Modelling non-Gaussian 3He diffusion signal behaviour using a fractional dynamics approach

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Introduction

The diffusion of ^{3}He gas in the lung has been shown to deviate from Gaussian behaviour when measured with MR pulsed gradient methods. These deviations can arise from a variety of geometrical and time dependent factors [1]. Two approaches have been used to model these non-Gaussian effects: the cylinder model and diffusional kurtosis. The cylinder model [2] models the airways as non-connected cylinders and its validity is limited to short diffusion times and relatively low gradient strengths [3]. Diffusional kurtosis [4] uses the second term of a cumulant expansion to model non-monoexponential signal decay. However, diffusional kurtosis has no direct physical meaning that can be associated with lung structure and the method can only be used for a limited range of b-values [5] without introducing higher order terms. In this work, a different approach to model non-Gaussian lung diffusion in the lungs is presented. The anomalous diffusion stretched-exponential model has been shown to follow from the extension of the Bloch-Torrey equation using operators of fractional calculus [6].

In systems that exhibit anomalous diffusion, the mean displacement $\langle x^2 \rangle$ in one direction is given by, $<x^2> = 2\,D\,\tau^{2H}$, where D is the free diffusion coefficient and τ is the diffusion time. H is a parameter that can be connected to the order of the differential operator in a generalized fractional order diffusion equation [6] and it is equal to ½ for normal (Brownian) diffusion. In the simplest case (fractional order operators in space only [6]), the solution of the diffusion equation is given by a stretched exponential function:

$$S(b) = S_0 \exp\left[-(b\ DDC)^{\alpha}\right] \qquad (1)$$

The DDC is a measure of the rate of signal decay with b and the heterogeneity index α describes the deviation of A from a single exponential decay. This model does not require an assumption about the distribution of apparent diffusion rates or the number of compartments present in the voxel [7]. This technique can be used to quantify non-Gaussian signals arising from multiple sources which is the case of diffusion in the lung [1]. It has been shown [7] that this model fits diffusion data from brain MR experiments and that its parameter α (heterogeneity index) reflected microscopic tissue structure.

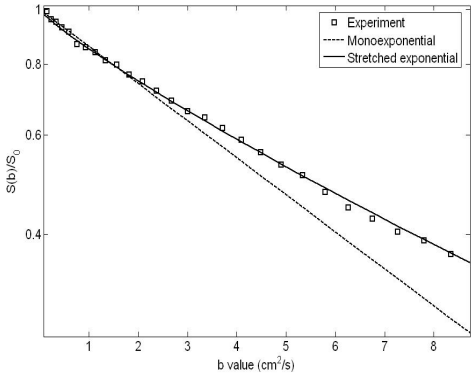

Figure 1. Fit of the stretched exponential model to the global diffusion data obtained from the spectroscopic experiments with the gradient diffusion in the x direction.

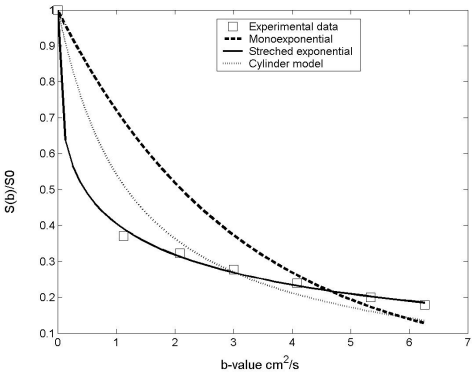

Figure 2. Fit of the stretched exponential model and the cylinder model to the imaging diffusion data obtained from a ROI in the right lung of a 28 years old healthy volunteer.

Methods

Hyperpolarized helium of polarization ~20% was obtained using a Helispin polarizer (GE, USA). Experiments were performed on two healthy volunteers on a 3T Philips Intera whole body MRI system with a transmit/receive linear Helmholtz coil of 20 cm loop diameter loop (Pulseteq, UK). For diffusion spectroscopy experiments, bulk diffusion data from the whole lung was obtained from FID acquisition with a 7° flip angle after bi-polar diffusion gradients with timing parameters as used in [1]. The gradient strength G was varied in 60 equal steps from -30 to 30 mT/m. For slice selective in-vivo experiments a 5 cm was used with a 5° flip angle in a 7-interleaved diffusion sequence with parameters (ramp time = 0.5ms, plateau length = 0.8ms, and b-values = 0, 1.12, 2.09, 3.00, 4.09, 5.34, 6.26 cm^2/s). Imaging parameters of the 2D SPGR sequence were: 384x384 mm^2 FOV, 64x64 matrix, TE/TR = 1.57/56 ms and BW = 500 Hz/pixel. The data was corrected for RF depletion of the polarization and Eq. 1 was then fitted to the experimental data to obtain estimates of DDC and α.

Gradient direction	DDC	α
X	0.12	0.91
Y	0.11	0.84
Z	0.15	0.91

Table 1. Estimated DDC and α from spectroscopic diffusion experiments in a 28 years old healthy volunteer

Results and Discussion

Fig.1 shows that the stretched exponential model provides a good fit to the non-monoexponential signal decay in global diffusion experiments. Table 1 summarizes the results from these experiments with gradients in all three directions. Fig. 2 shows a comparison of the fits of the slice selective diffusion data to the cylinder model and the stretched exponential model. A superior fit is obtained with the stretched exponential when compared to the cylinder model fit for this set of data. Since the stretched exponential model is not constrained by assumptions about the geometry of the restricting geometry or limited to a specific range of gradient strengths or timing parameters, it may be able to reveal information about the scaling properties of lung geometry from ^{3}He MR diffusion data acquired over different time scales. This information may be sensitive to different lung diseases that affect airway morphology at different generations of the lung branching structure. DDC may be related to the size of structures relevant for the length scale of the experiment (i.e. dependent on Δ), while α may describe the complexity of the geometry of restricting boundaries at that given scale. The investigation of the relationships between these parameters and morphometric properties of the lung and lung disease will be the subject of future research.

Conclusion

The results obtained in this work demonstrate that the anomalous diffusion stretched-exponential model fits well the behaviour of the ^{3}He lung MR signal. This model can potentially provide valuable information about lung microstructure at different length scales.

Acknowledgement
Funding from EU Phelinet network and UK EPSRC # EP/D070252/1 is acknowledged.

References

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