Optimization of Steady State Free Precession Sequences for Hyperpolarized 3He lung MRI

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Introduction In previous work the magnetization response of hyperpolarized (HP) 3He gas to a SSFP sequence was simulated using matrix product operators [1]. The simulations account for the effect of gradient diffusion dephasing with a time/sequence dependent effective T2 of the ^{3}He and also the non-recoverable longitudinal magnetization of a HP sample. In this work the theoretical simulations were compared with NMR and MRI experiments with HP ^{3}He and the results were used to optimize a SSFP sequence for in-vivo HP ^{3}He lung MRI. The results obtained with optimized SSFP are compared with an optimized 2D spoiled gradient echo sequence (SPGR).

Methods ^{3}He MRI was performed on a 1.5 T system (Philips, Eclipse) with max. gradient strength 27 mT/m & max slew 72 mT/m/ms. The system has T-R capabilities for 3He at 48.5 MHz. Gas was polarised to 30% with rubidium spin-exchange apparatus (GE). A low pass quadrature TR birdcage coil was used for phantom work, a flexible twin saddle quadrature coil for in-vivo work. Gas phantom studies were conducted with 1 l Tedlar plastic bags filled with 100 ml ^{3}He and 900 ml N_2. In-vivo ventilation imaging was performed with ethics approval on 2 healthy subjects with a breath-hold of a gas mixture of 300 ml ^{3}He/700 ml N_2. A 2D SSFP sequence was programmed with TE/TR = 5/10 ms which had an $\alpha/2$ –TR/2 start-up pre-pulse followed by n=1:128 α pulses, the phase of which were cycled: $(-\alpha_x)^n$. Two variants of the sequence were used with high and low b-value readouts. The high b-value b(TE)=0.292 scm^{-2} / b(TR)=0.584 scm^{-2} version was used for investigations of SSFP in phantoms in order to assess the effects of diffusion dephasing. The readout gradient waveform for this sequence had linear ramps, a constant gradient during sampling =16.6 mTm^{-1}, 256 samples & BW = 250 kHz. A low b-value version b(TE)=0.0757 scm^{-2}/ b(TR) = 0.1514 scm^{-2} (BW = 62.5 kHz, 4.2 mTm^{-1}, 128 samples) was used for all SSFP imaging to reduce diffusion dephasing. The performance of SSFP as a function of flip angle was investigated in phantoms and in-vivo and the results compared to the performance of a 2D spoiled gradient echo sequence [2] with the same BW = 62.5 kHz, n=1:128 views and optimized α =7.2° for sequential phase encoding. The results were compared against theoretical simulations which were performed using the method described in [1].

Results and Discussion

Fig. 1 Simulations of SSFP & SPGR SNR as a function of α

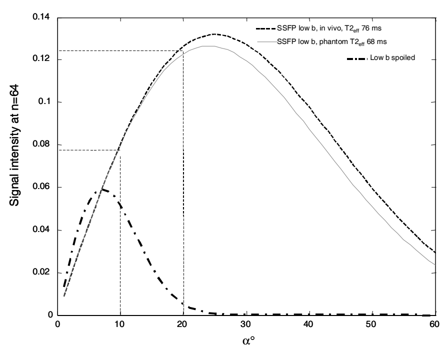


Fig. 2. SSFP 3He phantom imaging performance with flip angle

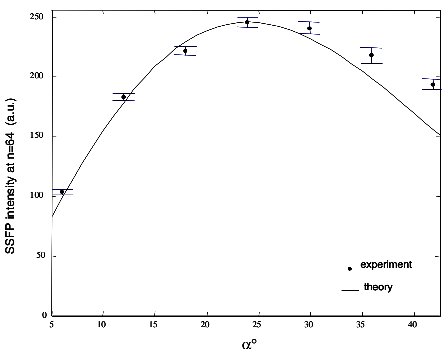


Fig. 3 SSFP NMR of HP ^{3}He –data shows good fit to theory

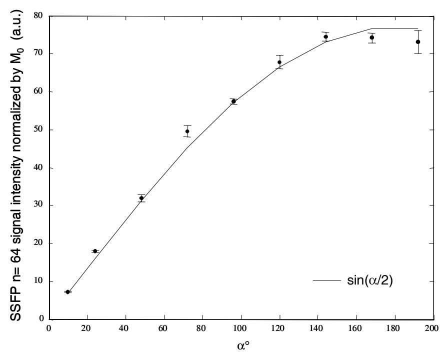
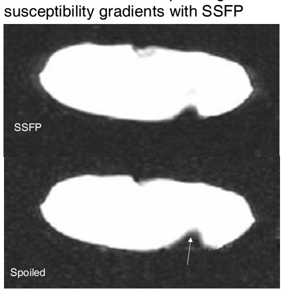


Fig. 4. SSFP phantom imaging versus SPGR note reduced dephasing from susceptibility gradients with SSFP



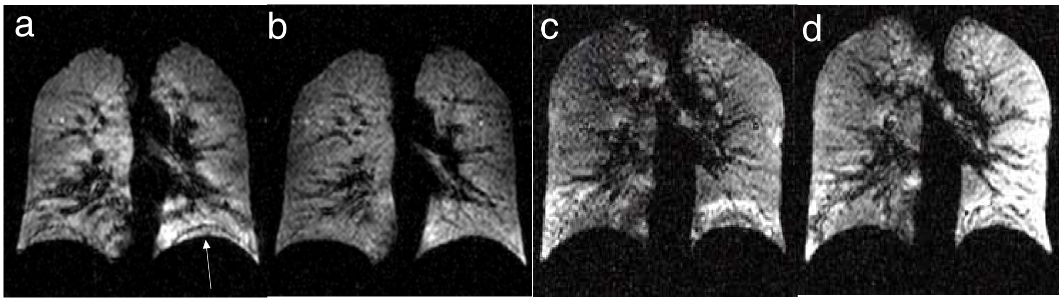


Fig 5a coronal SSFP image acquired with α = 20°. Fig 5b is the SPGR image from the same slice acquired with the same volume of gas. Note the characteristic banding in the SSFP image –arrow. Figs 5c and 5d are coronal SSFP images from the same slice in a second subject, acquired with α = 10° and α = 20° respectively. SNR increases with α without a noticeable change in the level of blurring.

Phantom experiments, confirm predicted theory of increased SNR with SSFP through use of higher flip angles (α) when compared to optimized spoiled gradient echo (SPGR) - (Fig. 1 & 2). SSFP with α=20°, and 128 sequential phase encodes, showed higher (1.7 x) SNR than optimized SPGR –also see Fig.4. Simulations and experiments show some compromise to SNR and PSF at high α due to diffusion dephasing from the readout gradient (Fig.2). In ^{3}He NMR experiments, diffusion dephasing can be mitigated, and the effective T2 is long (>1 s). Under these circumstances SSFP behaves like CPMG with sin(α/2) weighting of SNR (Fig. 3). Experiments and simulations were also performed to characterize off-resonance behaviour of the SSFP HP ^{3}He signal. Banding artifacts [3] were observed in some in vivo SSFP images, close to the diaphragm (arrow) where B_0 inhomogeneity is highest. Despite these artifacts, higher (1.6 x) SNR was observed with SSFP in-vivo when compared to SPGR (Fig. 5). The predicted theory of increasing SSFP SNR with increasing α was observed in the range α =10°-20° (Fig. 5c-d) without compromise to image quality through blurring caused by excessive k-space filtering [4].

Conclusion It has been demonstrated theoretically and experimentally that SSFP can provide high spatial resolution images of lung ventilation at breath-hold with HP ^{3}He at 1.5 T with the potential for higher SNR than SPGR methods. Although HP gas M_0 is not renewable, under the right conditions of long effective T2, a pseudo-steady state can be achieved within the time course of an MR imaging experiment. When effective T2 is shortened by diffusion dephasing, SSFP yields a decaying magnetization response. Nevertheless this non-steady state can still be used to good effect in vivo as it provides higher SNR for a given level of broadening in the PSF than an optimized SPGR sequence. Although the SSFP images show higher SNR, their diagnostic utility at high B_0 remains to be verified, largely because of the prevalence of banding artifacts, which may be misdiagnosed as ventilation defect.

References [1] Proc. ISMRM. 13 (2005) 50. [2] Magn Reson Med. 2004;52(3):673-8 [3] Proc. ISMRM. 10 (2002) 2019. [4] Magn Res Med 2002;47:687-695 **AcknowledgementS** EPSRC #GR/S81834/01(P) # EP/D070252/1, GE Health, Spectra Gases, Aerosol Society UK