Image Contrast Enhancement using Selective Adiabatic Pulses that Alternate Frequency Sweep Directions

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Introduction: Selective adiabatic full passage (AFP) pulse trains with single frequency sweep (SFS) direction have been utilized to generate $T_{2\rho}$ contrast in phantoms and human brains [1, 2]. Previous research also demonstrated that enhanced diffusion weighting can be produced using selective AFP pulse trains that alternate frequency sweep (AFS) direction [3]. Preliminary phantom experiments indicated that selective AFP-AFS pulse trains improved image contrast in phantoms in comparison to that of the selective AFP-SFS pulse trains [4]. However, up to date the contrasting mechanism for the AFP-AFS pulses is unclear, and the applicability of the AFP-AFS pulse trains for in vivo imaging is unknown. In this study, further theoretical and experimental work is performed to understand contrast enhancements generated by the selective AFP-AFS pulse trains.

Methods: Bloch equation simulation was conducted to evaluate the transverse magnetization magnitude generated by the AFP-SFS and AFP-AFS pulse trains using the NMRSIM from Bruker ($M_x(0) = M_y(0) = 1/\sqrt{2}$, $M_z(0) = 0$, $B_1(max) = 2297.83$ Hz, pulse length (T_p)= 4 ms, R-factor = 20, size of shape = 1000 points). Imaging experiments were performed on an 11.7 T Bruker Avance 500 micro-imaging system with a Bruker gradient coil utilizing a birdcage transmit/receive RF probe-head (ID = 2.8 cm). AFP-SFS and AFP-AFS pulse trains were constructed using four hyperbolic secant (HS_1) AFP pulses with single- and alternate-frequency sweep directions in adjacent AFP pulses, respectively (R-factor = 20, size of HS_1 shape = 1000 points). A phantom comprised of a plastic tube (ID = 1.5 cm) and three glass vials (ID = 5 mm) was bounded together using paper tapes to form four compartments. The plastic tube was filled with a mixture of 10 micron ORGASOL polymer beads and 100 μM $MnCl_2$ dissolved in 5% agar and formed compartment 1 (C-1). The three vials contained 50, 100, and 150 μM $MnCl_2$ dH_2O solutions and formed compartments 2 to 4 (C-2 to C-4), respectively. Single slice images were acquired from the phantom by varying the echo time (TE) using a customized SE sequence containing paired AFP-SFS/AFS pulse trains for signal intensity (SI) contrast measurements (contrast = $|SI_{(C-1)}-SI_{(C-4)}|/|SI_{(C-1)}+SI_{(C-4)}|$, TE = 50 – 90 ms in steps of 10 ms, TR = 2 s, FOV = 40 x 40 mm^2, Matrix = 256 x 256, slice thickness = 5 mm, number of average = 1, number of dummy scans = 2, MLEV-4 phase cycling, scan time = 8 min 32 s). Single slice images were also collected in vivo from a C57B216 mouse model with middle cerebral artery occlusion (MCAO) 24 hours after the surgery using the customized SE sequence (TE/TR = 49/2000 ms, FOV = 25 x 25 mm^2, Matrix = 128 x 128, slice thickness = 2 mm, number of average = 4, number of dummy scans = 2, MLEV-4 phase cycling, scan time = 8 min 32 s).

Results: Bloch equation simulation results (Fig. 1) indicated that the transverse magnetization magnitude (M_{xy}) generated by the AFP-AFS pulse train was stable and close to the maximum value over the range of RF offset (Ω), whereas the M_{xy} value produced by the AFP-SFS pulse train fluctuated significantly and deviated from the maximum M_{xy} magnitude for different Ω-values. Figure 2 demonstrated that image contrast increased significantly at greater TE values. Images in Figure 3 showed that greater image contrast was generated using the selective AFP-AFS pulse trains than that of the selective AFP-SFS pulse trains both in the phantom and in the stroke mouse model.

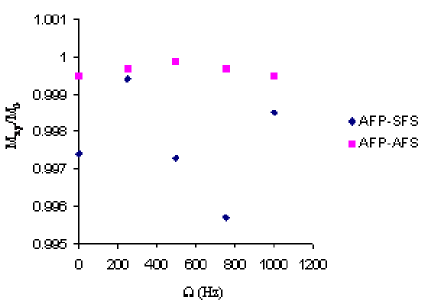

Figure 1. Simulated transverse magnetization magnitude (M_{xy}/M_0) generated by AFP-SFS/AFS pulse trains as a function of RF offset

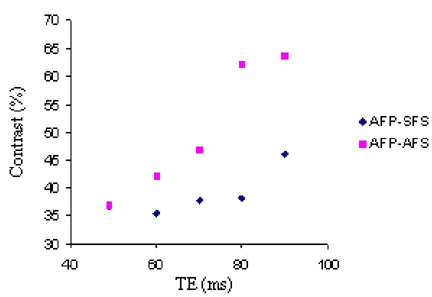

Figure 2. Contrast generated by AFP-SFS/AFS pulse trains as a function of TE for the phantom.

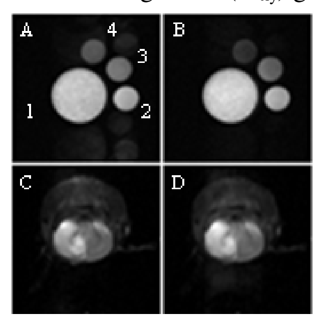

Figure 3. Phantom and mouse brain images collected using AFP-SFS-SE (A, C) and AFP-AFS-SE (B, D) pulse sequences at TE = 80 ms (A, B) and TE = 49 ms (C, D).

Discussion: Simulation results (Fig. 1) suggested that the paired AFP-AFS pulse trains is less susceptible to off-resonance effects associated with selective adiabatic refocusing pulses. Two effects generated by the AFP-AFS pulse trains jointly contribute to the image contrast enhancement. One is the signal sensitivity increase caused by accurate spin refocusing of the selective AFP-AFS pulse trains (Fig. 1). Another is the enhanced diffusion weighting generated by the cumulative nonlinear phase dispersion of the selective AFP-AFS pulse trains [3]. The former effect dominates in the restricted diffusion medium, such as C-1 in the phantom (Fig. 3B) and the stroke lesion in the mouse brain (Fig. 3D), whereas the latter effect becomes apparent in the free diffusion medium at longer TE, such as C-4 in the phantom (Fig. 3B).

References and Acknowledgments: [1] S. Michaeli, et al, J. Magn. Reson. 169 (2004) 293-299. [2] S. Michaeli, et al, Magn. Reson. Med. 53 (2005) 823-829. [3] Z. Sun, et al, J. Magn. Reson. 188 (2007) 35-40. [4] Z. Sun, et al, Proceedings of the 14th Annual Meeting of ISMRM, Seattle, WA, USA, 2005 (Abstract 2999). Thanks to the Small Animal Imaging Center at the Ohio State University for the MRI scan time.