Time-Dependent Noble Gas Diffusion NMR in Porous Media and Implications for Lung Study

R. Mair,[1] G. Wong,[1] D. Hoffmann,[1] S. Patz,[2] M. Hürlimann,[3] L. Schwartz[3] and R. Walsworth[1]
[1] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA*
[2] *Department of Radiology, Brigham and Women's Hospital, Boston, MA, USA*
[3] *Schlumberger-Doll Research, Ridgefield, CT, USA*

Purpose

The purpose of this study was to determine if NMR measurements of the time-dependent diffusion of noble gas imbibed in porous media can be used to predict the surface area-volume ratio (S/V_p) and tortuosity of the medium. (Tortuosity is a measure of long-scale pore connectivity.) Implications for the use of this technique to yield functional S/V_p and tortuosity images in lungs are considered in light of the results obtained.

Introduction

With the advent of laser-polarization [1], the noble gases ^{3}He and ^{129}Xe have proven valuable for MRI of animal and human lungs [2,3]. Laser-polarized ^{3}He has yielded high-quality images depicting gross variations in gas penetration in diseased lungs [4]. However, quantitative information about lung physiology has been less forthcoming. Noble gas NMR techniques to measure regional variations in alveolar S/V_p and tortuosity may be important for diagnosing lung disease [5]. Expressions linking the time-dependence of the diffusion coefficient of imbibed fluids to the S/V_p and tortuosity of a porous medium have been theoretically derived [6,7], although not fully verified with NMR measurements of water diffusion [8]. The use of noble gas NMR allows the verification of such expressions, as well as consideration of the extension of these methods to *in-vivo* lung functional studies.

Methods

NMR spectroscopic measurements of the diffusion coefficient of ^{129}Xe gas in random packs of spherical glass beads were made as a function of the diffusion time in the Stejskal-Tanner PGSE sequence. A highly modified pulsed-gradient stimulated echo technique incorporating alternating bi-polar gradient pulses [9] was used to alleviate the effects of very short T_2 and the presence of large background gradients due to magnetic susceptibility differences between the glass beads and the gas. The experiments were carried out on a GE Omega/CSI NMR system at 4.7 T, operating at a frequency of 55.3 MHz for ^{129}Xe. 3 atm pressure of xenon gas and 2 atm of O_2 were frozen into a glass cell containing the packed beads, which was then sealed and warmed to room temperature.

Results

Fig. 1 shows the measured time-dependent diffusion of thermally-polarized xenon gas in packs of glass beads. Indicated on the figure are the theoretical relationships for the medium's S/V_p (valid at short diffusion times) and tortuosity (the asymptote at long times). The data from all bead packs reach the tortuosity limit, unlike water, which diffuses too slowly to reach this limit before T_1 relaxation destroys the signal [8]. However, only for larger beads do the experimental data match the theoretical S/V_p prediction.

Discussion

We have demonstrated that NMR measurements of time-dependent diffusion of imbibed noble gases can accurately determine important structural information about porous media. However, there are challenges to applying this new NMR method to *in vivo* systems. Experiments using thermally polarized xenon are extremely time-consuming. Thus laser-polarized noble gas would be required in a medical setting. However, at high magnetic fields, complex pulse sequences to measure time-dependent diffusion cannot be applied in one shot to a single sample of laser-polarized gas [10]. In addition, we have measured deviations from the theoretical S/V_p in smaller beads, which additional data shows is due to significant diffusion of the gas spins during the application of the gradient pulse — a violation of the essential finite pulse approximation of the Stejskal-Tanner method. In moving to human imaging systems — with weaker, slower, gradient sets than used here — this problem will only be exaggerated.

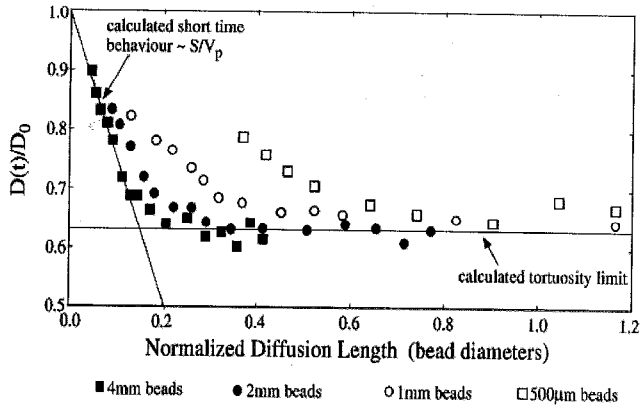

Figure 1. Time-dependent diffusion measurements for thermally-polarized xenon gas imbibed in randomly packed spherical glass beads. Each sample contains beads of a uniform diameter, ranging from 500 μm to 4 mm. The data are displayed as the time-dependent diffusion coefficient normalized to the free gas diffusion coefficient, $D(t)/D_0$, as a function of the free gas diffusion length in the time t normalized to the bead diameter $b^{-1}\sqrt{D_0 t}$. t ranged from 12.5 to 2000 ms for these data.

References

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