Abstract
MR lung imaging using hyperpolarized $^3$He shows significant potential for the study of pulmonary function and disease. Pulse sequences that maximize the signal-to-noise ratio (SNR) will make the best use of the limited world supply of $^3$He. Although high-flip-angle techniques (e.g., RARE, TrueFISP) theoretically provide much higher SNR than that for the widely-used low-flip-angle, gradient-echo methods, the former suffer from substantial diffusion-induced signal loss during the echo train unless the spatial resolution is low ($>10$ mm). We have derived and experimentally tested an optimized gradient waveform for TrueFISP $^3$He MRI that has low diffusion-induced signal loss, and should thus permit high SNR, good-quality images to be acquired with an in-plane resolution of 4 mm.

Introduction
The non-equilibrium nature of the hyperpolarized magnetization, combined with the limited supply of $^3$He, favor the use of single-shot, high SNR pulse sequences such as RARE or TrueFISP, which, in principle, minimize the amount of $^3$He required for a given resolution. Several researchers have demonstrated hyperpolarized gas imaging using conventional single-shot RARE sequences, although the high diffusion coefficient of $^3$He, about 10 times larger than that for water, results in substantial diffusion-induced signal loss during the echo train unless the spatial resolution is low. Therefore, the majority of $^3$He studies have been performed using short-TR, low-flip-angle, gradient-echo (GRE) pulse sequences [1, 2].

In this work, we explore high-flip-angle pulse sequences that are optimized to minimize diffusion-induced signal loss, thus providing much higher SNR than low-flip-angle GRE methods while maintaining good image quality. In particular, we present an optimized readout gradient waveform for a TrueFISP pulse sequence and experimentally verify theoretical predictions of its performance using a $^3$He phantom.

Theory
Achieving high SNR in a rapid, single-shot pulse sequence requires relatively high flip angles and coherent transverse magnetization that is maintained across repetitions. From the perspective of the RF pulses, storing phase-encoded magnetization along the longitudinal axis should be avoided to minimize diffusion-induced signal loss. This requires either that the refocusing RF pulses are 180° (i.e., RARE), or that the zeroth moments of all gradients are equal to zero at each RF pulse (i.e., TrueFISP). Additional design considerations are suggested by recalling that the b value corresponding to a gradient waveform is the area under the squared k-space trajectory. For example, a circular sampling trajectory, starting at the center of k-space, provides relatively low b values for all but the last few steps in the acquisition.

Although typical rectangular sampling trajectories are globally suboptimal from the perspective of minimizing diffusion-induced signal loss, they nonetheless warrant consideration due to their robust imaging performance and widespread use. For ideal gradient performance (i.e., infinite slew rates), it is generally advantageous to make the associated waveforms as compact as possible. However, this approach does not hold when real gradient-system performance is considered. For example, Fig. 1 shows the b value versus data sampling period (T$_S$) for a readout gradient waveform with a zeroth moment of zero, as appropriate for a TrueFISP pulse sequence, a spatial resolution of 4 mm, and a maximum slew rate of 40 mT/m/ms. After reaching a minimum at T$_S$ = 1.8 ms, the b value increases rapidly with decreasing data sampling period. However, TrueFISP pulse sequences require a short TR to minimize susceptibility-induced image artifacts. As a compromise, we chose a T$_S$ of 1.28 ms for experimental testing. The corresponding b value is only 10% higher than the theoretical minimum.

Experimental Methods
The readout gradient waveform described above was implemented in a TrueFISP pulse sequence on a 1.5 T whole-body imager (Magnetom Vision, Siemens Medical Systems, Iselin NJ, USA), modified to operate at 48 MHz by the addition of a broadband RF amplifier and a $^3$He volume RF coil. Projection images were acquired of a torso-shaped phantom containing two high-pressure gas cells (Amersham Health, Durham, NC, USA). Each cell contained a mixture of O$_2$ and thermally polarized $^3$He and had the following characteristics: T1/T2, 1180/630 ms; diffusion coefficient, 0.26 cm$^2$/s. Pulse sequence parameters included: TR/TE, 6.14/3.07 ms; matrix, 128*128; FOV, 512 mm; flip angle, 70°; no phase encoding.

Experimental Results
Figure 2 shows good agreement between the theoretically calculated signal decay from T2 relaxation and diffusion-induced signal attenuation, and the experimentally measured signal intensities. Note that roughly half of the signal loss is due to T2 decay. For in-vivo lung imaging, the T2 of $^3$He is estimated to be several seconds. Thus, for a typical healthy human lung (apparent diffusion coefficient $\sim$0.2 cm$^2$/s [3]), this gradient configuration should result in only 30% signal attenuation from diffusion for 128 RF pulses, making it potentially viable for high SNR, good-quality imaging of the lung.

Conclusions
Optimization of the RF-pulse and gradient configurations is important to minimize diffusion-induced signal loss. We have demonstrated a readout gradient waveform appropriate for a TrueFISP acquisition that provides sufficiently low signal attenuation to be suitable for in-vivo hyperpolarized $^3$He lung imaging. Compared to the commonly used low-flip-angle, GRE techniques, an optimized TrueFISP acquisition should provide a several-fold increase in SNR, requiring a corresponding smaller amount of $^3$He for equivalent spatial resolution and image quality.

References

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