Implementation of a self-refocused adiabatic spin echo pulse-pair modulated using the power independent of the number of slices (PINS) technique for simultaneous B1-insensitive multi-slice imaging

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Introduction: Simultaneous multi-slice imaging using multiband excitation and parallel imaging is a powerful technique to dramatically reduce image acquisition time for studies using functional and diffusion weighted imaging sequences at high field [1]. The technique is especially useful at high magnetic fields, where the increase in signal-to-noise ratio may be parlayed into improved spatial resolution, requiring acquisition of thin slices, while remaining within SAR limits. However, with increased field strength come challenges such as increased B_1 inhomogeneity and RF power deposition. Adiabatic 180° pulses provide B_1-insensitive refocusing of the magnetization but they deposit quadratic phase across the slice that needs to be refocused. A "power independent of the number of slices" (PINS) technique has been shown to be capable of exciting multiple slices without increasing power deposition [2]. We created an adiabatic Shinnar Le-Roux (SLR) 180º PINS pulse and a matched-phase 90º PINS pulse to generate a multi-slice spin echo with refocused quadratic phase and improved immunity to B_1-inhomogeneity. This may be applied to accelerate any spin echo imaging technique at 3 and 7 T.

Method and Simulations: We used the SLR algorithm to generate an adiabatic refocusing pulse [4] which was modulated with a comb function to produce a 180° adiabatic PINS pulse with a duration of 14 ms. The $\beta_{180°}$ polynomial calculated during the creation of the refocusing pulse was used to design a $\beta_{90°}$ for a matched-phase 90° pulse [3]. Fig. 1 shows the adiabatic 180° and matched-phase 90° RF pulse waveforms and the corresponding gradients (interleaved with the nulls of the RF pulses). At adiabatic threshold, the maximum amplitudes of the 180° and 90° pulse were 9.8 µT and 6.3 µT. The slice profile for the pulse was simulated for B_1 amplitudes at and above adiabatic threshold by 10% - 40%, to test B_1-insensitivity; Fig. 2 shows the resultant slice profiles. There is some variation in slice amplitude due to the non-adiabatic 90° and some failure of phase-matching for RF amplitudes above adiabatic threshold, but the multiband slice profile shape and magnitude is largely maintained for approximately a 30% change in B_1. The frequency of the comb for the matched-phase pulse is twice that of the adiabatic 180° and the magnitude of the gradient is twice as large during excitation as it is during refocusing, in order to maintain refocusing of the quadratic phase. The pulses were integrated into a spin-echo sequence with the following parameters: TE = 42.6 ms, TR= 600 ms, FOV=24 cm, matrix size =64x64. Images were made of a cylindrical phantom at 3T (GE Whole Body Magnet) for three different gradient amplitudes.

Results: Figures 3 A and B shows the simulation and phantom image of the slice profile obtained for one gradient amplitude. Figures 3 C and D demonstrate the effect of increasing the amplitude of the multi-slice select gradients that are interleaved with the RF pulses. The initial gradients produced a slice periodicity of 5.6 cm and a slice thickness of 2.2 cm. Increased gradient amplitude, at the same sampling frequency, result in thinner slices, and a higher spatial-frequency for excitation. A 29% increase in gradient amplitude changed the periodicity to 4.5 cm and thickness to 1.8 cm, while increasing the amplitude by 70% changed the periodicity to 3.2 cm and thickness to 1.3 cm. To obtain these images, the read-out direction was altered to play in the slice-select direction, so the images obtained are projections through the excited bands that demonstrate the multi-slice profile. When used in imaging sequences, the readout will be in the in-plane direction.

Discussion: We implemented a spin-echo sequence using an adiabatic SLR PINS to refocus multiple slices simultaneously. A matched-phase 90° pulse was used to refocus the phase in the echo. Previous work has combined the PINS and an adiabatic VERSE-DANTE pulse for inversion [5]. The adiabatic SLR PINS approach presented here achieves low RF pulse amplitude by spreading the RF energy uniformly over the pulse waveform, is less sensitive to off-resonance, and enables the creation of a matched phase 90° pulse to refocus quadratic phase, so that the adiabatic PINS 180° may be used to produce a spin echo. The sampling frequency and gradient amplitude chosen here can be changed to obtain the desired slice thickness and separation for a particular application. Greater slice separation can be achieved by increasing the sampling frequency for the PINS pulse pair. Multiband approaches may be coupled with parallel imaging to simultaneously excite and disentangle several slices. The adiabatic PINS SE sequence with the matched-phase excitation results in greater immunity to B_1-inhomogeneity and reduced RF power for multi-slice acquisition. Future work will be focused on applying this technique *in vivo* to accelerate diffusion tensor imaging at 7T.

References: [1] Feinberg DA, et al. J Magn Reson Imaging. 2012 Jun;35(6):1274-89. [2] Norris D, et al. Magn Reson Med. 2011 Nov; 66(5):1234-1240. [3] Balchandani P, et al. Magn Reson Med. 2012 Apr; 67(4):1077-1085. [4] Balchandani P, et al. Magn Reson Med. 2010 Sept; 64(3):843-51. [5] Koopmans PJ, et al. Magn Reson Med. 2013 June;69(6):1670-1676.

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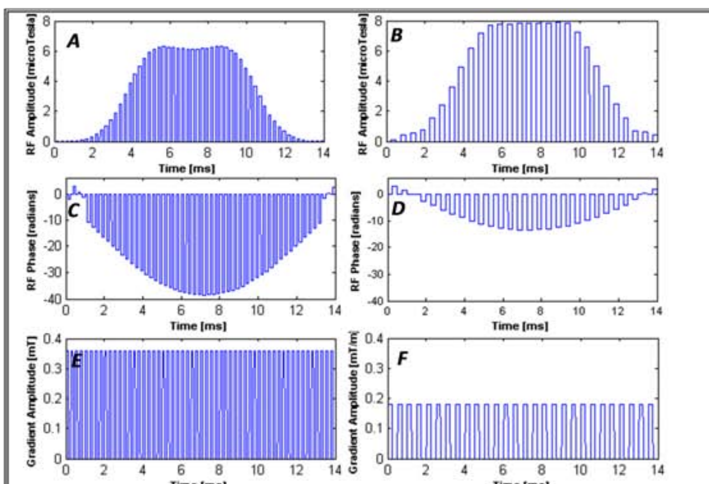

Figure 1: *Amplitude and phase of the matched-phase 90° pulse (A,C) and adiabatic multi-band 180° pulse (B,D). The amplitude of the multiband slice-select gradient interleaved with the 90° pulse (E), and the 180° pulse (F).*

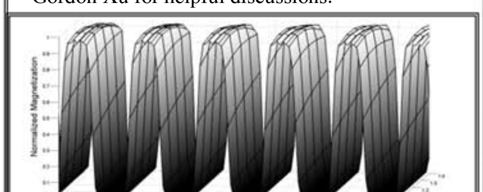

Figure 2: *Simulated multi-slice spin echo profile for 3 different B_1 amplitudes above adiabatic threshold*

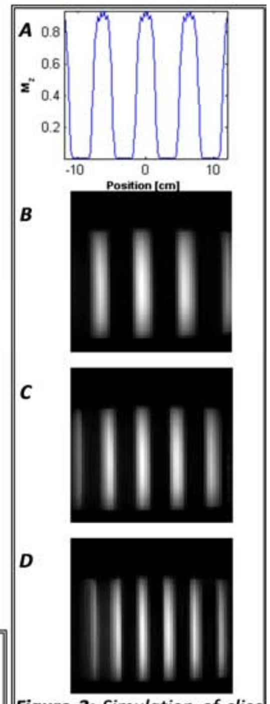

Figure 3: *Simulation of slice profile using g_{ex}=0.36 mT/m and g_{ref}=0.18 mT/m (A). Images acquired at the initial amplitude (B), 28% increase in gradient amplitude (C) and 70% increase in amplitude (D).*