Intrinsic Diffusion Sensitivity of the bSSFP Signal: Optimizing the flip angle in the presence of Strong Read Out Gradients

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Introduction: In fields like molecular imaging and MR microscopy, gradient amplitudes of several hundred mT/m are typically needed in order to achieve the aimed very high resolutions of several tenths of micrometers. Even if projects using clinical scanners exist [1], such strong imaging gradient systems are predominantly used for clinical research at ultra-high field small animal scanners. However, strong imaging gradients can introduce noticeable diffusion sensitivity in MRI [2-5]. The balanced Steady State Free Precession (bSSFP) sequence is one of the main standard rapid imaging sequences which particularity is that the gradients in each imaging direction are fully balanced within each repetition interval [6]. This high SNR sequence is already established in clinical routine.

In previous work, we described the diffusion-induced signal loss of the bSSFP steady-state by the b-values of imaging gradients [7,8]. It was shown that the b-value of the read out gradient leads to a steady-state with decreased amplitude. In this work, based on simulations and measurements, we show that the standard flip angle maximizing the bSSFP signal is not optimal anymore when diffusion is taken into account in high-resolution imaging. Hence, a change of flip angle depending on the strength of the RO gradients can provide an additional increase of signal.

Method: MRI experiments were performed on a 7T small animal scanner (Biospec 70/20, Bruker BioSpin, Ettlingen, Germany) with a maximum gradient amplitude of 676 mT/m and maximum slew rate of 4750 mT/(m*ms) using a mouse quadrature volume coil. Sequence parameters for the measurements were: TR=7.42 ms, 5000 dummy scans followed by 256 pulses where either no gradients or only RO gradients are turned on: flip angles were varied in simulations and measurements from 0° and 10° respectively to 90° in 5° steps. The pre- and rephasing gradient lobes of the read out gradient have a duration of 0.912 ms and an amplitude of 320.65 mT/m, while the gradient lobe during signal acquisition has a duration of 1.71 ms and an amplitude of 320.08 mT/m. The total b-value is 11.07 mm²/s, voxel size in in read out direction is 43 µm. A sphere of 18 mm diameter and 3 ml volume filled with distilled water was used as a phantom. T_1, T_2 and the diffusion constant D were measured to T_1=2792 ms, T_2=1034 ms, D=1.94*10^{-3} mm²/s. Simulations of the bSSFP sequence signal based on the extended phase graph (EPG) [9] with diffusion method and using the same parameters were implemented in Matlab. The exact trapezoidial shapes of the gradient pulses were used for b-value calculation. As diffusion effects due to RO gradients solely accentuate the transversal magnetization dephasing (comparable to increased T_2 effects), the bSSFP steady-state signal can be easily simulated by replacing $E_2 = e^{-TR/T_2}$ by $E_2' = E_2 e^{-bD}$ in the standard on-resonant bSSFP steady-state magnetization equation. Consequently, the diffusion effects only lead to a lower steady-state. Similarly, the flip angle maximizing the signal can be then defined as $\alpha_{OptDiff} = \cos^{-1}\frac{E_1 - E_2'}{1 - E_1 E_2'}$ with $E_1 = e^{-TR/T_1}$.

Results: The dependency on flip angles of theoretically expected steady-state signals without readout gradient (M_{StSt}) and with readout gradient (M_{RO}) considering diffusion are shown in figure 1. The flip angle maximizing the steady-state signal while no diffusion attenuation occurs ($\alpha_{OptStSt}$) is shifted to lower flip angles ($\alpha_{OptDiff}$) when RO gradients are turned on. The theoretical values obtained are $\alpha_{OptStSt} \approx 62°$ and $\alpha_{OptDiff} \approx 31°$ and correspond quite well to the measured values (figure 1).

For a specific tissue, several useful quantities can be determined: The loss of signal due to diffusion when using the standard flip angle $\alpha_{OptStSt}$ (Eq.1) as well as while using $\alpha_{OptDiff}$ instead of $\alpha_{OptStSt}$ (Eq.2). Also the gain of signal that can be obtained by using $\alpha_{OptDiff}$ instead of $\alpha_{OptStSt}$ when diffusion is considered can be quantified (Eq.3). All equations show no dependency on T_1 but only on T_2 relaxation.

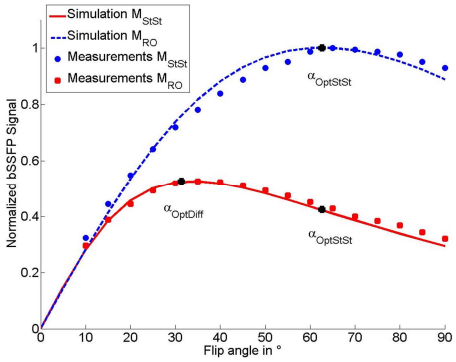

Figure 1: The bSSFP steady-state signal dependency on flip angles was simulated and measured without (b=0 mm²/s, blue curve) and with (b=11.07 mm²/s, red curve) diffusion attenuation due to RO. A shift of the optimal flip angle maximizing the signal can be observed from $\alpha_{OptStSt} \approx 62°$ to $\alpha_{OptDiff} \approx 31°$.

$$\frac{M_{RO}(\alpha_{OptStSt})}{M_{StSt}(\alpha_{OptStSt})} = \frac{1-E_2^2}{1-E_2E_2'} \quad (1), \quad \frac{M_{RO}(\alpha_{OptDiff})}{M_{StSt}(\alpha_{OptStSt})} = \sqrt{\frac{1-E_2^2}{1-E_2'^2}} \quad (2), \quad \frac{M_{RO}(\alpha_{OptDiff})}{M_{RO}(\alpha_{OptStSt})} = (1-E_2E_2')\sqrt{\frac{1}{(1-E_2'^2)(1-E_2^2)}} \quad (3)$$

Simulations show that especially for tissues with long T_2 and increasing b-values, the signal loss due to diffusion effects related to RO gradients is not negligible: Hence, for a b-value of 11.07 mm²/s e.g. about 40% of signal remains for a tissue with $T_2 \approx 1$s (figure 1 and 2 (left)). As can be seen in figure 2 (right), the change of flip angle from $\alpha_{OptStSt}$ to $\alpha_{OptDiff}$ allows a signal increase of about 20%.

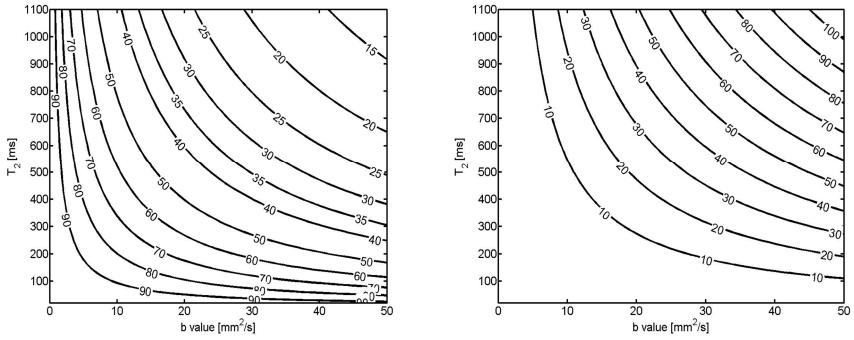

Figure 2: (left) Simulations show the percentage of signal remaining when diffusion attenuation due to RO gradients are taken into account in comparison to the signal expected when no diffusion effects occur: $\frac{M_{RO}(\alpha_{OptStSt})}{M_{StSt}(\alpha_{OptStSt})} x100$. Simulations are done for a realistic range of T_2 values and b-values. A strong impact is observed on tissues with long T_2. (right) A substantial increase of signal can be obtained when using $\alpha_{OptDiff}$ instead of $\alpha_{OptStSt}$. The gain of signal was simulated for different T_2 and b-values. Shown here is the additional signal obtained in percent: $\frac{M_{RO}(\alpha_{OptDiff}) - M_{RO}(\alpha_{OptStSt})}{M_{RO}(\alpha_{OptStSt})} x100$.

Discussion:

In fields like MR-microscopy, very strong gradients (several hundred mT/m) are needed to achieve high resolution. In this work, the flip angle dependency of diffusion induced signal damping due to the read out gradients of the bSSFP sequence were examined. After showing through simulations how signal attenuation augments with increasing T_2 and b-values, we showed that the use of $\alpha_{OptDiff}$ instead of $\alpha_{OptStSt}$ allows a substantial increase of signal. Both the signal loss occurring and the possible re-gain of signal by flip angle adjustment show no dependency on T_1 relaxation.

References: [1]McNab et al., NeuroImage 80:234-245(2013), [2]Wu and Buxton., JMR 90:243-253(1990), [3]Weigel et al., MRM 67(6):1528-1537(2012), [4]Bieri et al., MRM 67(3):691-700 (2012), [5] Zur et al., MRM 6(2):175-193 (1988), [6]Scheffler et al., Concepts in MR 11(5):291-304(1999), [7] Bär et. al., ISMRM 2014 (4324), [8] Bär et. al., ESMRMB 2013 (52), [9] Weigel et al., JMR 205(2):276-285(2010)