Magnetic Field Strength Dependence of the Signal-to-Noise Ratio for Hyperpolarized ^{129}Xe Gas MR Imaging of Rat Lungs

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Introduction

In Hyperpolarized Noble Gas (HNG) MR imaging, the available magnetization is independent of magnetic field strength. Furthermore, above a cut-off Larmor frequency when the sample (i.e. body) noise dominates the RF coil noise [1], the signal-to-noise ratio (SNR) is expected to be independent of magnetic field strength and indeed decreases with field for band-matched imaging due to a reduction in the transverse relaxation time, T_2* [2]. This cut-off frequency predicts the maximum achievable signal-to-noise ratio (SNR) and depends on the sample/coil size and geometry and for human lungs, is predicted to correspond to intermediate field strengths (0.1-0.5 T). However, this SNR maximum does not occur until much higher fields for small coils typically used for small animal imaging. This means high field strengths are advantageous from an SNR standpoint for HNG imaging of small animal lungs. In this work the magnetic field strength dependence of the SNR for imaging of small animal lungs is theoretically predicted and experimentally verified for rat lung images obtained at 17 mT and 1.89 T.

Methods

The 1.89 T imaging was performed within the 30 cm bore of a superconducting magnet (Magnex, Exon, England). The 17 mT imaging was performed in the fringe field of the superconducting magnet using a passive shimming technique described previously [3]. The 17 mT system used a 26 cm diameter gradient/shim coil set (Bruker, Ettlingen, Germany) powered by the gradient/shim power supplies of the 1.89 T system and controlled by an MRRS console (Surrey, U.K.). At 17 mT, the RF coil was a split-solenoid design of diameter 4.5 cm and tuned to 200 kHz. At 1.89 T, a birdcage coil of diameter 12 cm (22.17 MHz) was used.

Hyperpolarized natural abundance xenon gas (26.4% ^{129}Xe) was produced from a gas mixture (1% Xenon, 10% Nitrogen and 89% Helium) using a continuous-flow polarization system that used a 60W diode array laser (λ=794.8 nm, Coherent, Santa Clara, USA) and produced xenon polarizations of up to 22% [4].

Lung images were obtained from excised rat lungs that were dried in a non-collapsed state of inhalation with the outer surface sealed by epoxy [5]. A plastic tube inserted into the trachea allowed evacuation of the air from the lungs, prior to filling with xenon gas. At 1.89 T, imaging was performed using a 3D gradient-echo pulse sequence with variable flip angle (FOV: 60 mm; data matrix: 32x32x16, TR: 16 ms, TE: 4 ms, 20 kHz bandwidth). At 17 mT, a 2D gradient-echo pulse sequence with variable flip angle (FOV: 80 mm; 32x32, TR: 16 ms, TE: 5 ms, 10 kHz bandwidth) was used. No slice selection was used in order to obtain image SNR values close to those obtained at 1.89 T.

The theoretical field dependence of the SNR for rat lungs was obtained using a model described previously [2]. For desiccated lung, it was assumed that susceptibility effects were negligible and that only field inhomogeneity and diffusion contributed to T_2*. For in vivo lung, a susceptibility difference of 9×10^{-6} in the tissue-gas space interface and a restricted diffusion coefficient for xenon of 0.021 cm^2s^{-1} was assumed. The ratio of the gas-space volume to sample volume for in vivo lung was assumed to be 0.1. The SNR values estimated from the images were properly scaled [2] to account for the different pulse sequences and hardware characteristics (e.g. receiver noise figure, coil sensitivity).

Results and Discussion

The images obtained from the desiccated lungs (Fig. 1 and 2) showed similar values of SNR (~25) since the imaging parameters were properly selected with that goal, by increasing the voxel size at 17 mT. When compared to the predicted field dependence (Fig. 3), these SNR values show reasonable agreement with the theory and validate the SNR model for small samples. Although the lung images obtained in this work are not expected to show contributions of susceptibility effects to T_2* since the water was removed during the lung preparation, the SNR field dependence for in vivo lung imaging is qualitatively similar (except for a small shift down field due to T_2* effects), as shown in Fig. 3. The experimental results obtained at 17 mT indicate the feasibility of xenon lung imaging at ultra-low field strengths (< 0.15 T).

For ^3He, the expected SNR values are approximately three times larger (and the optimum field strength lower) than for xenon due to its larger gyromagnetic ratio. However, the reduced susceptibility effects and longer T_2* values give xenon advantages in spatial resolution over helium.

The results presented here assumed an *ad-hoc* model for T_2* [2]. Despite the reasonable agreement of the model with reported experimental data [2], further studies of the field dependence of T_2* mechanisms of HNG in the lungs and elsewhere would be useful.

Conclusion

This study validates the theoretical model for field dependence of the SNR for HNG imaging of small samples and indicates that high fields (7 - 10 T) may be optimal for HNG imaging of the lungs of small animals.

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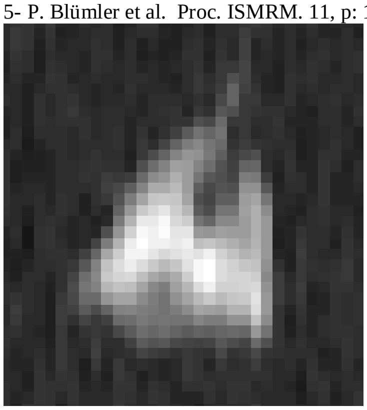

Figure 1. Gradient-echo image (2D) of the desiccated rat lungs at 17 mT.

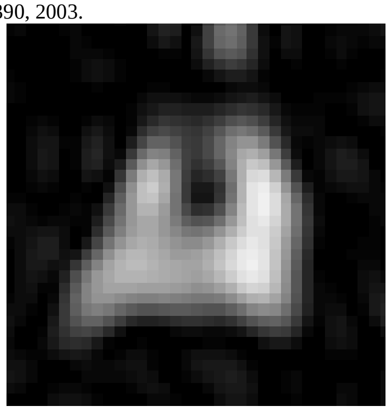

Figure 2. Gradient-echo image (slice from 3D image) of the desiccated rat lungs at 1.89 T.

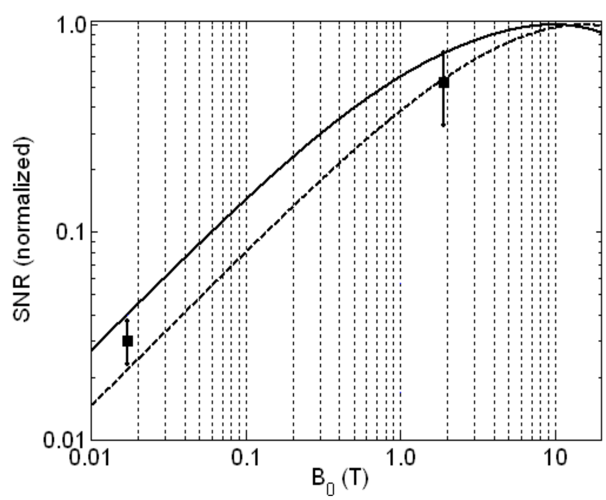

Figure 3. Comparison of measured SNR values and the theoretical field strength dependence of the SNR for live (solid line) and desiccated (dashed line) rat lungs.