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

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Introduction
The diffusion of 3He 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].

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 (Pulseteq, UK). For diffusion spectroscopy experiments, bulk diffusion data from the whole lung was obtained from FID acquisition and that its parameter \( \alpha \) (heterogeneity index) reflected microscopic tissue structure.

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 3He 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 \( \alpha \)), while \( \alpha \) 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 3He lung MR signal. This model can potentially provide valuable information about lung microstructure at different length scales.

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References
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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.

<table>
<thead>
<tr>
<th>Gradient direction</th>
<th>DDC</th>
<th>( \alpha )</th>
</tr>
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<tbody>
<tr>
<td>X</td>
<td>0.12</td>
<td>0.91</td>
</tr>
<tr>
<td>Y</td>
<td>0.11</td>
<td>0.84</td>
</tr>
<tr>
<td>Z</td>
<td>0.15</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table 1. Estimated DDC and \( \alpha \) from spectroscopic diffusion experiments in a 28 years old healthy volunteer.