Rapid Three-dimensional Hyperpolarized ^{3}He Imaging of the Lung using an Optimized Steady-state Free-precession Pulse Sequence: Increased SNR without Off-resonance Banding Artifacts

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Introduction: Although MRI using hyperpolarized gases (HPG) can provide unique functional and structural information about the lung, these agents are prepared using expensive, dedicated equipment, and the most commonly used agent, ^{3}He, is in limited world supply. Thus, a longstanding goal of techniques developed for HPG-MRI has been to maximum the signal-to-noise ratio (SNR) obtained from a given dose of gas. It was shown in previous studies at 1.5T that a steady-state free-precession (SSFP, e.g., TrueFISP) pulse-sequence configuration can provide a substantial SNR increase over the commonly used low-flip-angle, spoiled gradient-echo (e.g., FLASH) methods [1,2]. However, SSFP techniques have not gained widespread acceptance for lung imaging due to the presence of off-resonance banding artifacts near the diaphragmatic border. In this work we describe an optimized 3D-SSFP sequence that permits HPG lung imaging with high SNR while suppressing off-resonance banding artifacts.

Theory: Analogous to proton SSFP imaging, a straightforward approach for suppressing field-inhomogeneity-induced intensity variations in SSFP HPG-MRI is to shorten the TR. Previous studies used a TR of 6 or 10 ms at 1.5T [1,2], implying that a TR substantially shorter than these values is required to suppress off-resonance banding artifacts. As the TR becomes very short, however, high-flip-angle spatially-selective RF pulses would occupy a substantial fraction of the TR period. A configuration that permits much shorter RF pulses, and thus much shorter TRs, is revealed by examining the predicted SNR behavior of SSFP imaging as a function of the number of phase-encoding (PE) steps (Fig. 1). These plots were generated using computer simulations assuming sequential PE and include the effects of T1 (assumed to be either 20 s or infinite) and T2 (assumed to be 140 ms) relaxation, and diffusion-induced signal attenuation from the imaging gradients (assumed ADC 0.2 cm^2/s for ^{3}He in lung). The *b* values for the readout and phase-encoding gradients, which were used to generate the simulated results shown here, were determined from the actual imaging pulse sequence described below.

An interesting finding is that if the optimum flip angle (Fig. 1b) is chosen, the predicted SNR for SSFP imaging (Fig. 1a) is independent of the number of PE steps, except for the effect of T1 relaxation. This is because at the optimum flip angle, the signal decrease from additional excitations is exactly balanced by the noise decrease due to additional averaging. (A similar effect is seen with spoiled-GRE imaging at the optimum flip angle.) Another interesting finding is that the optimum flip angle for SSFP imaging decreases to quite low values for a large number of PE steps. This suggests that whole-lung 3D SSFP imaging may be advantageous, as it would permit a short, non-selective RF pulse to be used. It can also be shown that a high receiver bandwidth (~1000 Hz/pixel) provides an SNR that is within ~20% of the predicted maximum possible SNR for any bandwidth [3]. Thus, by combining a 3D acquisition with a high receiver bandwidth and asymmetric echo sampling, a TR less than 2 ms can be achieved for a spatial resolution of ~4 mm.

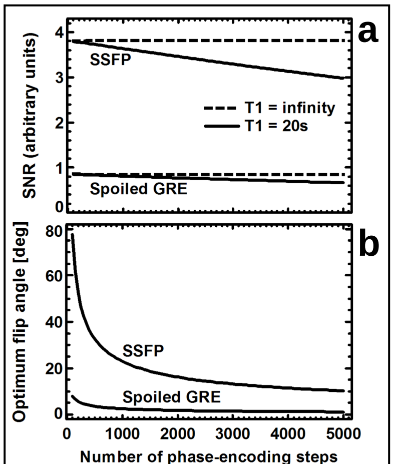

Fig. 1. (**a**) Predicted SNR for SSFP and spoiled-GRE methods versus number of PE steps for T1 = 20 s or ∞; TR = 2 ms. (**b**) Corresponding optimum flip angles.

Methods: ^{3}He studies were performed in 7 healthy subjects using a 1.5-T whole-body scanner (Sonata, Siemens Medical Solutions) equipped with the multi-nuclear option and a ^{3}He chest RF coil (Clinical MR Solutions). The ^{3}He gas was polarized by collisional spin exchange with an optically-pumped rubidium vapor using a prototype commercial system (Magnetic Imaging Technologies, Inc.). All experiments were performed under a Physician's IND (# 57866) for imaging with hyperpolarized ^{3}He using a protocol approved by our institutional review board. Informed consent was obtained in all cases. Parameters for coronal 3D-TrueFISP acquisitions of the whole-lung included: TR, 1.73-1.77 ms; TE, 0.74-0.78 ms; flip-angle, 6-10°; bandwidth, 1149-1698 Hz/pixel; matrix, 128x80x60; PE order, sequential; spatial resolution, 3.9x3.9x3.9 mm^3; acquisition time, 8.3-8.5 s. In four of the subjects, a 3D-FLASH data set (TR, 2.4 ms; TE, 0.94 ms; flip-angle, 1.2°) with matched bandwidth and spatial resolution was acquired to permit a SNR comparison.

Results: Representative images reconstructed in 3 orthogonal planes from the 3D-TrueFISP acquisition are shown in Fig. 2. High image quality was obtained in all subjects, and no intensity banding artifacts were seen near the diaphragmatic border. Figure 3 shows a comparison of matched 3D-TrueFISP and 3D FLASH acquisitions, illustrating the higher SNR obtained with the 3D TrueFISP method. The average ratio of the 3D-TrueFISP SNR to that for 3D-FLASH, corrected for any differences in dose, was 3.7 ± 0.4 (mean ± STD), compared to theoretically predicted ratios of 2.8 – 3.2 for the various flip-angle, bandwidth combinations.

Conclusions: We have shown that an optimized implementation of 3D-SSFP imaging, with TR <2 ms, yields 3-4 times higher SNR than widely-used low-flip-angle spoiled-GRE methods while suppressing intensity banding artifacts that were seen with earlier 2D implementations of the SSFP method. 3D-SSFP imaging thus requires a much lower dose of hyperpolarized gas than a comparable spoiled-GRE acquisition. In addition, 3D-SSFP imaging yields high-quality reconstructions in any image plane in an acquisition time of less than 10 s, which may be advantageous for certain applications.

References: **1.** Mugler JP et al. ISMRM 10 (2002); 2019. **2.** Wild J et al. JMR 2006; 183:13. **3.** Mugler JP et al. ISMRM 16 (2008); submitted.
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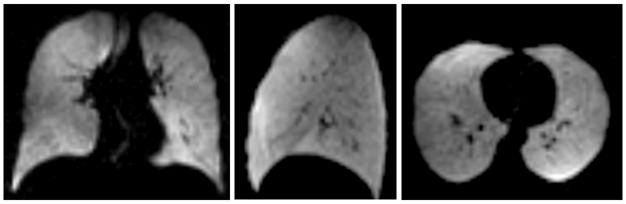

Fig. 2. Coronal, sagittal and axial TrueFISP (TR/TE/FA 1.7/0.7/6°) ^{3}He images of the human lung reformatted from a single 3D data set with isotropic 3.9-mm spatial resolution.

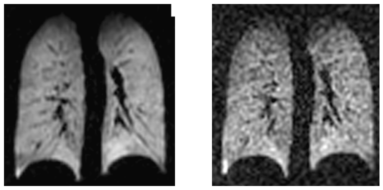

Fig. 3. Comparison of 3D-TrueFISP (left) and 3D-FLASH (right) acquisitions in the same subject.