Fast Spin Echo Imaging with Quadratic Phase-Modulated non-CPMG Echo Train in Parallel Transmit – a Simulation Study

S-K. Lee[1], M. W. Vogel[2], W. A. Grissom[2], G. C. McKinnon[3], and P. H. Le Roux[4]
[1]GE Global Research, Niskayuna, NY, United States, [2]Advanced Medical Applications Laboratory, GE Global Research, Munich, Bavaria, Germany, [3]Applied Science Lab, GE Healthcare, Waukesha, WI, United States, [4]Applied Science Lab, GE Healthcare, Palaiseau, France

Introduction: Removing phase constraint in parallel transmit (pTx) RF pulse design is known to improve the homogeneity of amplitude images [1,2]. This approach, however, is not directly applicable to fast spin echo (FSE) imaging because of violation of the CPMG condition. In order to meet this condition, joint design of excitation and refocusing pulses has been proposed [3]. Here we explore an alternative approach of using quadratically phase modulated RF pulses [4] to form multiple spin echoes in the non-CPMG regime. Numerical simulation shows that non-CPMG FSE implemented by simultaneous phase modulation in all transmit channels successfully produces homogeneous amplitude images with phase-relaxed pTx RF pulses.

Theory: For a given RF pulse in pTx, simultaneous and identical phase modulation in all channels produces the same phase modulation in the total transmit RF field at a given voxel. Le Roux's nCPMG method consists of modulating refocusing RF pulse phases quadratically in a predefined fashion, following a 7-echo preparation period [4]. Both in- and out-of-phase spin components contribute equally to the ensuing echo train to allow uniform amplitude image reconstruction insensitive to the CPMG condition. For receiver phase compensation, double scan of half k-space or off-line calibration have both been demonstrated experimentally [4].

Results: Spokes-trajectory-based, slice-selective excitation and refocusing pulses were designed [5] with N_{sp} = 1,3,5,7 without phase constraint using simulated B_1^+ maps in a male pelvis in a 8-ch TEM body coil. Figure 1 shows designed pulse shapes and Bloch-simulated, isolated pulse performances. Note significant variation in the nutation and excitation phases. We conducted fast FSE simulation using the z-polynomial formalism [6] on all 16 combinations of the designed 90 and 180 pulses. For Le Roux's nCPMG sequence, published phase formula [4] was used for quadratic modulation and preparation, and double k-space scan was emulated for image reconstruction. In order to focus on the RF phase effect, we chose a single, relatively long echo spacing (esp) of 10 ms to fit the longest, 7-spoke RF pulse. With quadratic phase modulation, it is verified that both real and imaginary components of the echo signal decay similarly, i.e., per T_2 (Fig. 2). Figure 3 shows the images for all RF combinations, demonstrating RF phase-insensitive image homogeneity in nCPMG FSE as compared to conventional FSE. Lower overall image intensities in the nCPMG case are due to T_2 decay in the preparation period; as esp is reduced, nearly full signal is recovered (Fig 3. inset).

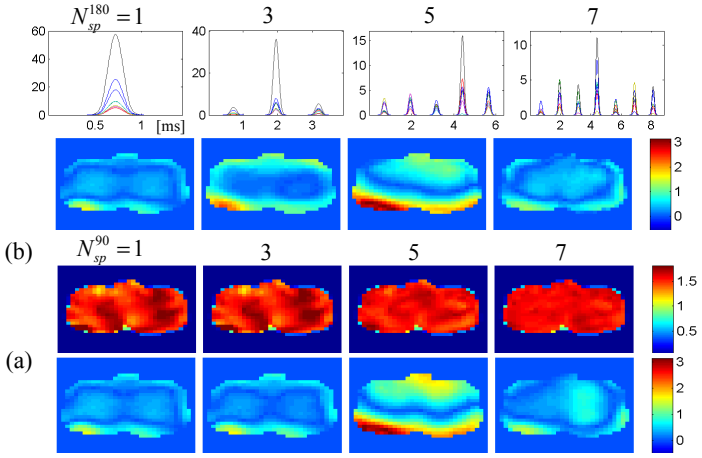

Figure 1. (a) Eight channel RF amplitudes (top) and nutation axis phase maps (bottom, in rad) for N_{sp}^{180}-spoke refocusing pulses. (b) Tip angle (top) and excitation phase (bottom) of N_{sp}^{90}-spoke 90° pulses (not shown).

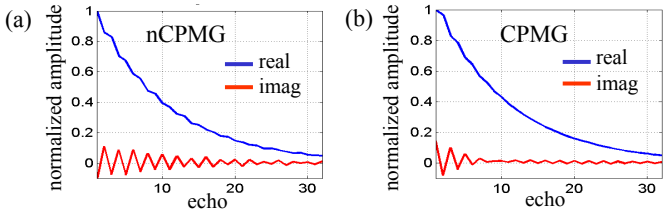

Figure 2. Complex echo amplitude decay in quadratic phase-modulated FSE (a), and conventional FSE (b). RF pulses used are a 7-spoke 90 pulse followed by a train of 1-spoke 180 pulses. T_2/esp = 100/10ms.

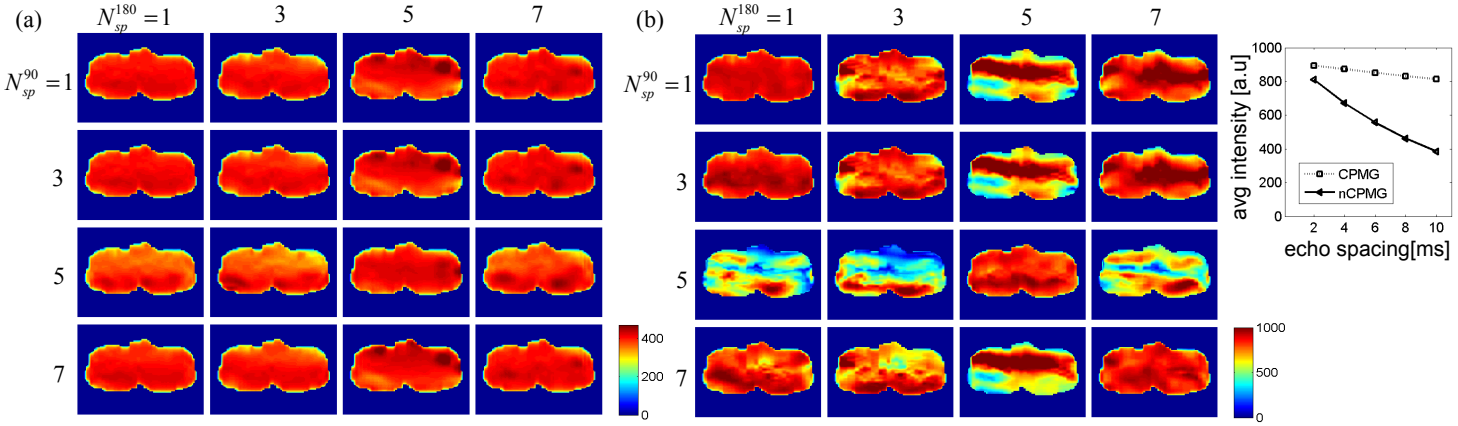

Figure 3. Simulated FSE images with quadratic phase-modulated (a), and CPMG (b) echo train with 4×4 combinations of spokes 90°/180° pulses. T_1/T_2/TE/shots = 1 s/100 ms/10 ms/4. Echo spacing was 10 ms in all cases. Inset on the far right shows image intensity vs esp for a 7-spoke 90° pulse followed by 1-spoke 180° pulses.

Discussion: Le Roux's nCPMG FSE allows recovering nearly full signal in a long-echo-train FSE in the presence of spin/RF phase mismatches. We find that quadratic phase modulation can be implemented in pTx to enable FSE imaging with phase-unconstrained RF pulses. The extra degrees of freedom in RF design could be used to better manage SAR.

References: [1] Kerr AB et al, Proc. ISMRM 1694 (2007) [2] Setsompop K et al, MRM 59:908 (2008) [3] Xu D et al, Proc. ISMRM 174 (2009) [4] Le Roux P, JMR 155:278 (2002) [5] Grissom WA et al, Proc. ISMRM 99 (2010) [6] Le Roux P et al, MRM 30:183 (1993).

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