Optimized Gradient Echo Imaging for Hyperpolarised Nuclei - a Simulation Study

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Introduction: The gradient echo (GRE) sequence is a standard sequence in MRI. Provided that transverse magnetisation is spoiled to zero at the end of a repetition interval ("ideal spoiling"), a steady state builds up leading to pure T_1 weighting. In practice, spoiling in GRE imaging is performed by means of a spoiler gradient alone or by a spoiler gradient in combination with dedicated RF pulse phase cycling (RF spoiling). However, only with the latter case magnetisation can be manipulated such that the ideal spoiling case is approximately fulfilled in the steady state. In RF-spoiling, the RF pulse phase φ is cycled according to $\varphi = n(n-1)\psi/2$. The RF spoiling increment ψ is usually chosen to obtain a T_1-weighted steady-state according to the Ernst amplitude (e.g. $\psi = 50°$, 117°; note that the non-RF spoiled case is identical to $\psi = 0°$) [1]. When GRE is used for imaging hyperpolarised nuclei such as ^{13}C, the GRE sequence operates in a different scenario: Hyperpolarisation decays ultimately to zero; no signal can be recovered by means of T_1-relaxation between two consecutive RF pulses. Therefore, not T_1-weighting as for the thermal equilibrium case is targeted, but exploiting the signal over as many sequence repetition cycles as possible. This is usually accomplished by small flip angles for GRE imaging of hyperpolarised nuclei [2-4]. We present a simulation study that not only focuses on optimizing the flip angle of GRE for improved signal exploitation, but simultaneously the spoil increment ψ.

Method: An RF spoiled GRE sequence (FLASH) was simulated based on Bloch equations with Matlab R2011a. Hyperpolarisation conditions were represented by choosing a M_0 magnetisation of 10^4 instead of 1 as used for Boltzmann conditions. The following parameters were used for the simulations: 360 isochromats, 1000 pulses, T_1 = 25 s, T_2 = 2.5 s (corresponding to ^{13}C hyperpolarised pyruvate [5,6]), TR = 30 ms, TE = 5 ms, ψ = 0°…180°, flip angle α from 1° to 10° in 1° steps and from 10° to 50° in 5° steps. No diffusion attenuation of the signal was assumed. Simulations assuming ideal spoiling were performed as well, by simply setting the transverse magnetisation M_{xy}= 0 at the end of each repetition interval.

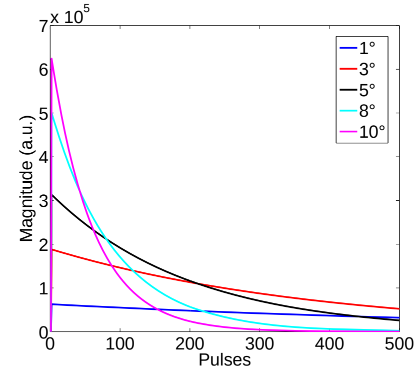

Figure 1: Simulations of ideal spoiling situation for several flip angles

Results: As expected, simulations in the case of ideal spoiling for several flip angles (Fig.1) show a non-vanishing signal amplitude over a higher number of pulses for small flip angles. This confirms the approach of using small flip angles as formerly described [2-4]. When RF-spoiling is simulated, the situation is different. In Fig. 2, the results for two chosen flip angles (5°, 10°) and selected values of the phase increment as well as the ideal spoiling case are shown. The signal is best exploited for ψ = 1°, displayed values for comparison are ψ = 0° (non-RF-spoiled GRE) and the standard values for T_1 weighted RF-spoiling for Boltzmann conditions (ψ = 50°, 117°). Note that the ideal spoiling case is not approximated by any of the shown ψ values, which indicates that transverse magnetisation is not completely destroyed by RF-spoiling but can be employed as means of prolonging the useable time of the hyperpolarised signal. In Fig. 3, the evolution of the signal (flip angle 10°) over 500 pulses is shown for all phase increments (ψ = 0°...180°). A plot of the signal after (arbitrarily chosen) 200 pulses shows that small phase increments (ψ = 1°) are most promising for obtaining high signal over a relatively long RF pulse train.

Discussion: According to our simulations, GRE imaging can be optimized by choosing small RF-spoil increments ψ when hyperpolarised compounds are imaged. The "second best" choice is GRE without RF-spoiling, i.e. ψ = 0°. Note that the values of ψ = 50° or 117° as used for standard thermal equilibrium ^{1}H RF spoiled GRE imaging are detrimental for imaging hyperpolarised nuclei. This fact has to be considered when standard GRE protocols are used. The equipment for performing hyperpolarised ^{13}C imaging is currently under installation in our lab. We plan to confirm our results as soon as possible on phantoms, in order to verify the validity of our simulation. The influence of diffusion of ^{13}C hyperpolarised liquid substances will then be explored as well. Besides of diffusion, the choice of the optimal combination of spoil increment and flip angles depends on T_1, T_2 and TR, which gives further motivation for improved simulations or even analytical optimization of GRE with respect to flip angle and RF spoil increment.

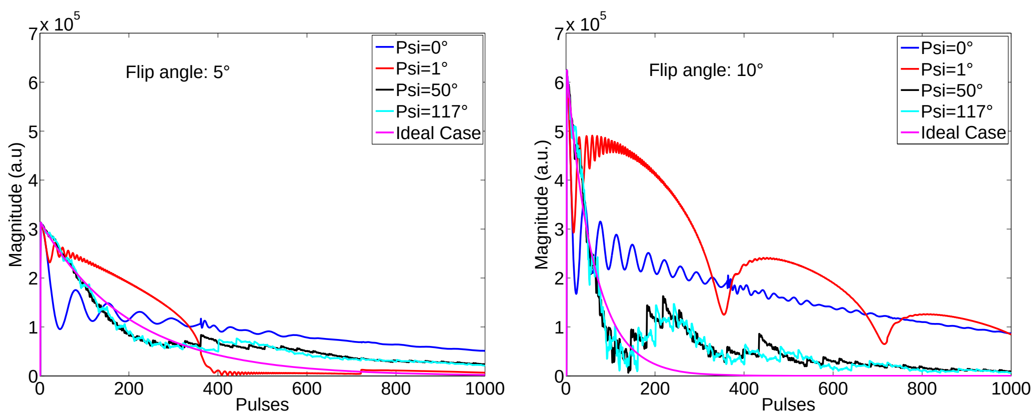

Figure 2: RF spoiling simulations in hyperpolarisation conditions for flip angles of 5° and 10° for different ψ.

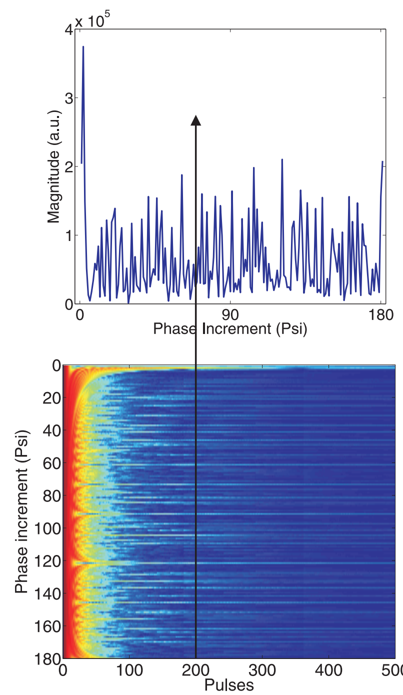

Figure 3: Color-coded representation of the evolution of the signal for ψ = (0°..180°) over 500 pulses. The line plot after 200 pulses (top), demonstrates that ψ = 1° provides the highest signal.

References: [1]Scheffler, Concepts Magn Reson 11(5):291-304(1999) [2]Middleton et al., MRM 33:271-275(1995) [3]Möller et al., MRM 47:1029-1051(2002) [4]Wild et al., JMR 183:13-24(2006) [5]Golman et al., MRM 59(5):1005-1013(2008) [6]Svensson et al., MRM 50(2):256-262(2003)