Finite Element Simulations of Short-Range ^{3}He Diffusion in a Model of Branching Acinar Airways: Implications for In Vivo Lung Morphometry

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Introduction

A method for in vivo ^{3}He MR lung morphometry ("cylinder model") has been developed [1] which estimates airway dimensions from ^{3}He diffusion experiments using expressions obtained from computer simulations in simplified models of alveolar ducts. Limitations of this method caused by partially relying on the Gaussian phase approximation were recently reported [2] and it was also suggested that further limitations may arise from the geometrical assumptions (i.e. absence of branches). In a recent paper [3], branching effects were found to be negligible and cylinder model to remain valid for branching structures based on results from Monte Carlo simulations with a single diffusion time (1.8 ms). In this work, we use finite element simulations of diffusion in a model of branching alveolar ducts to investigate in detail the effects of acinar branching structure on short-range ^{3}He diffusion measurements.

Methods

Finite element computer simulations of ^{3}He diffusion in a geometric model of acinar airways (Fig. 1) were implemented in Comsol Multiphysics. The Bloch Torrey equation was solved for a bipolar diffusion gradient as used in [1] with diffusion time Δ between 1.6 and 6 ms and gradient amplitude scaled to obtain b values between 0 and 8.5 s/cm^2. The diffusion signal was calculated by integration of the transverse magnetization over the central duct only.

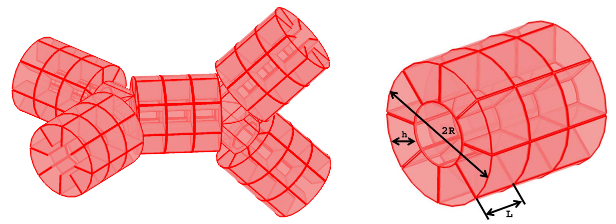

Figure 1. Geometric model of acinar airways: L=240 μm, R=350 μm and h= 200 μm. Branches at the ends of the central duct are rotated 90° with respect to each other.

Results and Discussion

Transverse diffusivity (D_T): Diffusion signals were obtained with the gradient perpendicular to the central duct. Due to the presence of branches, D_T decreases linearly with increasing b, which is the opposite of the linearly increasing behaviour predicted by the cylinder model (Fig.2). D_T depends on the duct length, with smaller D_T values for longer ducts, a dependence not present in the cylinder model theory. Furthermore, the signal attenuation distribution in the central duct depends on the relative orientation of the planes formed by the branches at either end of the duct (Fig. 3), which contradicts the argument used in [2] that this effect can be neglected.

Longitudinal diffusivity (D_L): Diffusion signals were obtained with the gradient parallel to the central duct. Fig. 4 shows the disagreement between the results of simulations and the cylinder model. D_L does not decrease linearly with b for all diffusion times as predicted in [1], it shows significant quadratic dependence and for diffusion times above ~2.3ms, it actually *increases* with b. Furthermore the intercept D_{L0} (at b=0) decreases with Δ, instead of remaining constant as predicted by the cylinder model. This is a consequence of the use of only one diffusion time in the simulations [1], which results in an analytical model with an incorrect dependence on diffusion time. This is crucial, since this dependence of the cylinder model has been used [4] to explain the results of lung diffusion experiments over a broad range of Δ (1.6 – 10 ms) and to extract information about the structural changes produced by emphysema.

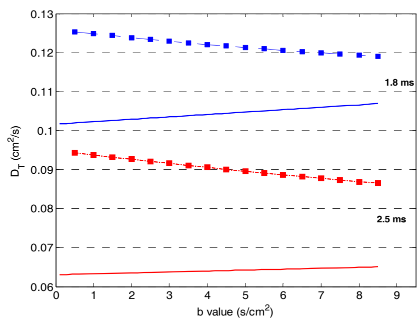

Fig. 2. Comparison of DT vs. b behaviour obtained from the simulations (symbols) and the cylinder model theory (solid lines) for Δ= 1.8 and 2.5 ms.

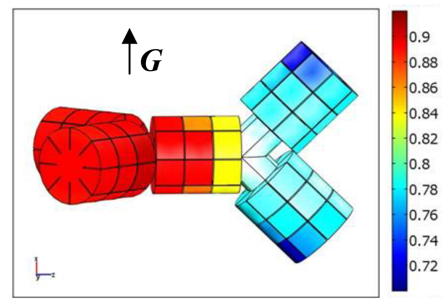

Fig. 3. Signal attenuation distribution (S/So) in the branching duct after the application of a bipolar gradient. The effect of the angular orientations of the branches is evident.

Bulk diffusivity: The bulk signal was calculated as the superposition of signals obtained for 91 uniformly-distributed gradient orientations with respect to the central duct axis. The signal behaviour deviates significantly from the cylinder model prediction (Fig.5) as a consequence of the limitations of the expressions for D_L and D_T due to branching effects (discussed above and summarized in Table 1), together with non-Gaussian effects demonstrated in [2]. This deviation increases with increasing Δ, due to the incorrect D_L dependence on Δ. As a consequence, the errors when estimating two geometric parameters (e.g. R and h, with L fixed) from the simulated data also increase with increasing Δ (e.g. from 13% at 1.8 ms to 43% at 6 ms for h). It was not possible to obtain a stable fit of the cylinder model with its three parameters (R, h and L) since the estimated parameters strongly depended on fit starting parameters and varied widely, showing that several not unique solutions exist. This raises serious questions on the ability of the cylinder model to extract all its parameters from the measured diffusion signals.

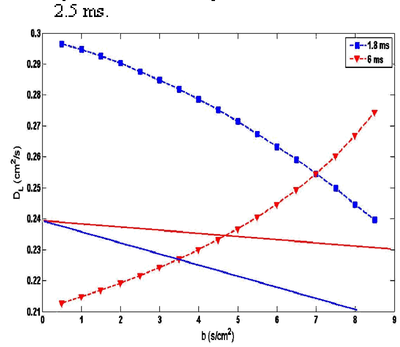

Fig. 4. Comparison of DL vs. b behaviour obtained from the simulations (symbols) and the cylinder model theory (solid lines) for Δ= 1.8 and 6 ms.

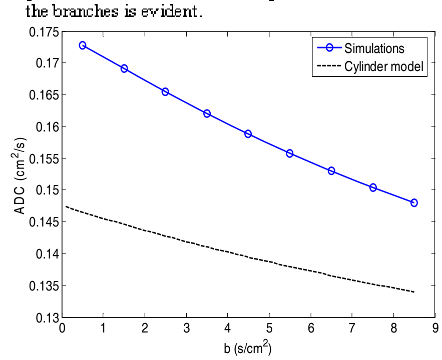

Fig. 5. Comparison of behaviour of the bulk ADC vs. b obtained from the simulations (symbols) and the cylinder model prediction (dashed lines) for Δ= 1.8 ms.

	Cylinder Model	Simulations
D_{L0}	independent of Δ	depends on Δ
D_L vs b	linear dependence	non linear
β_L	always ≥ 0	≤ 0, for Δ>2.3 ms
β_T	≥ 0	≤ 0
D_L and D_T	Independent of duct length	Dependent on duct lenght

Conclusions

Branching effects have significant influence in ^{3}He diffusivity, even at short diffusion times. The expressions of the cylinder model theory do not account for significant dependences upon diffusion time and branching geometry and airway length, as a consequence of the incorrect treatment of branching effects.

References

1-Sukstanskii et al, JMR 190, 200-210, 2008. 2. Parra-Robles et al, JMR 204, 228-238, 2010. 3. Sukstanskii et al, JMR 2010, doi: 10.1016/j.jmr.2010.09.005

Acknowledgements: Marie Curie Actions, EU Phelinet project. EPSRC Grant EP/D070252/1