Side Effects of the Spoiler Gradient in Gradient Echo Sequences: Diffusion Attenuation of the Signal from Nuclei in Thermal Equilibrium and in Hyperpolarised State

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Introduction: The signal obtained by gradient echo sequences depends on the sample parameters T_1 and T_2 as well as on the imaging parameters TR, flip angle and echo time (see, e.g. [1]). In the case of RF-spoiled gradient echo, the spoil increment ψ describing the RF-pulse phase cycle is another imaging parameter that is considered. What is often neglected, however, is potential diffusion weighting of the signal governed by the diffusion constant of the sample and the b-values of the imaging gradients. The unbalanced moment of the imaging gradients in any direction is equivalent to a spoiler gradient, which is fundamental for unbalanced gradient echo sequences (FISP) and RF-spoiled gradient echo sequences (FLASH). Here, we show the dependency of the FISP and FLASH steady state on the b-value of the spoiler gradient. Additionally, we show simulations of the evolution of the gradient echo signal over the sequence repetition cycles for the signal being in hyperpolarized state. This signal evolution has been described previously [2], but the simulation is now considering the effect of diffusion. In hyperpolarisation conditions, the magnetization amplitude is not converging to a steady state but decays ultimately to zero. In previous investigations [2], we have shown that the use of FLASH with optimized parameters (ψ = 1°, flip angle: 10°) allows signal exploitation over a larger number of sequence repetition cycles than for FISP and than for FLASH with a spoil increment as used for T1-weighting (ψ=50° or 117°) in the thermal equilibrium case. Now, diffusion effects were included into the simulations.

Method: The FLASH and FISP sequences were simulated based on the extended phase graph with diffusion method [3], implemented in Matlab R2011a. For the simulations in thermal equilibrium conditions, the following parameters were used: 256 pulses, TR = 20 ms, TE = 4 ms, a spoil increment of ψ = 0° (FLASH is identical to FISP in this case) and 117°, flip angle α = 40°, T_1 = 300 ms, T_2 = 95 ms and diffusion constant D = $2.146 \cdot 10^{-3}$ mm²/s (water). The spoiler gradient is assumed to be placed at the end of the sequence interval with rectangular shape duration t_{Grad} = 1.15ms and Amplitude G varied from 20.28mT/m to 466.44mT/m in steps of 40.56mT/m. This corresponds to b-values from 0.01 s/mm² to 7.9 s/mm² and to spoiling the magnetisation by values from 2 to 46 cycles along the slice direction. MRI experiments were performed on a 7T small animal scanner (Biospec 70/20, Bruker BioSpin, Ettlingen, Germany) with maximum gradient amplitude of 676 mT/m and maximum slew rate of 4750 mT/(m*ms) using a mouse quadrature volume coil. A 50 ml falcon tube filled with doped water ($CuSO_4$) was used as phantom for the experiments. Signal was obtained from a transversal slice of 2 mm thickness by means of slice selective excitation. T_1, T_2 and D were measured prior to the actual measurements.

Hyperpolarisation conditions were represented in the simulation by choosing a M_0 magnetisation of 10^4 instead of 1 as used for thermal equilibrium conditions. The following parameters were used: 2000 pulses, TR = 15 ms, TE = 5 ms, spoil increment of ψ = 1°. α = 10°, T_1 = 25 s, T_2 = 2.5 s, D = $2 \cdot 10^{-3}$ mm²/s corresponding to liquid (^{13}C [4,5]) and α = 3°, T_1 = 20 s, T_2 = 100 ms, D = $0.2 \cdot 10^{2}$ mm²/s corresponding to gas (^{3}He [6]). A slice selection gradient (t_{Grad} = 2.06ms, G=72.87mT/m) was simulated as well as a spoiler gradient preceding each pulse whereat t_{Grad} = 1.15ms and G = [20.28, 40.56, 81.12, 135.20] mT/m (liquids) and G = 0.34mT/m (gas). Results are compared to the case without diffusion (D = 0 mm²/s) and to the case of ideal spoiling (transversal magnetisation set to zero at the end of a sequence interval).

Results: Thermal equilibrium case: For each gradient amplitude, the signal of the steady state is shown for the simulated and measured data of FLASH (ψ =117°) and FISP (ψ =0°) (fig. 1). The steady state of FISP with highest diffusion gradient strength was used to normalize the curves. The signals of both sequences approach nearly the same steady state value for very high gradient amplitudes, as in this regime diffusion attenuation is a means of achieving perfect spoiling conditions. Hyperpolarised case: The effect of diffusion on the GRE signal evolution in hyperpolarised gas and liquid was simulated (fig. 2). As expected for hyperpolarised molecules in liquids, the impact of spoiler gradients is important: the observable signal oscillations vanish and the signal amplitude is rapidly attenuated. For hyperpolarized gas, the effect is minimal as diffusion constant in gas is already very high, and even in the case of diffusion constant artificially set to zero the signal evolution is close to the ideal spoiling case for the selected parameter set.

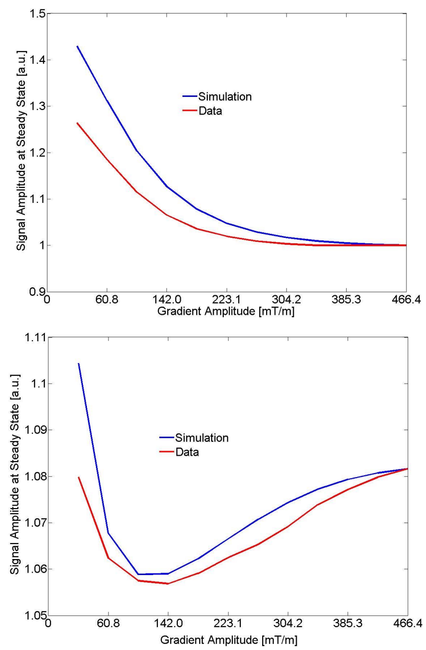

Figure 1: Simulations and experiments comparison at thermal equilibrium conditions for FISP (top) and FLASH (ψ = 117°, bottom). Spoiler gradient duration is t_{Grad} = 1.15ms.

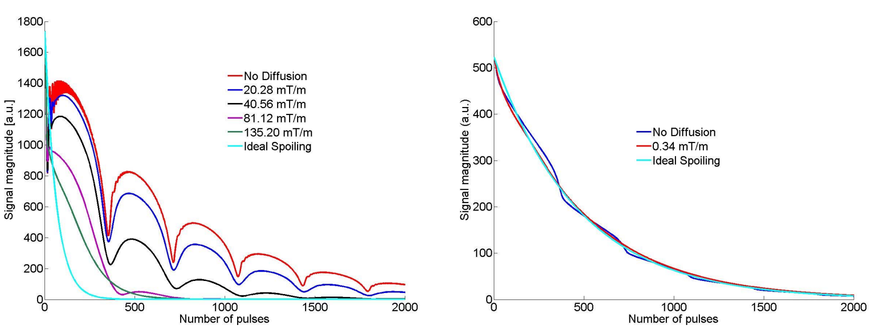

Figure 2: FLASH simulations (ψ = 1°) for different spoiler gradient strength for hyperpolarized molecules in liquids (left) and gas (right). In gas, the diffusion is so dominant that ideal spoiling behaviour is observed in any depicted conditions. Gradient duration is t_{Grad} = 1.15 ms.

Discussion: At thermal equilibrium condition, the impact of diffusion on the steady state obtained using GRE sequences was shown. Both FISP and FLASH converge to the same steady state value for high spoiler gradient amplitudes (as shown already for FISP [7]). The signal decreases for FLASH for intermediate gradient amplitudes before it increases with high gradient amplitudes and finally enters the ideal spoiling regime. The impact of diffusion gradient strength on the signal amplitude was also analysed for imaging hyperpolarised compounds. Especially for hyperpolarized molecules in liquids (^{13}C e.g.), the impact on the signal behaviour is essential. For hyperpolarized gas, the signal evolution can be described with ideal spoiling and the difference between FLASH and FISP vanishes completely. The equipment for performing hyperpolarised ^{13}C imaging is currently under installation in our lab and therefore, we plan to verify also our results for hyperpolarized conditions as soon as possible on phantoms.

References: [1]Scheffler, Concepts Magn Reson 11(5):291-304(1999) [2]Bär et al., ISMRM 2012, p.4160 [3]Weigel et al., JMR 205(2):276-285(2010) [4]Svensson et al., MRM 50(2):256-262(2003) [5]Golman et al., MRM 59(5):1005-1013(2008) [6]Wild et al., JMR 183:13-24(2006) [7] Gudbjartsson and Patz, MRM 34(4):567-579(1995)