Simulations of the hyperpolarized 129Xe SSFP and SPGR pulse sequence signal response

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Introduction Imaging hyperpolarized (HP) ^{129}Xe in the gas phase is the basis for promising techniques to assess lung function such as XTC [1], but suffers from an intrinsically lower SNR compared to HP ^{3}He MRI owing to the lower gyromagnetic ratio. Typically, spoiled gradient echo (SPGR) sequences are used, but recently steady-state free precession (SSFP) sequences have attracted interest for imaging hyperpolarized agents, as the transverse magnetization can be recycled by balanced gradients, resulting in higher SNR [2,3]. In this preliminary work we show computations for *in vivo* HP ^{129}Xe MRI that suggest an SNR improvement by a factor of 3.2 by using an optimized SSFP sequence instead of a bandwidth matched optimized SPGR sequence.

Methods SPGR and SSFP sequences were simulated by matrix multiplication [2]. The magnetization vector **M** evolves according to $\mathbf{M}^{n+1}=\mathbf{PCR}_{\alpha}(n)\mathbf{PCSM}^{n}$. **C** and **P** are the relaxation and free precession matrix respectively, and $\mathbf{R}_{\alpha}(n)$ is the RF induced rotation by α, which includes phase cycling of π between alternate pulses for SSFP. For SPGR the spoiling matrix **S** removes all transverse magnetization, while it is set to identity for SSFP.
The simulated sequences had 128 sequential phase encoding steps, a FOV of (300 x 300) mm^2, slice thickness 20 mm, TR 6 ms and TE 3 ms. The RF excitation was modeled by a 900 µs Gaussian pulse, and B_0=1.5 T was assumed; field inhomogeneity was expressed by a Lorentzian frequency distribution of FWHM 16 Hz centered on the gas phase resonance at 0 ppm.
To simulate ^{129}Xe in human lungs we assumed T_1=20 s, T_2=100, a diffusion coefficient of D=0.040 cm^2/s [4] and T_2^*=20ms [5]. Diffusion dephasing due to gradients was accounted for by introducing an effective $T_{2,eff}(TE)=TE/(\boldsymbol{b}(TE)D+TE/T_2)$. $\boldsymbol{b}$(TE) was calculated from the time integral of the read and slice gradient waveforms, yielding $\boldsymbol{b}(TE)$=0.1399 s/cm^2. The contribution of the phase gradient to $\boldsymbol{b}$ was found to be negligible. This results in a $T_{2,eff}(TE)$ = 84.3 ms, or a reduction of T_2 by 16%, compared to 24% found for *in vivo* ^{3}He [2].
The influence of ^{129}Xe dissolved in lung tissue was tested by including additional peaks into the spectrum at 197 ppm and 212 ppm, corresponding to the lung parenchyma and RBC compartments respectively [1] and amounting to ~2% of the total intensity. The off-resonance effect due to these phases was negligible. However, our approach is static, assuming no exchange between Xe gas and dissolved phase. Chemical exchange is expected to shorten $T_{2,eff}$, as the T_2 of Xe dissolved in tissue is considerably shorter.

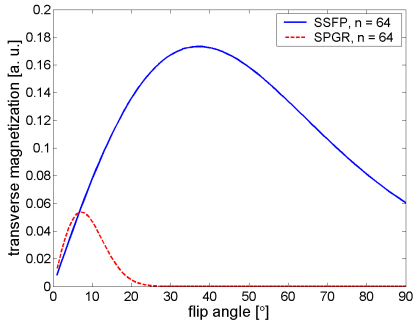

Figure 1: SPGR and SSFP ^{129}Xe signal amplitude at the center of k-space (n=64) as a function of flip angle.

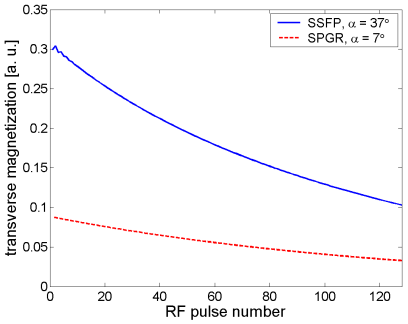

Figure 2: signal amplitude versus RF pulse number for optimal flip angles (SPGR: α=7°, SSFP: α=37°).

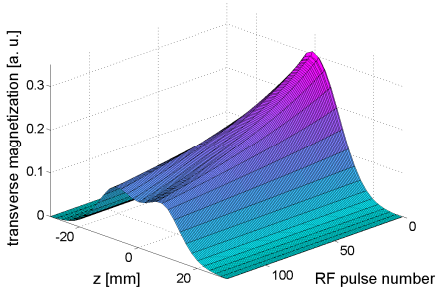

Figure 3: evolution of the excitation profile across the slice with RF pulse number for the SSFP sequence with α=37°.

Results and Discussion Figure 1 shows the signal amplitude for ^{129}Xe SSFP and SPGR for the center of k-space (n=64) as a function of flip angle, to give an estimate of the achievable SNR. For SPGR the maximum is at α≈7° as expected, while for SSFP we find an optimal α=37° and an SNR improvement by a factor of 3.2, compared to an optimum SSFP flip angle α=24° and SNR improvement over SPGR by a factor of 2 previously found for *in vivo* ^{3}He [2]. This is related to the lower Xe diffusion coefficient, leading to a higher $T_{2,eff}$ compared to ^{3}He for similar T_1 and T_2, which enables a higher flip angle and higher signal. However, as we neglect chemical exchange between gaseous and dissolved Xe, it is likely that the true $T_{2,eff}$ is shortened further, and our prediction merely presents an upper limit for SNR improvement.
Figure 2 shows the transverse magnetizations as function of RF pulse number with phase encode gradient set to zero for both SPGR and SSFP at their optimal flip angle. As for hyperpolarized ^{3}He samples SSFP does not lead to a flat steady state due to the non-recoverable hyperpolarization, the signal decay over the phase encode steps imposes a k-space filter which will result in edge blurring, as in the case of SPGR.
In the results shown in Fig. 1 and 2 we assumed an uniform flip angle across the slice. In fact the edges of the slice experience a lower flip angle, and the magnetization in the center is depleted faster. This leads to slightly lower signal for low pulse number and slightly higher signal for later pulses, but does not significantly change our findings. The data is not shown, in order to conserve space. In Figure 3 we show the evolution of the excitation profile across the slice with RF pulse number for SSFP, with α=37° in the center. The depletion in the center is less than what would be expected for SPGR at the same α, owing to the recycling of transverse magnetization in SSFP.
In this preliminary theoretical work we have shown that SSFP sequences are likely to present improved SNR in *in vivo* ^{129}Xe imaging compared to SPGR. Our model predicts a factor of 3.2 as the upper limit of SNR increase if optimized flip angles are used for both SPGR and SSFP. Further work will include experimental verification of these preliminary results and inclusion of the chemical exchange between gas phase and lung tissue into the theoretical model.

References [1] Ruppert *et al.*, MRM 51, 676-687 (2004); [2] Wild *et al.*, JMR 183, 13-24 (2006); [3] Svensson *et al.*, MRM 50, 256-262 (2003); [4] J.P. Mugler III., personal communication; [5] Driehuys *et al.*, PNAS 103, 18278-18283 (2006)
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