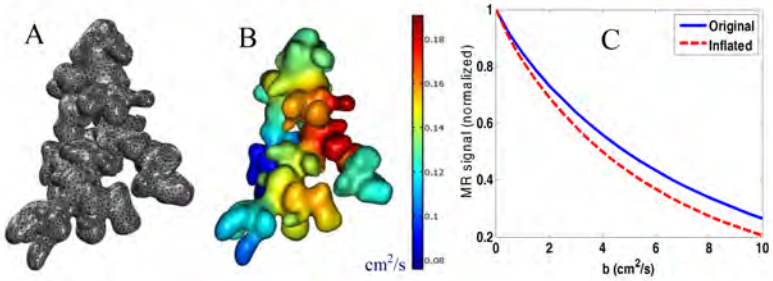

Fig 3. Sample volume mesh (A) used in FE simulations and (B) 3D diffusivity distribution obtained for Δ=1.8 ms, b= 10 s/cm². Simulated MR signals (C) showing the effect of lung inflation [4] by isotropic airway enlargement (70% volume increase).

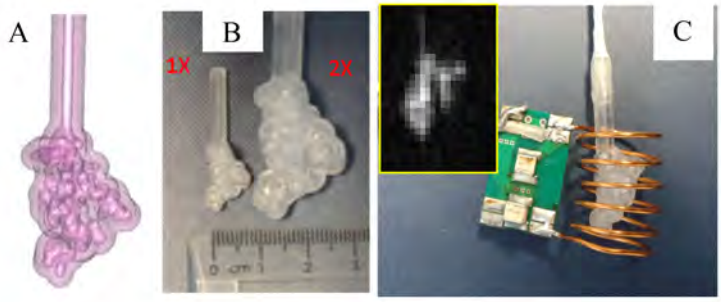

Fig 4. Model developed for 3D printing (A), two acinar airways phantoms printed at two different scales (B) and RF coil used for ^{3}He MR experiments (C). The inset in (C) shows a ^{3}He MR image obtained from the phantom.

MR Phantom Experiments: Realistic airways phantoms were built by 3D printing of the segmented airway models. The 3D models were created with Mimics Innovation Suite (Fig. 4A) and printed (Fig 4B) with stereolithography technology using a rigid, transparent, material (TuskT, Materialise NV, Leuven, Belgium). The models were printed at the actual scale of the airways and double scale. ^{3}He MR diffusion signals and images from the phantoms were obtained in a GE 1.5T clinical scanner using solenoidal T-R coils (Fig. 4C) built to maximize the filling factor and hence SNR. Hyperpolarized gas (30% ^{3}He 70% N_2) was delivered using a syringe after evacuation of the air within the phantom.

Results and Discussion: The simulated MR signals (Fig. 3C) and diffusivity distributions (Fig. 3B) showed the signal behaviour obtained in lung diffusion MR experiments, including non-Gaussian behaviour and localized diffusion [2]. Figure 4C (inset) shows a hyperpolarized ^{3}He image of one of the printed phantoms, confirming that all the structures inside the airways are properly ventilated. Diffusion measurements obtained from the phantoms confirmed the average diffusivity values obtained from the simulations.

Conclusions: 3D models of lung acinar structure were obtained through segmentation of micro-CT images and used in numerical simulations of gas diffusion MR. Realistic phantoms were obtained from these models by 3D printing and used in ^{3}He MR experiments. These models and phantoms provide a new simulation and experimental framework to develop new MR methods and theoretical models to study lung anatomy and physiology and these techniques could be readily extended to ^{1}H diffusion in realistic anatomical structures such as neuronal tracts.

References:

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