Framework for comparing relative SNR and SNR efficiency of diffusion weighted sequences in neuro-imaging

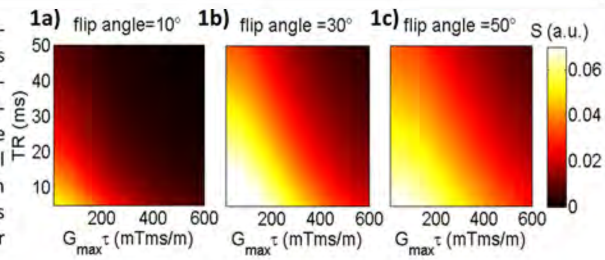
Benjamin Fürsich[1,2], Tim Sprenger[1,2], Axel Haase[1], and Marion I. Menzel[2]
[1]IMETUM, Technical University, Munich, Bavaria, Germany, [2]GE Global Research, Munich, Germany

Introduction: Diffusion MRI provides a useful research tool for microstructure analysis of brain white matter (WM) fibers. The most widely used pulse sequence for diffusion weighted imaging (DWI) based on 2D single-shot echo-planar imaging (EPI) readout with Stejskal-Tanner diffusion preparation, only reaches relative poor signal-to-noise ratios (SNR). [1] Modern pulse sequences try to overcome the limited SNR and SNR efficiency of this technique. On the one hand simultaneous multi-slice (SMS) sequences, provide higher SNR efficiency. [2] On the other hand multi-shot techniques reach for higher SNR using a segmented k-space acquisition. Promising multi-shot techniques in neuro-imaging were presented by Engström *et al.* using a 3D multi-slab EPI (MS-EPI) sequence [3] and by O'halloran *et al.* utilizing a 3D diffusion weighted steady state free precession sequence (DW-SSFP) [4]. In this work a framework to compare different DWI sequences in terms of SNR and SNR efficiency is provided and applied to a typical whole brain DWI scenario.

Theory: The derived relative SNR (rSNR) given in (1) is proportional to the actual SNR and normalized to the rSNR of the 2D DW-EPI sequence. It is determined by the signal intensity S of a sequence and the volume efficiency υ given by the excited volume fraction of a sequence (Table 1). The rSNR efficiency η_{rel} given by (2), states how efficient data is sampled per unit time. It is determined by the rSNR times a sampling efficiency ρ, which is defined by the fraction of time during which data is acquired [5]. $\text{rSNR} = S \cdot \sqrt{\upsilon} \propto \text{SNR}$ (1) $\eta_{rel} = S \cdot \sqrt{\rho} \cdot \sqrt{\upsilon} \propto \frac{\text{SNR}}{\sqrt{T_{\text{Scan}}}}$ (2)

Table 1	2D DW-EPI	3D MS-EPI	3D DW-SSFP
Sampling efficiency ρ	$\frac{T_{acq}}{T_{\text{acq}}+T_{\text{prep}}}$	$\frac{T_{acq}}{T_{acq}+T_{prep}}$	$\frac{T_{aqc}}{T_R}$
Volume efficiency ν	$\frac{a_{\text{fac}}}{N_{\text{Slices}}}$	$\frac{1}{N_{slabs}}$	1 (full volume excited)
Signal amplitude S	$e^{-\frac{T_{\text{prep}}}{T_2}} \cdot (1-e^{-\frac{T_R}{T_1}})$	$e^{-\frac{T_{prep}}{T_2}} \cdot (1-e^{-\frac{T_R}{T_1}})$	analytic model
b-value	$\gamma^2 G_{\text{max}}{}^2 \tau^2 (\delta + \frac{2\tau}{3})$	$\gamma^2 G_{max}{}^2 \tau^2 (\delta + \frac{2\tau}{3})$	$-\frac{1}{D}\ln\left(\frac{S_{SSFP}(D)}{S_{SSFP}(D=0)}\right)$
Repetition time T_R	$\frac{N_{\text{Slices}}}{a_{\text{fac}}}(T_{\text{prep}}+T_{\text{acq}})$ with $T_{\text{prep}} = 2\tau + \delta + T_{\text{dead}}$	$N_{slabs}(T_{prep}+T_{acq})$	$T_{acq} + \tau + T_{dead}$

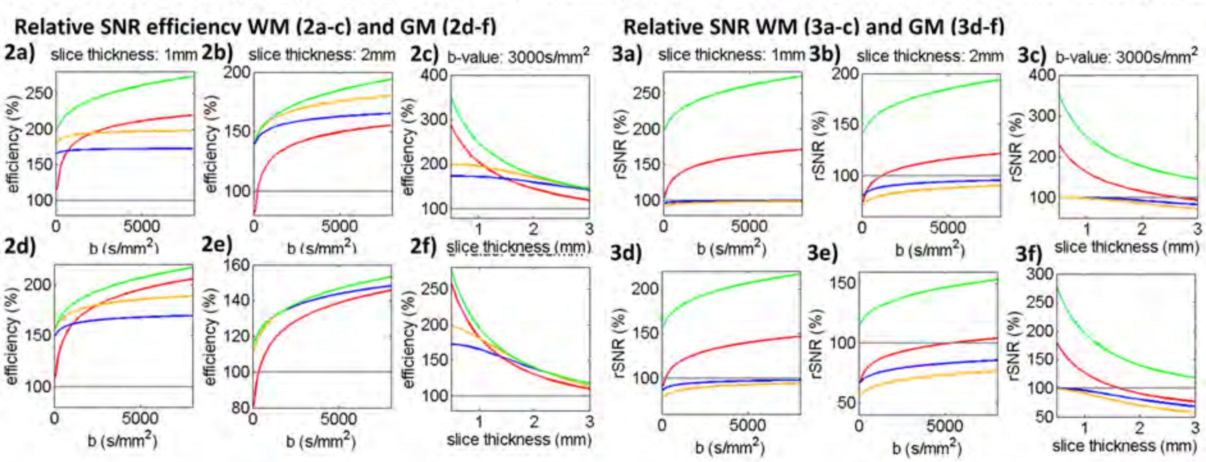
Methods: A volume of 12cm in slice encoding direction was considered in the calculation, similar to a complete brain scan. A fixed maximal gradient strength G_{max}=50mT/m was assumed. Calculation of η_{rel} and rSNR (see table 1) were performed for 2D DW-EPI, 2D SMS DW-EPI (with a multi-band acceleration factor a_{fac} of 3 and 4), 3D MS-EPI and 3D DW-SSFP with varying b-values and variable slice thickness for WM (T_1=830ms, T_2=80ms, D=0.7·$10^{-9}$$m^2$/s) and grey matter (GM) (T_1=1330ms, T_2=110ms, D=0.75·$10^{-9}$$m^2$/s). Fixed values for acquisition time $T_{\text{acq}} = 30ms$ dead time T_{dead}=15ms and time in between the diffusion gradients $\delta = 10ms$ were assumed for 2D DW-EPI, 2D SMS DW-EPI and 3D MS-EPI. The diffusion gradient duration τ was calculated for each b-value respectively using Stejskal-Tanner preparation. The number of excited volume slabs N_{slabs} with an optimal slab thickness was calculated for 3D MS-EPI, corresponding to a favourable TR in terms of T_1 saturation. An optimization of the 3D DW-SSFP sequence parameters was conducted based on calculation of signal amplitudes using an analytic model provided by Freed *et al.* [6]. Signal amplitudes of 10^6 different parameter combinations, with variable flip angle, TR, and τ were evaluated (fig. 1a-c). η_{rel} and an effective b-value b_{eff} was calculated for each parameter set, taking T_{dead}=5ms into account during each TR. The parameter set with the highest η_{rel} and b_{eff} matching the wanted b-value $\pm$1% was chosen (3).



$$\eta_{\text{rel,optimal}}(b) = \max(\eta_{\text{rel}}(T_R, \alpha, G_{\max}\tau)_b) \quad \text{with } b = b_{\text{eff}} \pm 1\% \quad (3)$$

Results: Figures 2a)-f) show the rSNR efficiency of the evaluated sequences normalized to the 2D DW-EPI sequence (grey) for different slice thickness and b-values. The highest efficiencies were calculated for 3D MS-EPI (green). At 1mm slice thickness and WM (fig. 2a) this sequence provides a gain of 100%-150% efficiency compared to 2D DW-EPI. 2D SMS DW-EPI (yellow, blue) performs nearly as good as 3D MS-EPI (green) for thicker slices (2mm-3mm). At a slice thickness of 2mm and b=3000 2D SMS DW-EPI (yellow, blue) provides approximately 80% (a_{fac}=4)(60% for a_{fac}=3) higher efficiencies for WM (fig. 2b) and 40% (a_{fac}=4)(40% for a_{fac}=3) gain for GM (fig. 2e) compared to 2D DW-EPI (grey). 3D DW-SSFP (red) yields overall lower efficiencies than 3D MS-EPI (green), but becomes more efficient than 2D SMS DW-EPI (yellow, blue) for thin slices and high b-values. For a b-value of 3000 and 1mm slice thickness, 3D DW-SSFP (red) provides a gain of approximately 100% efficiency for WM (fig 2a) and 80% for GM (fig 2d) compared to the reference of 2D DW-EPI (grey). Figures 3a)-f) show the comparison of rSNR levels. The SNR of 2D SMS DW-EPI (yellow, blue) is lower than for 2D DW-EPI (grey). Again 3D MS-EPI (green) yields the highest SNR and with increasing gain towards lower slice thickness (fig. 3c,f). 3D DW-SSFP also provides an advantage in SNR compared to 2D DW-EPI at low slice thickness.

Discussion: A framework for comparing rSNR and rSNR efficiency of different diffusion weighted sequences was presented. For the assumed scanner and sequence parameters the 2D SMS DW-EPI seems most practical at lower resolutions. It provides a high efficiency and high number of sampled q-space points per unit time. However, the SMS technique does not improve SNR of a single acquisition and may lead to an increased Rician bias at low slice thicknesses. Furthermore, SMS DW-EPI only allows limited in plane accelerations. Hence, this evaluation depicts 3D MS-EPI as a method of choice for performing a complete brain scan at high resolution. It should be noted, however, that the calculated gains in efficiency for the segmented 3D sequences (DW-SSFP, MS-EPI) may be slightly lower in reality, due to extra dead time needed for navigators, g-factor penalties due to parallel imaging, incomplete phase correction and distortion of the steady state of DW-SSFP due to motion.



References:

[1] Turner *et al.* Radiology 1990; 177(2):407–414. [2] Setsompop *et al.* NeuroImage 2012; 63(1):569 – 580. [3] Engström *et. al.* Magnetic Resonance in Medicine 2013; 70(6):1507–1514.[4] O'halloran *et al.* Magnetic Resonance in Medicine 2012; 68(2):430–440. [5] Miller *et al.* Neuroimage 2012, 59(3):2284–97. [6] Freed *et al.* The Journal of Chemical Physics. 2001; 115(9): 42-49.