Root-Flipped Multiband Radiofrequency Pulses

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Target Audience Researchers interested in simultaneous multislice (SMS) MRI.

Introduction Multiband pulses used in SMS imaging are conventionally generated as a sum of single-slice-selective pulses. Because of this, the peak RF amplitude increases linearly with number of excited slices [1]. For a large SMS slice-acceleration factor the pulse may quickly reach the peak power limit of the RF amplifier and the SAR limits. This is principally a problem for multiband refocusing pulses used in spin echo SMS imaging. It has been shown that applying optimal phases to each slice-select pulse prior to summation can reduce the peak power of a multiband pulse [1,2]. Another approach is to shift the single-slice pulses in time before summation so that their main lobes do not coincide [3]. We propose a method to design multiband refocusing and matched excitation pulses based on the SLR method [4] and root flipping [5,6]. Compared to both phase-optimized and time-shifted pulses the proposed method achieves significantly shorter pulse duration for a given peak RF power.

Theory Figure 1(a) shows that for a pulse designed using the SLR algorithm, the timing of the main lobe depends on the position of its β filter's passband roots relative to the unit circle. Therefore, as illustrated in Fig. 1(b), the passband roots of each band of a multiband pulse can be configured so that the main lobes of the bands do not coincide, leading to a lower peak power compared to direct summation. To design multiband pulses, first a minimum-phase multiband β filter is designed for the refocusing pulse. Then a Monte Carlo method is used to find the optimal root configuration that evenly distributes the pulse's energy over its duration. To design a minimum phase β filter, a linear phase filter is first designed whose magnitude response equals the square of the minimum phase filter's magnitude response. The linear phase β filter b is designed by solving a convex optimization problem which minimizes the passband and stopband ripples of the filter response. After b is designed, the minimum phase β filter's magnitude response is computed as the square root of b's magnitude response, and the phase response is the Hilbert transform of b's log-magnitude response. Once the complex-valued response is formed, the final minimum phase filter β is calculated as its IDFT.

After the minimum phase multiband β filter is designed, to efficiently search the space of root-flipping patterns a Monte-Carlo optimization approach is used [7]. In each Monte-Carlo trial, a randomly selected set of roots is flipped by replacing it with the complex conjugate of its inverse. After the roots are flipped, they are multiplied back out to obtain the root-flipped β filter coefficients, and the inverse SLR transform is used to transform these coefficients and the corresponding minimum-phase α filter coefficients into the corresponding RF pulse. The RF pulse with the minimum peak magnitude across all Monte Carlo trials is saved as the output of the minimization.

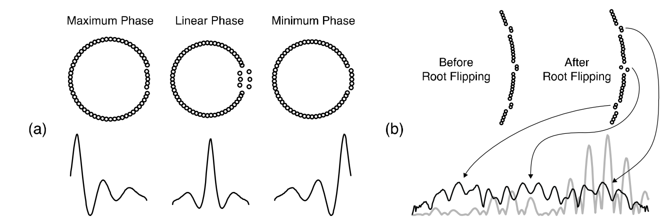

Figure 1: *(a) The position of the complex passband roots with respect to the unit circle determines the position of the main lobe within a single-band pulse. (b) To minimize the peak amplitude of a multiband pulse, the passband roots of each band can be configured so that its main lobe does not coincide with the other bands' main lobes.*

Methods Simulations were performed to compare the phase-optimized, time-shifted and the proposed root-flipped pulses. Pulses were designed over a range of time-bandwidth products (TB = 4 to 10), number of bands (N_b = 2 to 10), and band separation (Δ = 2 to 40 slice widths). The pulse durations were computed subject to peak $|B_1|$ of 13μT. Phantom and in vivo experiments were performed on a 7T Philips Achieva scanner (Philips Healthcare, Cleveland, OH) with a birdcage coil and a 32-channel receive-only head coil. Phantom experiments compared the signal profile of a 3-band root-flipped pulse to that of a 3-band aligned-echo time-shifted pulse with the same slice characteristics. Both the pulses were designed with TB = 4 to excite 3 slices of thickness 3 mm and slice gap of 3 cm. The echo times were set to minimum allowed values, which was 28.3 ms for time-shifted and 17.6 ms for root-flipped pulses and TR=321 ms, FOV=20×20×26 cm and 1600×1600×13 matrix size. In vivo experiments used a TB = 4 root-flipped pulse to excite 3 slices with 3 cm slice gap and 3 mm slice thickness. Images were acquired with TR/TE of 237/17.6 ms, FOV 24×24×16 cm and 480×480×16 matrix size.

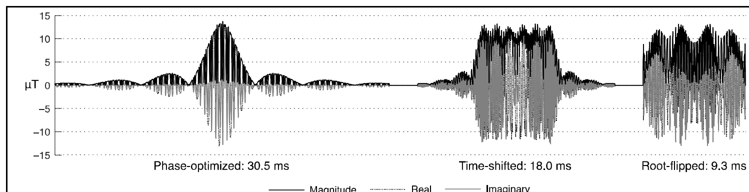

Figure 2: *Comparison of six-band time-bandwidth product 6 pulse shapes designed by phase optimization, time-shifting and root-flipping for a peak RF magnitude of 13 μT. The root-flipped pulse has significantly shorter duration.*

Results and Discussion Figure 2 shows that for a peak $|B_1|$ of 13 μT the proposed pulses have the shortest duration of 9.3 ms, compared to phase-optimized and time-shifted pulses which are of duration 30.5 ms and 18 ms, respectively. Figure 3(a) plots the duration of TB = 6 pulses designed by the three methods as a function of number of bands, averaged across band separations. Figure 3(b) plots the durations of 5-band pulses as a function of TB. Averaged across number of slices, TB product and slice separation, the root flipped pulses have 46% shorter durations than time-shifted pulses with the same peak amplitude. In Fig. 4 the measured and simulated slice profiles are plotted for both time-shifted and root-flipped pulses. The shorter root-flipped pulse allowed a shorter TE of 17.6 ms compared to 28.3 ms for the time-shifted pulse, resulting in less T_2 decay and higher signal. The in vivo slice profiles in Fig. 5 show that the root-flipped pulse excited the desired slices at the target locations and slice thickness.

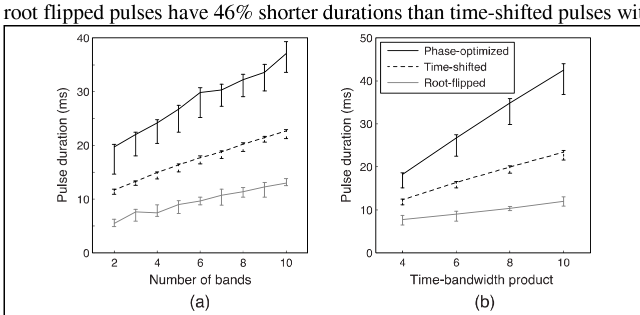

Figure 3: *Durations of multiband pulses subject to 13μT maximum |B1+|. (a) Duration versus number of excited bands, for a time-bandwidth product of 6. (b) Duration versus time-bandwidth product for 5 bands. Error bars indicate maximum and minimum durations.*

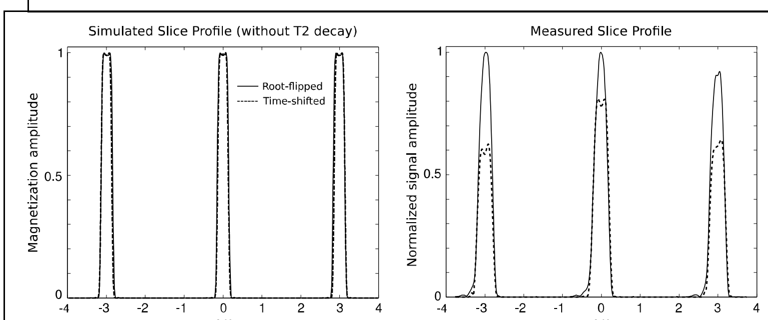

Figure 4: *(Left) Bloch simulations showed that without T_2 decay, both time-shifted and root-flipped pulses produce maximum signal at the desired locations. (Right) In the experiment, the shorter root-flipped pulse allowed a shorter TE, resulting in less T_2 weighting and higher signal.*

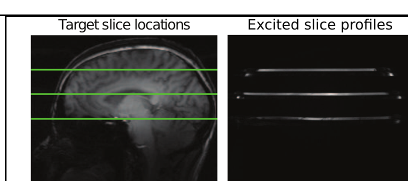

Figure 5: *Root-flipped pulse slice profiles measured in a human head at 7 T.*

Conclusion We have described a method to design multiband refocusing pulses that are of shorter duration than existing pulses for the same peak RF amplitude.

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