Spin-Lattice Relaxation and Diffusion of Hyperpolarized ^{3}He in Phantoms

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Background and Significance

Measurements of the apparent diffusion coefficient (ADC) of hyperpolarized noble gases in lung tissue are potentially very useful for the determination of structural or functional changes due to lung disease or lung injury in the lung airways [1]. The diffusion time dependence of the ADC of liquids or gases in porous restricting media, as measured with NMR pulsed field gradient (PFG) techniques allows the determination of the surface-to-volume ratio (S/V) and the tortuosity of the medium. The drop in ADC in the short diffusion time limit, in which the molecules/atoms diffuse distances that are small compared to the restricting sizes, allows in principle the determination of the surface-to-volume ratio [2]. In the limit of long diffusion times in connected pore-spaces, a lower, diffusion-time independent, long-range ADC can be observed. The ratio of the long-range ADC to the free diffusion coefficient is the inverse of the tortuosity of the medium for very long diffusion times [3,4].

Diffusion coefficients of liquids and gases differ by several orders of magnitude. Therefore, for a given diffusion time, liquids and gases probe significantly different distances. In liquids the diffusion times accessible by PFG NMR are ultimately limited by the spin-lattice relaxation time (T_1) of the nuclear spins (when stimulated echo techniques are used). When applying PFG measurements to hyperpolarized gases the polarization is quickly destroyed when using large flip angles. As a result, gradient recalled echoes are most often used in combination with very small flip angles, which limits (by T_2*) the range of diffusion times that can be explored. Nevertheless, the much larger gas diffusion coefficients probe distances that are still much larger than in the case of a liquid.

T_1 of pure ^{3}He can be many tens of hours in appropriate containers, but is strongly reduced by the presence of impurities on the container walls. In a porous medium in which the pore sizes are a few mm or less, the spin-lattice relaxation is typically limited by relaxivity at the wall, not by the diffusion coefficient of the gas. For a given wall material, $1/T_1$ should be the product of the surface relaxivity, the surface-to-volume ratio, and the mean thermal speed. Thus, T_1 may also be a probe of the surface-to-volume ratio of the restricting pores.

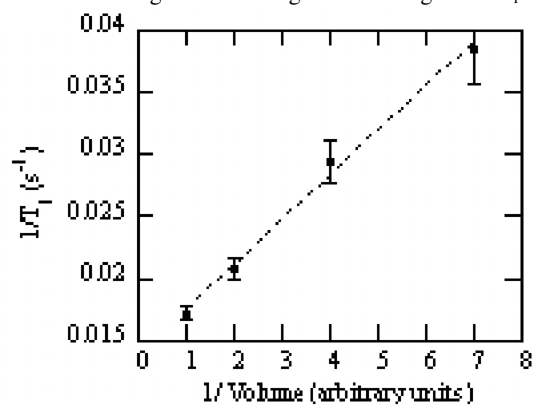
In this work we have measured the ADC as well as T_1 in a compressible foam phantom and in other phantoms with more clearly known surface-to-volume ratios. The foam model can be considered as a crude model of lung in the sense that it has a variable surface-to-volume ratio.

Methods

The ^{3}He gas is hyperpolarized by spin-exchange optical pumping (SEOP) at a pressure of 8 atm in a glass cell. This cell is then positioned in the fringe-field of the superconducting magnet. The phantom is repeatedly evacuated and flushed with nitrogen to remove residual oxygen from the system. Some gas is then released into the phantom and the gas pressure is monitored with a simple gauge. The T_1 of the gas was determined by periodically monitoring the FID height by applying a very small flip angle. We measured the ADC for all diffusion times using one single gas filling of the phantom to avoid pressure dependent effects of the diffusion coefficient. The ADC was determined using 10 different gradient strengths. A T_1 correction was applied to the ADC measurements.

Results

The figure to the right shows $1/T_1$ versus 1/Volume of the foam. However, the relationship does not extrapolate to the origin, indicating that we may not have removed all the oxygen from the foam. We found that this particular foam was already in the long-range ADC limit, even for the highest compression and the shortest used diffusion times (approximately 1ms), indicating its very high porosity. A bipolar gradient recalled PFG sequence, which was designed to reduce the effects of cross-terms between internal and external magnetic field gradients, gave us the same results for the foam, indicating that internal gradient effects were not substantial. A phantom of parallel cylinders of diameter 2mm yielded very good agreement between the experimentally (with PFG NMR) determined radius and the actual radius.



Conclusion

We acquired with a single bolus of gas an entire set of ADCs using multiple diffusion times and multiple gradient strengths in a porous medium within a time of the order of the spin-lattice relaxation time. The T_2* decay of the FID limits the accessible range of diffusion times to a few ms or tens of ms at most in a porous system due to inhomogeneous line broadening. The surface-to-volume ratio of the restricting pore can be determined from the short diffusion time ADC measurements provided the pores are not much less than approximately a millimeter.

The surface-to-volume ratio dependence of the T_1 relaxation may provide an alternative or supplement to PFG diffusion measurements to determine microscopic geometric data. This may be useful in very small structures for which helium diffusion is already in a highly restricted regime (helium atoms diffuse distances large compared to the pore size).

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