Nonlinear-Phase Multiband 90°-180° RF Pair With Reduced Peak Power

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Purpose: Multiband RF pulses are central to signal excitation in simultaneous multislice (SMS) acquisitions [1-4]. The peak amplitude of a multiband pulse increases with the number of simultaneously excited bands. To avoid long pulse duration, the peak amplitude of the multiband pulse needs to be reduced [5,6]. Here we design nonlinear-phase multiband pulses with reduced peak amplitude compared to linear-phase pulses. We use a pair of 90°-180° nonlinear-phase multiband pulses to generate linear-phase echoes.

Methods: The pulse design steps are:

1. Design a single-band nonlinear-phase spin-echo (SE) pulse that has lower peak amplitude than a linear-phase pulse. Two alternative methods can be employed for this step. **(A) Quadratic-phase design**: First design a linear-phase SE pulse using the SLR algorithm [7], then design a quadratic-phase SE pulse by setting $F_q(\omega) = F_l(\omega)\exp(ik\omega^2)$, where $F_q(\omega)$ and $F_l(\omega)$ are the frequency profiles of the quadratic-phase pulse and the linear-phase pulse, respectively, $\omega \in [-\pi, \pi]$ is the normalized frequency, and k is a variable controlling how much quadratic phase is added. **(B) Min-flip design**: First design a minimum-phase SE pulse, then design a nonlinear-phase SE pulse by flipping the passband zeros of the Beta polynomial of the minimum-phase pulse and searching through all possible root combinations for a pulse with minimum peak amplitude.

2. Design a single-band phase-matched excitation pulse. The 90°-180° pulse pair is able to generate a linear-phase spin echo. To achieve this, we set the Beta polynomial of the 90° pulse to be $\beta_{90} = \beta_{180}^2/\sqrt{2}$, where β_{180} is the Beta polynomial of the SE pulse designed in step 1.

3. Modulate the single-band pulses into multiband pulses. The multiband pulse is $RF_m(t) = \Sigma_n RF_s(t)\exp(i\cdot 2\pi\cdot f(n)\cdot t)\exp(i\theta(n))$, where n=1...N is the index for the individual bands, RF_s is a single-band 90° or 180° pulse, f(n) is the center frequency of the n^{th} band, and θ(n) is a reference phase added to the n^{th} band to further reduce the peak amplitude of the multiband pulse. There are two choices for θ(n). (A) Use the optimal phase schedule determined by exhaustive search [8]. (B) Let $\theta(n) = cn^2$, where c is a constant. This adds a quadratic phase in the slice direction and is a very close approximation to the optimal phase schedule.

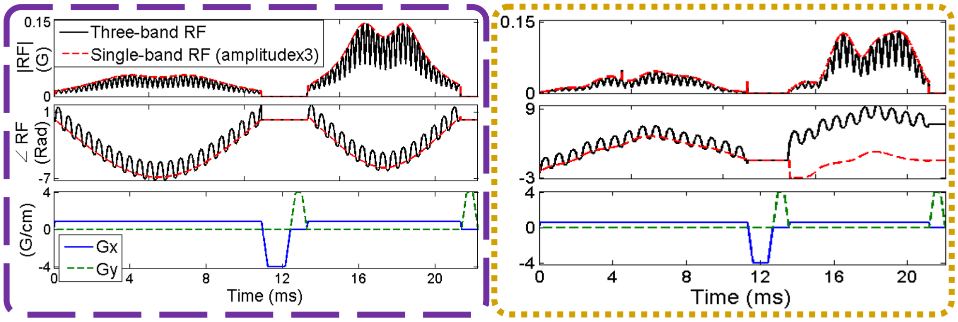

Fig. 1. RF and gradient waveforms of 3-band 90°-180° quadratic-phase (left panel) and min-flip (right panel) pulse pairs. Single-band 90°-180° pulse pairs are also plotted for comparison.

Results: Fig. 1 displays the RF and gradient waveforms of 3-band quadratic-phase (left panel) and min-flip (right panel) 90°-180° RF pairs. The peak of the nonlinear-phase SE pulse is reduced to 44% (quadratic-phase design, TBW=6) and 61% (min-flip design, TBW=4) of a linear-phase SE pulse. The optimal phase schedule [8] is used when the single-band pulses are modulated into multiband pulses, and the peak of the 3-band pulse is reduced by 26% compared to directly summing the 3 bands. Fig. 2 displays the measured and simulated slice profiles of the 3-band quadratic-phase (upper panel) and min-flip (lower panel) 90°-180° pairs. The slice profiles are measured on a GE 3T MR750 scanner using a single channel receive coil. The RF and gradient waveforms in Fig.1 are used as the excitation and refocusing pulses to acquire spin-echo images. Fig. 2 shows that an excited band exhibits nonlinear in-slice phase after the 90° pulse alone is applied, but generates a linear-phase echo after the 90° and 180° pulses are both applied. The frequencies excited earlier by the quadratic-phase pulse experience more T_2 decay, which causes tilting of the measured profile in the passband. The out-of-slice phase difference between measurement and simulation is simply caused by the poor SNR out-of-slice.

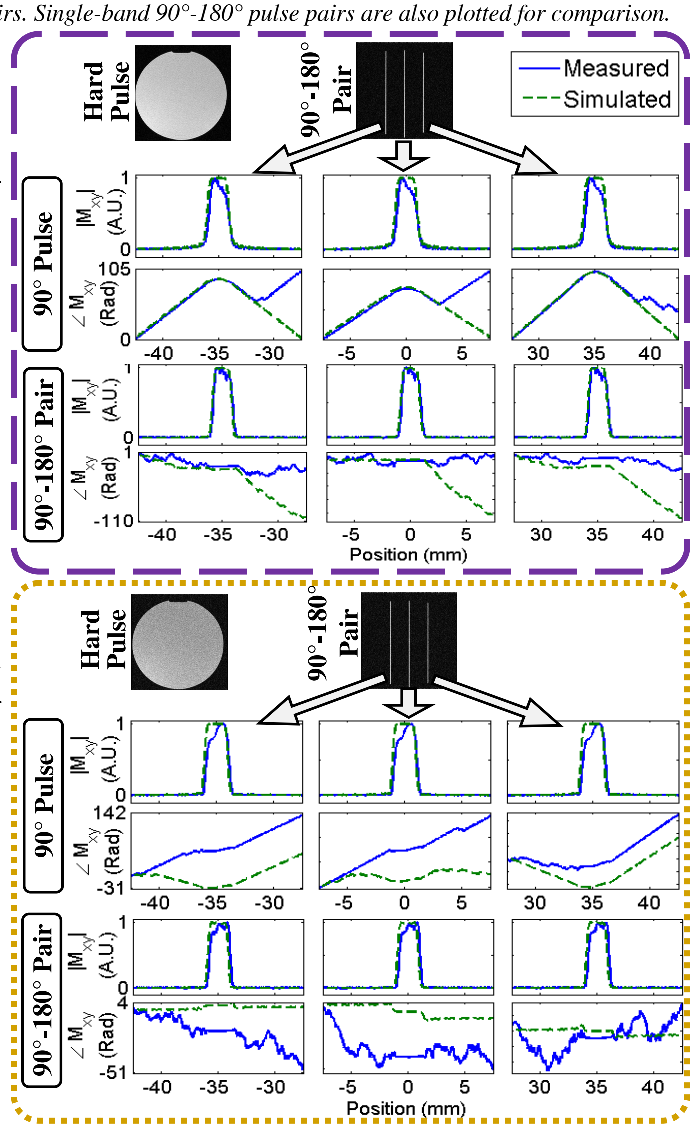

Fig. 2. Measured and simulated RF profiles of 3-band quadratic-phase (upper panel) and min-flip (lower panel) 90°-180° pairs. Slice thickness is 2mm, band gap is 35mm. Slice profiles are calculated by dividing the image acquired using the multiband pulse by the image acquired using a hard pulse. The slice select direction is the same as the readout direction, and the slice profile is averaged along the phase encoding direction. The 90°-180° pair refocuses the in-slice phase. The out-of-slice phase is not of interest here. Tilting of the measured profiles are caused by T_2 effects, which are ignored in the simulation.

Discussion and Conclusion: In this work, nonlinear-phase multiband 90°-180° pulse pairs with reduced peak amplitude are designed. In the quadratic-phase design, trade offs must be made between the truncated RF pulse duration, peak power reduction and slice profile fidelity. In the min-flip design, the RF pulse does not need to be truncated and generates a sharp slice profile. The nonuniform magnitude in the passband of the nonlinear-phase pulse is of minimal concern as long as the pulse duration is short compared to the T_2 value of the tissue being imaged, because of signal averaging over the entire slice. Compared to the Power Independent of Number of Slices (PINS) [5] multiband pulses, the proposed pulses do not excite signal outside the volume of interest. Compared to the time-shifted multiband pulse [6], the proposed pulse is able to introduce the same effective echo time to each individual slice and meanwhile align all echoes in time.

References: 1. Moeller S, et al. MRM. 2009;63:1144-1153. 2. Setsompop K. et al. MRM. 2012; 67: 1210-1224. 3. Feinberg DA, et al. PLoS One 2010;5:e15710. 4. Breuer FA, et al. MRM. 2005;53:684-691. 5. Norris DG, et al. MRM. 2011;66:1234-1240. 6. Auerbach EJ, et al. MRM. 2013;69:1261-1267. 7. Pauly J, et al. IEEE Trans Med Imaging 1991;10:53-65. 8. Wong E. ISMRM. 20 (2012). p. 2209.