Intrinsic Diffusion Sensitivity of the bSSFP Signal: Influence of Strong Phase Encoding Gradients on Image SNR

Sébastien Bär[1], Matthias Weigel[1,2], Jürgen Hennig[1], Dominik Von Elverfeldt[1], and Jochen Leupold[1]
[1]Department of Radiology, Medical Physics, University Hospital Freiburg, Freiburg, Germany, [2]Radiological Physics, University of Basel Hospital, Basel, Switzerland

Introduction:

In fields like MR-microscopy and molecular imaging, gradients with very high amplitude (several hundred mT/m, hence very high b-values) are necessary to achieve high resolution. Such strong gradient systems are mainly used in combination with ultra-high field small animal scanners for clinical research even if some projects using clinical scanner already exist [1]. However, strong imaging gradients can introduce noticeable diffusion sensitivity in MRI [2-4]. The balanced Steady State Free Precession (bSSFP) sequence is one of the standard rapid imaging sequences established in the clinical routine. Its characteristic is that all gradients are fully balanced during the repetition interval. In previous work, we showed that the intrinsic diffusion sensitivity of the varying phase encoding gradients (PE) leads to severe modulations of the steady state signal of the bSSFP sequence [5]. In this work, based on simulations and measurements we demonstrate the impact of those diffusion effects on the resulting signal to noise ratio (SNR) of the images.

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 as follows: 5000 dummy scans (readout (RO) and slice selection (SliSel) gradients only) followed by 1024 pulses with all imaging gradients turned on: TR=8ms, TE=4ms, flip angle α=50° and a slice thickness of 2mm. The phase encoding gradient has a duration of T_{PE}=2.44ms and its amplitude was varied from $+G_{PE}$ to $-G_{PE}$. Experiments with different resolutions in PE direction were performed by changing the maximal G_{PE} = [25.69, 67.6, 135.2, 202.8, 270.4, 338, 405.6] mT/m, thus, leading to different inherent diffusion sensitivities quantified in terms of the resulting b-factor (See Tab. 1 for corresponding voxel sizes and b-values). Intergradient duration between the PE gradient and PE rewinder gradient was 2.24ms. A standard linear phase encoding view ordering scheme was chosen. The slice selection and read out gradients were not varied: $T_{RO} = T_{SliSel}$ =2.3ms, G_{RO} = 28.1mT/m, G_{SliSel} = 7.98mT/m. This corresponds to a resolution of 0.182 mm in read out direction. A tube with diameter 14.5mm filled with distilled water was used as a phantom and T_1, T_2 and the diffusion constant D were measured as follows: T_1=2.798s, T_2=794.12ms, D=2.0825*10^{-3}mm²/s. The image SNR was measured for each different value of the PE gradient amplitude by ROI analysis. Additionally, simulations in Matlab of the bSSFP sequence SNR based on the extended phase graph (EPG) with diffusion method [6] were done using the same parameters and all imaging gradients on the three axes. The SNR without diffusion effects was calculated via the 'standard SNR formula' in 2D: $SNR_{voxel} \propto \Delta x \cdot \Delta y \cdot SliceThick \cdot \sqrt{N_{ACQ} \cdot N_x \cdot N_y \cdot \Delta t}$, where $\Delta x, y$ are the voxel dimensions in RO and PE directions, $N_{x,y}$ the number of k-space samples and Δt is the sampling rate.

Results:

Using the SNR formula, the SNR estimations considering the different maximal PE gradient amplitude values were calculated and compared to the experimentally obtained SNR values (Tab. 1). The ratio $\frac{SNR_{25.69\text{mT/m}}}{SNR_{X\ mT/m}}$ was calculated in each case and an additional attenuation of the SNR due to diffusion could be stated (see Tab.1).

In the left image in Figure 1, simulations of the signal behaviour of a bSSFP sequence including diffusion effects are plotted for the different amplitudes of the PE gradients. At the echo time (512 pulses), the SNR ratio has been calculated in the same way as for the theoretical and experimental SNR ratios. Since the only parameter changed was the varying balanced phase encoding gradients, the actual SNR loss could be directly attributed to the diffusion induced signal attenuation introduced by the PE gradients. In the right image in Figure 1, the comparison between the experimental and simulations results is shown: The loss of SNR is in accordance with the simulation.

PE gradient amplitude	b-value	Voxel size in PE dir.	Signal Attenuation:	$\frac{SNR_{25.69\text{mT/m}}}{SNR_{X\ mT/m}}$	Supplemental Attenuation	
[mT/m]	*mm²/s*	*µm/pixel*	*Theor. Expectation*	*Exp. Data*	*Exp./Theo.*	*Simulation*
67.6	7.236	74.219	2.632	2.653	**1.008**	**1.070**
135.2	28.946	37.109	5.263	6.242	**1.186**	**1.250**
202.8	65.128	24.740	7.895	11.140	**1.411**	**1.422**
270.4	115.783	18.555	10.526	16.383	**1.556**	**1.572**
338.0	180.911	14.844	13.158	22.386	**1.701**	**1.712**

Table. 1: The theoretically expected SNR attenuation is calculated for different maximal PE gradient amplitudes. The same was then done experimentally and a supplemental signal attenuation could be observed.

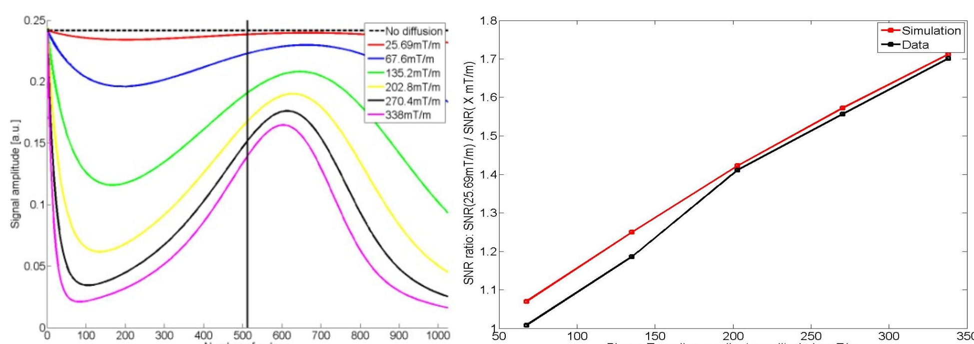

Figure 1: (left) Simulations of the bSSFP signal in presence of diffusion for the different maximal PE gradient amplitudes G_{PE} = [25.69, 67.6, 135.2, 202.8, 270.4, 338, 405.6] mT/m. Signal attenuation was calculated through the signal ratio at the echo time after 512 pulses (right.) Simulated and measured SNR attenuation: The detected SNR attenuation is consistent with the predicted diffusion effect due to the phase encoding gradients.

Discussion:

In fields like MR-microscopy, very strong gradients (several hundred mT/m) are needed to achieve high resolution. In this work, diffusion effects due to the phase encoding gradients of the bSSFP sequence were examined. First, we could observe supplemental signal attenuation when comparing the experimental SNR to the expected theoretical SNR. Second, we could show through simulations, that this attenuation is linked to the diffusion effects due to the varying phase encoding gradients.

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]Bär et. al., ESMRMB 2013 (52), [6]Weigel et al., JMR 205(2):276-285(2010)