Diffusion-Weighted SSFP at 7T

Rafael O'Halloran[1], Eric Aboussouan[1], Murat Aksoy[1], Eric Peterson[1], and Roland Bammer[1]
[1]*Radiology, Stanford University, Stanford, CA, United States*

TARGET AUDIENCE – Researchers interested in high-resolution diffusion-weighted imaging at 7T.

PURPOSE – To study the feasibility of DW-SSFP in humans at 7T. DW-SSFP could be a promising candidate for DW MRI at 7T since it is less sensitive to the shorter T2s of human tissue at higher field strength and has a lower SAR burden than spin-echo-based sequences conventionally used.

METHODS – *Signal Calculation:* The field strength dependence of the steady state signal was investigated using the approximations of Wu and Buxton[1] calculated for white matter (WM) and grey matter (GM) using the following parameters: T_1(WM,3T) = 850ms, T_1(GM,3T) = 1200ms, T_1(WM,7T) = 1200ms, T_1(WM,7T) = 2100ms,[2] T_2(WM,3T) = 71ms, T_2(GM,3T) = 68ms, T_2(WM,7T) = 47ms, T_2(WM,7T) = 46ms[3].

MRI: Whole brain DW-SSFP was performed on 2 healthy subjects using 3T and 7T MRI systems (GE, Heathcare) using a 32-channel receive coil (Nova). Parameters were: Flip angle: 25°, Resolution 1.37x1.37x1.37 mm, FOV: 220x220x220 mm, TR: 34 ms, Diffusion gradient 0.4 G/cm x 6 ms, scan time 2.5 min per volume. The readout was a spiral projection trajectory with 4000 interleaves. A single-shot stack-of-spiral navigator was acquired following the diffusion-encoding gradient. Three orthogonal diffusion-encoding directions were acquired. A diffusion-weighted EPI scan with 5mm thick slices, 28 slices, and in-plane resolution of 1.7 mm x 1.7 mm was acquired for an anatomical comparison. For DW-SSFP images, rigid- and non-rigid-body-motion-induced phase corrections were performed prior to reconstruction with iterative SENSE[4]. *B1 Mapping:* To assess the uniformity of the B1 field in the 7T system B1 maps were obtained in Subject 2 using a Bloch-Siegert mapping sequence[5].

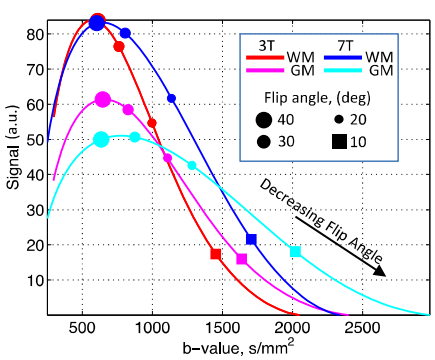

Fig. 1 – The effect of field strength on the DW-SSFP steady-state signal for a range of *b*-values. Note that to change the *b*-value, the flip angle was changed while holding all other parameters constant. Flip angles of 40, 30, 20, and 10 degrees can be located on each curve by their symbols indicated in the legend.

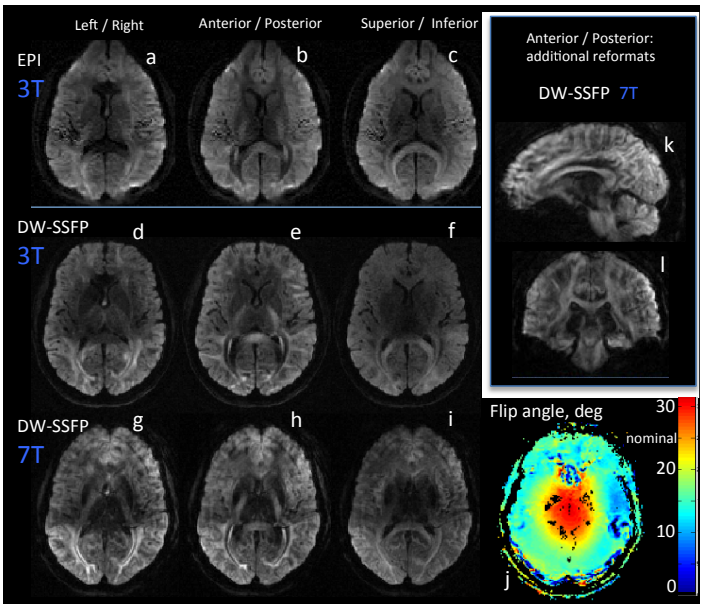

Fig. 2 – Axial reformats from the 3 diffusion-encoding directions from the EPI scan (a-c) and the DW-SSFP at 3T (d-f) and 7T (g-h) with the corresponding flip angle map on the 7T system (j). A sagittal (k) and coronal (l) reformat of the 7T dataset with anterior/posterior encoding are also shown to emphasize the 3D full brain coverage.

RESULTS– Figure 1 demonstrates the field dependence of the steady state signal for WM and GM. Even with the shorter T2's and longer T1's the steady state signal at 7T (light blue and dark blue) is comparable to the signal at 3T (red line and magenta line) for high flip angles and is higher than the signal at 3T at low flip angles. Recall that for DW-SSFP, as the flip angle decreases the b-value increases. This provides an advantage at 7T where the low flip angles are desirable for SAR considerations and the extra signal at high b-values could be exploited. **The reason for the higher 7T signal at low flip angles is the greater contribution of stimulated echo at lower flip angles. Because the spin coherences of stimulated echoes spend time in the longitudinal plane and the T1's at 7T are longer, stimulated echo pathways contribute more at 7T.**

In Figure 2, 3T (Fig 2d-f) and 7T (Fig 2g-i) images from all 3 diffusion-encoding directions acquired in subject 2 are compared to an analogous slice from the EPI scan (Fig 2a-c). Overall the contrast and anatomical structure in the 3T and 7T images are similar to the EPI reference scan with perhaps the exception of the S/I-encoded volume from 3T (Fig 3f). Comparing the 3T to 7T images from the S/I encoded volume (Fig 2f,i) there appears to be greater contrast in in the 7T image. This is likely due to the lower flip angle (on the order of 15 degrees) especially in the outer edge of the brain causing higher b-value and greater contrast. **The lower flip angles also lead to decreased motion sensitivity which, combined with the higher motion in the S/I direction, will lead to higher contrast at 7T due to better phase coherence in the steady state.** Note that, in general, the 7T images are blurrier, likely due to B0 inhomogeneity.

DISCUSSION and CONCLUSIONS – These results indicate that with some B0 and B1 mitigation strategies, DW-SSFP may be a viable alternative to spin-echo EPI at 7T. The blurring seen with DW-SSFP at 7T may be an acceptable trade-off since EPI is limited as well by the B0 blurring and also by gradient strength limitations. With DW-SSFP these limitations can be addressed by the ability to choose shorter readouts and build the image over many shots. Furthermore, these results suggest that perhaps a lower flip angle of around 15 degrees is preferred, not only for 7T but also for 3T DW-SSFP imaging. Lower flip angles trade off some SNR for decreased motion sensitivity and higher b-values with no increase in diffusion gradient duration and hence scan time.

REFERENCES – [1] Wu and Buxton. Effect of diffusion on the steady-state magnetization with pulsed field gradients. J Magn Reson 1990, 90: 243-253. [2] Rooney et al. Magnetic Field and Tissue Dependencies of Human Brain Longitudinal H2O Relaxation in Vivo. MRM 2007, 57:308–318. [3] Cox and Gowland. Measuring T2 and T2' in the brain at 1.5T, 3T and 7T using a hybrid gradient echo-spin echo sequence and EPI. In Proc. ISMSM 2008 #1411. [4] O'Halloran et al. 3D Isotropic High-Resolution Diffusion-Weighted MRI of the Whole Brain with a Motion-Corrected Steady-State Free Precession Sequence. MRM 2013, 70:466–478. [5] Khalighi et al. Adiabatic RF pulse design for Bloch-Siegert B + mapping. MRM 2013, 70: 829–835.

FUNDING – NIH (5R01EB011654, 5R01EB008706, 5R01EB002711, P41 RR009784), the Center of Advanced MR Technology at Stanford (P41RR09784), Lucas Foundation, Oak Foundation.