Experimental study of gas diffusion in a pulmonary acinus model

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Introduction

Using MRI with Hyperpolarized (HP) gases, one can measure diffusion of Helium-3 in the lungs and detect changes due to pathologies such as emphysema [1]. *In vivo* measurements showed deviation to a simple Gaussian behavior with a single apparent diffusion coefficient (ADC), when considering the signal attenuation as a function of diffusion gradient intensity; this was explained by a model of anisotropic diffusion with longitudinal (D_L) and transverse (D_T) diffusion coefficients [2]. The 3D architecture of the pulmonary acinus is a dichotomic branching structure, which could also play a role in the observed behavior. In this work we used a 3D structure like the one suggested by Kitaoka *et al.* [3] and performed diffusion measurements on it. Data were compared to numerical simulations and to two currently used diffusion models.

Materials and Methods

A phantom was made by stereolithography from standard epoxy (Figure 1) with a branching internal structure following the Kitaoka's algorithm [3]. The internal channel had a square section (3 mm size) and the total internal size was 28 mm, about 10 times larger than the original model. Helium-3 was polarized to 10% by optical pumping (OP) with the metastable technique and transferred from the OP volume into a storage glass cell [4]. The accumulated gas was transferred into the phantom at a pressure of 760 hPa and a temperature of 293 K. The corresponding free diffusion coefficient D_0 was then 2.6 cm^2/s.

NMR experiments were performed on a 0.1 T whole-body MR scanner (Magnetech, France) controlled by an Apollo sequencer (Tecmag, Houston, TX, USA). A saddle coil was used for transmission, and a Helmholtz pair (10 cm diameter) for reception. Both coils were tuned at 3.29 MHz (γ=2.04 10^8 s^{-1} T^{-1} for ^{3}He). The sequence consisted of 40 FIDs, collected during 256 ms at the same delay after a RF hard pulse (15° flip angle); spoiler pulses were applied on the three axes; the first 10 FIDs were sampled after bipolar gradient pulses of 10 ms total duration (2.2 ms ramp time and 0.6 ms plateau) and of amplitudes G ranging between 0 and 5.6 mT/m, to obtain diffusion-weighted signals; the last 30 FIDs were sampled to accurately determine signal loss by RF depolarization and T_1 relaxation. Diffusion weighting was measured on each of the three axes X, Y, Z in separate experiments. Each FID initial magnitude was determined by fitting the complex data to an exponential decay multiplied by a Gaussian function. Diffusion-weighted signals were corrected from the determined signal loss.

Monte Carlo simulations of the reflected Brownian motion with 10^6 particles were realized in the exact phantom geometry to compute the NMR signal attenuation by diffusion along each gradient axis [5].

Results

The FID initial magnitudes were determined with an accuracy better than 0.1%. Figure 2 shows signal attenuation as a function of G, for G applied on the X axis. The error bars (not shown on Figure 2) were smaller than 0.006. The numerical results drawn on the graph were in excellent agreement with the experiments. Best fits to the experimental data are also shown: i) the Gaussian model fitted best with ADC=1.39 cm^2/s, but only data for small G values followed that simple model; ii) the anisotropic diffusion model [2] fitted best with D_T=0.62 cm^2/s and D_L=3.79 cm^2/s; the agreement between measurement and theory extended to larger G values, except for the last 2 values. Comparable results were found when the diffusion gradient was applied on the Y axis and on the Z axis, in agreement with the phantom minor anisotropy.

Discussion and Conclusion

As for previous *in vivo* measurements [4] signal attenuation in the Kitaoka's model deviated from a simple Gaussian behavior. These experimental results confirmed the validity of the numerical simulations [5]. The ADC values twice smaller than D_0 are probably due to time-dependent diffusion [6]. The D_L values found from the fit to the anisotropic diffusion model were systematically larger than D_0, which has no clear physical interpretation . In conclusion, the numerical approach gives better account of the experimental results than the existing models over the whole range of gradient intensity. *In vivo* experiments, with stronger gradients, will eventually tell which diffusion model is relevant to healthy lung.

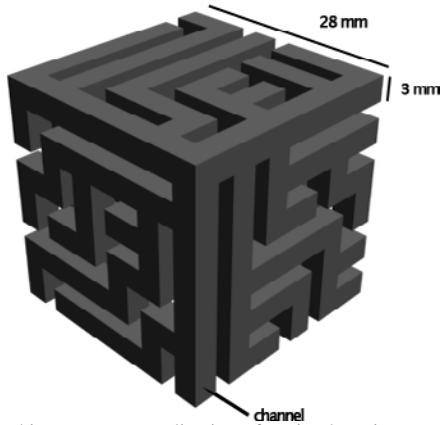

Fig. 1 Branching geometry realization of a Kitaoka acinus

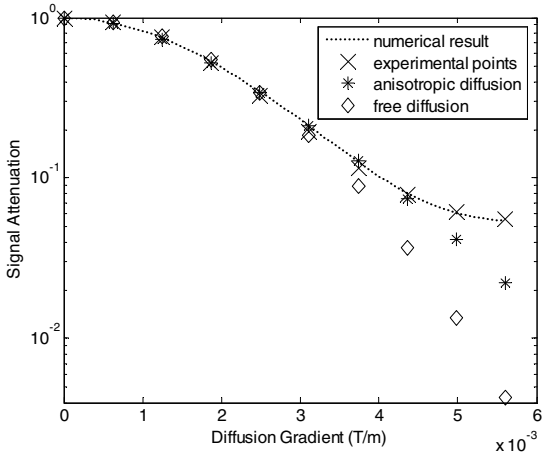

Fig. 2 Experimental signal decay, numerical simulation and fits to different models as a function of the applied diffusion gradient G

References

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