SSFP Imaging with Hyperpolarized 3He : Experiments and Simulations

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Introduction Steady state free precession (SSFP) sequences [1] offer the potential of increased SNR for imaging with hyperpolarized (HP) agents [2, 3] by recycling residual transverse magnetization with the finite longitudinal magnetization. In this work the magnetization response of HP ^{3}He gas to a SSFP sequence was analyzed using a matrix formalism [4]. Experiments on phantoms and with human subjects confirm the predicted theory and indicate increased SNR and reduced blurring due to k-space filtering can be achieved with SSFP compared to spoiled gradient echo methods currently used.

Theory A SSFP sequence $\alpha/2\text{-}TR/2\text{-}(\alpha\text{-}TR)^n$ was modeled, with $TE=TR/2$ and the phase of the α pulse alternated by 180° on alternate views. The evolution of the longitudinal and transverse magnetization was simulated using the matrix formalism proposed by Hargreaves [4]. This was extended for HP gases to account for a non-renewable polarization and a contribution to the transverse signal decay from diffusion attenuation. The 3D magnetization vector for the kth RF view is given by $\mathbf{M}_{k+1}=\mathbf{A}\mathbf{M}_k$ where $\mathbf{A}=\mathbf{PCR}_\pi\mathbf{R}_\alpha\mathbf{PC}$. Where; $\mathbf{P}(\tau)$ represents the free precession matrix rotation during a period τ for a spin with a frequency offset Δf. $\mathbf{C}(\tau)$ is the relaxation matrix, $\mathbf{R}_\alpha$ is the rotation matrix of the α pulse and $\mathbf{R}_\pi$ is the phase cycling matrix of the alternate α pulses. The effect of diffusion attenuation due to imaging gradients was incorporated by adding a term $\exp(-b(\tau)D)$ to the diagonal transverse relaxation terms, $\exp(-\tau/T_2)$, in $\mathbf{C}(\tau)$. The starting magnetization before the first α pulse was given by $\mathbf{M}_s=\mathbf{PCR}_{\alpha/2}\mathbf{M}_0$, where $\mathbf{M}_0=[0,0,M_0]$. The simulations accounted for B_0 inhomogeneity by assuming a Lorentzian distribution in resonant frequency of spins with a FWHM estimated from the T_2^* of the sample (FWHM $\approx 1/\pi T_2^*$).

Experimental Methods ^{3}He Gas was polarized on site to 30% with spin exchange apparatus (GE Health). A SSFP sequence $\alpha/2\text{-}TR/2\text{-}(\alpha\text{-}TR)^n$ was implemented on a whole body 1.5 T system equipped with a quadrature T-R coil of twin saddle design. Two variants of the sequence were used with TR=10 ms and 5 ms respectively. The 10 ms TR version was used for investigations of SSFP in gas phantoms (syringe containing 10 cc ^{3}He+40 cc N_2, $D=0.9\times10^{-4}$ s/cm^2) where long T1s of up to 20 minutes are found. In a further series of phantom experiments, off-resonance effects were investigated, whereby the spectrometer frequency was offset in 10 Hz increments in the range Δf = 0-60 Hz. The 5 ms TR version was used for all imaging experiments. The readout gradient waveform for this sequence had a constant gradient during sampling =16.6 mTm^{-1}, with 256 samples and a dwell time of 4 µs. The b values for this gradient were b(TE)=0.292 scm^{-2} and b(TR)=0.584 scm^{-2}. A range of α (5° - 45°) were studied. The relative SNR and k-space filtering of SSFP in vivo was investigated by turning off the phase encoding gradient and running the sequence with read gradients alone. Direct comparisons were then made with the same sequence, which was spoiled (FLASH) rather than balanced (SSFP). All in vivo imaging experiments were performed with a 2D slice thickness of 10 mm, 128 sequential phase encodings and a FOV=48 cm.

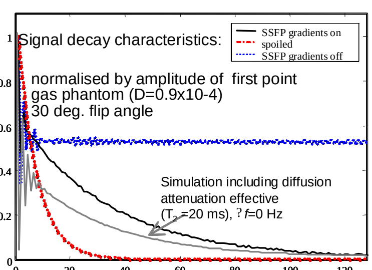

Fig.1

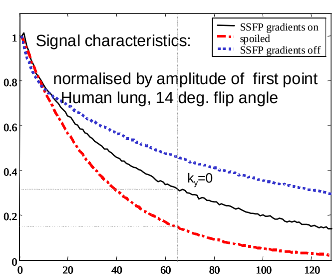

Fig.2

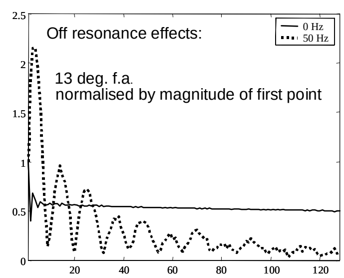

Fig.3

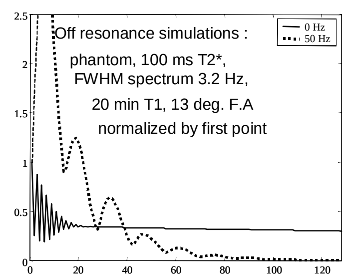

Fig.4

Results and Discussion Fig 1 indicates that in the absence of imaging gradients, SSFP can offer almost complete refocusing of transverse magnetization, potentially offering much higher SNR (proportional to the $k_y=0$ point) and very little broadening of the point spread function due to k_y filtering. The application of gradients will shorten the effective T_2^* due to diffusion dephasing and reduce the efficiency of SSFP, however in this experiment an improvement over the spoiled signal is still obvious in phantoms (Fig. 1) and in vivo (Fig. 2). This is in accord with the empirical findings of Mugler et al [2]. The off-resonance experiments (Fig. 3) display beating in the SSFP signal as Δf increases, the curve shapes show a good resemblance to those simulated (Fig.4) based upon estimates of the relaxation times and frequency dispersion in the phantom. Differences in simulated and experimental curves are due to estimates of the phantom T_2^* (from the FWHM of the spectrum), imprecision in experimental center frequency measurement, and assumptions of a Lorentzian distribution of frequencies due to B_0 inhomogeneity. Off-resonance effects were only noticeable in the in vivo images in the slices close to the diaphragm where B_0 inhomogeneity is high. The images shows very sharp edges indicating that the improved k_y filtering of SSFP can be put to use in obtaining high SNR images at high spatial resolution. With the modest flip angle of 14°, SSFP shows a 2-fold increase in SNR compared to FLASH with better spatial resolution –Fig.2. The SNR will improve with higher flip angles (SNR proportional to $\sin\alpha$), these were not possible at present due to RF power limitations. Future work will involve sequence optimisation to minimize diffusion attenuation and reduce TR to mitigate off resonance effects.

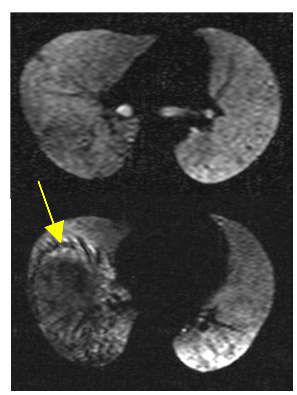

Fig.5. Axial 2D SSFP images:, α =15°, TR= 5 ms 10 mm slice, 128 p.e. views with sequential encoding. Note the off resonance artifacts in the axial slice close to the diaphragm (arrow)

References [1] Gyngell ML. Magn Reson Imaging. 1988, 6(4):415-9 [2] Mugler III JP et al Proc. Intl. Soc. Man. Reson. Med. 10, 2002. [3] Svensson J et al, Magn. Reson. Med. 2002; 50: 256-262. [4] Hagreaves BA et al, Magn. Reson. Med. 2001; 46: 149-158.

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