Studies of weakly restricted diffusion using hyperpolarized ^{3}He gas in cylindrical cells

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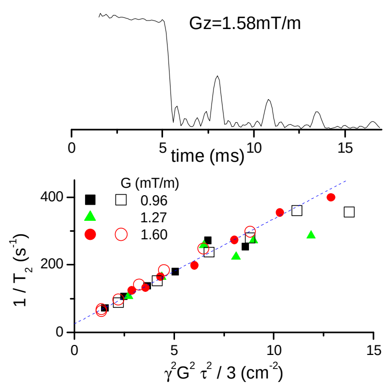
Introduction

Diffusive motion of nuclei during signal acquisition has a much stronger impact (through, e.g., blurring or edge enhancement [1]) on lung imaging with hyperpolarized gases than on conventional proton MRI. With air space dimensions ranging from tenths of millimeter (alveoli) to centimeters (main bronchi), diffusion regimes may vary from free diffusion to motional averaging or localization ([2] and Fig.2) depending on sequence parameters and on location within the lung. The interplay of restricted diffusion and of diffusion-sensitizing gradients also makes the analysis of apparent diffusion coefficients in this complex geometry especially challenging [3,4]. We report on MR relaxometry and 1-D imaging experiments in hyperpolarized ^{3}He confined in sealed glass cells with gas filling pressures, dimensions, and aspect ratios that considerably extend previous investigations [5].

Methods

Several cylindrical sealed glass cells containing pure helium-3 gas are used (length L=4.6cm, radius R=2.3cm, pressures up to 67mbar; L=12cm, R=0.75cm, pressures up to 400 mbar). Metastability-exchange optical pumping (MEOP) is performed *in situ* using a 2W laser and NMR is performed at 89kHz (2.7mT) using a dedicated MRI system [6,7]. Diffusion-induced attenuation of multiple spin- or gradient-echo trains are measured with a 10kHz sampling rate using CPMG sequences (with pulsed gradients) or (symmetric) bipolar gradients. Gradients are applied along the static field and cell axis (G_z) or along a cell radius (e.g., G_x). 180°-pulse duration is 0.8ms, echo periods 2τ range from 1 to 20ms and applied gradients from 0.1 to 1.5mT/m. Data are analyzed with in-house software, globally (in terms of echo amplitude) or point-by-point (in the frequency domain, to extract local decays when resolution permits).

Fig.1: Selected data for gradient echoes in a R=2.3cm, 67-mbar ^{3}He cell. Upper plot: 5-ms recording of 90°-FID signal followed by 4 echoes (2τ=2.8 ms). Lower plot: Decay rates of echo amplitudes for various G and τ (open symbols: G_z; solid symbols: G_x). Dotted line: guide for the eye with slope D=31.1cm^2/s, the ^{3}He free diffusion coefficient.



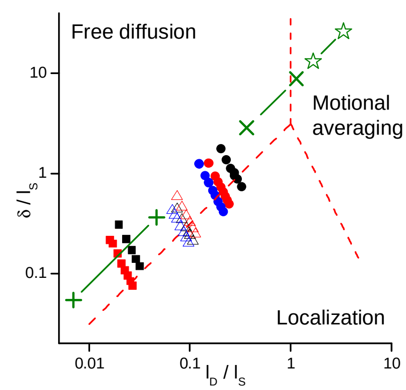


Fig.2: Correlation between δ and l_D for measurements in R=2.3cm (open symbols) and R=0.75cm (solid symbols) ^{3}He cells. Dotted lines: limits of diffusion regimes. Stars (resp. ×, +): min.–max. values for ^{3}He-N_2 mixtures (D=0.86cm^2/s) in an alveolar sac (resp. a transitional bronchiole, the trachea) for G=2.3mT/m and 2τ=4.1ms.

Results

Significant nuclear polarizations are routinely obtained with short pumping times (e.g., 4% after 30s), providing high SNR for all cells. Inter-echo attenuation ratios, $\exp(-2\tau/T_2)$, range from 0.11 to 0.9 for gradient echoes and to 0.995 for spin echoes. For each cell, compiled decay rates consistently fit with expectations for free diffusion (Fig. 1). A representative set of results is displayed in Fig. 2, where the reduced parameters l_D/l_S and δ/ l_S for plot axes allow immediate comparison between samples of different sizes or with different gas contents (diffusion length $l_D=(D\tau)^{1/2}$, where D is the ^{3}He diffusion coefficient; spatial resolution $\delta=\pi/\gamma G\tau$; sample size l_S=L/2 or R for the cylindrical cells, depending on gradient orientation).

Discussion

As illustrated by Fig. 1, the attenuation rates exhibit no significant departure from expectations for free diffusion, although they all correspond to measurements performed in the cross-over region between localization and free diffusion (Fig. 2). As τ increases at fixed G, the whole range of conditions from single-shot (RARE or EPI) to single-echo (e.g., FLASH) imaging sequences is probed. Typical values for ^{3}He-N_2 mixtures confined in lung airspaces are included in Fig. 2. The conditions of (weakly) restricted diffusion met in all airways larger than the acinar ones can be reproduced in our cells, taking advantage of the pressure dependence of D. For convenience, the experiments have been performed in a 2.7mT system currently under test [7]. Operation at 1.5T would increase the nuclear polarizations obtained with MEOP at the highest pressures, leading to improved accuracy of the measurements [8].

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[1] Callaghan P.T., et al., 1993, *J. Magn. Reson.*, **A110**, 347. [2] Hürlimann M.D. et al., 1993, *J. Magn. Reson.*, **A115**, 260. [3] Sukstanskii A.L. and Yablonskiy D.A., 2008, *J. Magn. Reson.*, **190**, 200. [4] Grebenkov D.S., 2007, *Rev. Mod. Phys.*, **79**, 1077. [5] Hayden M.H., et al., 2004, *J. Magn. Reson.*, **169**, 313. [6] Nacher P.J. et al., 2007, *Proc.15th. Intl. Soc. Mag. Reson. Med.*, 3290. [7] Safiullin et al., 2009, *this conference.* [8] Abboud M, et al, 2004, *Europhys. Lett.*, **68**, 480.