A perfectly refocused RF pulse design using zero-padding

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Introduction

RF excitation pulses for large flip angles can be designed very accurately by the well-known SLR algorithm [1]. The conventional SLR algorithm computes beta B(z) and alpha A(z) polynomials based on the flip angle profile and then calculates RF pulse using inverse SLR recursion. If the linear phase solution is selected for beta in the polynomial calculation, the corresponding minimum phase alpha will contribute some small non-linear phase to the excitation profile, which is 2 A*(z) B(z). This phase in the alpha profile can be precompensated in the beta profile before the inverse SLR transform. However, additional phase (typically ripples) still exists in the excited profile. This residual phase causes problems in some circumstances such as the STEAM sequence in MR spectroscopic imaging [2], where this residual phase must be correct in post-processing. In this work, we propose an improved algorithm for perfectly refocused RF excitation pulses using zero-padding techniques.

Method

The pulse design algorithm consists of the following steps: 1) choose a flip angle profile, compute beta profile; 2) compute beta polynomial using linear phase solution; 3) compute alpha polynomial using minimum phase solution; 4) zero-pad alpha and beta polynomials; 5) compute the phase of alpha profile, add back to beta profile, and then recalculate beta polynomial using Fourier transform; 6) compute RF pulse using inversion SLR recursion.

Depending on the way of zero-padding is done, there are several variations of this algorithm. Each has its own pros and cons, as will be illustrated in the results section. The first option is zero-padding the beta polynomial on both sides and alpha polynomial on the left side (high order side). As a consequence, the RF pulse is expanded on both sides, and the residual phase is compensated perfectly. The disadvantage, however, is that the echo time is increased. The second option is zero-padding both beta and alpha polynomials on the left side (high order side). This results in left side (negative direction on the time axis) expansion of the RF pulse. The echo time is then almost the same as that without zero-padding. However, the effectiveness of the residual phase reduction is also reduced. The third option combines the strengths of the above two options. It starts the design with a small number of data samples, and then expands the RF pulse to the desired size, using the zero-padding techniques as in the first option. Nonetheless, the RF pulse becomes less selective, since the transition band in the excited profile is increased.

Results

The algorithm has been tested by 1D simulation. Denoting N as the number of data samples, TBW as the time-bandwidth product that are used in the alpha and beta profile design before zero-padding, A_l (A_r) as the ratio of left (right) side zero-padding sample number to N, Fig.1 shows the RF pulses and the excited profiles using phase precompensation, without zero-padding and with different zero-padding modes (TBW is changed accordingly to keep the bandwidth of the excited profile the same). Fig. 1 a) and b) illustrate that increasing the number of data samples only cannot effectively reduce the residual phase, although the RF pulse becomes more selective. Fig. 1 c), d) and e) apply the three zero-padding options as described in the previous section, respectively. These results also manifest the pros and cons as discussed above. More phase suppression could be achieved if a larger number of zero-padding samples are used.

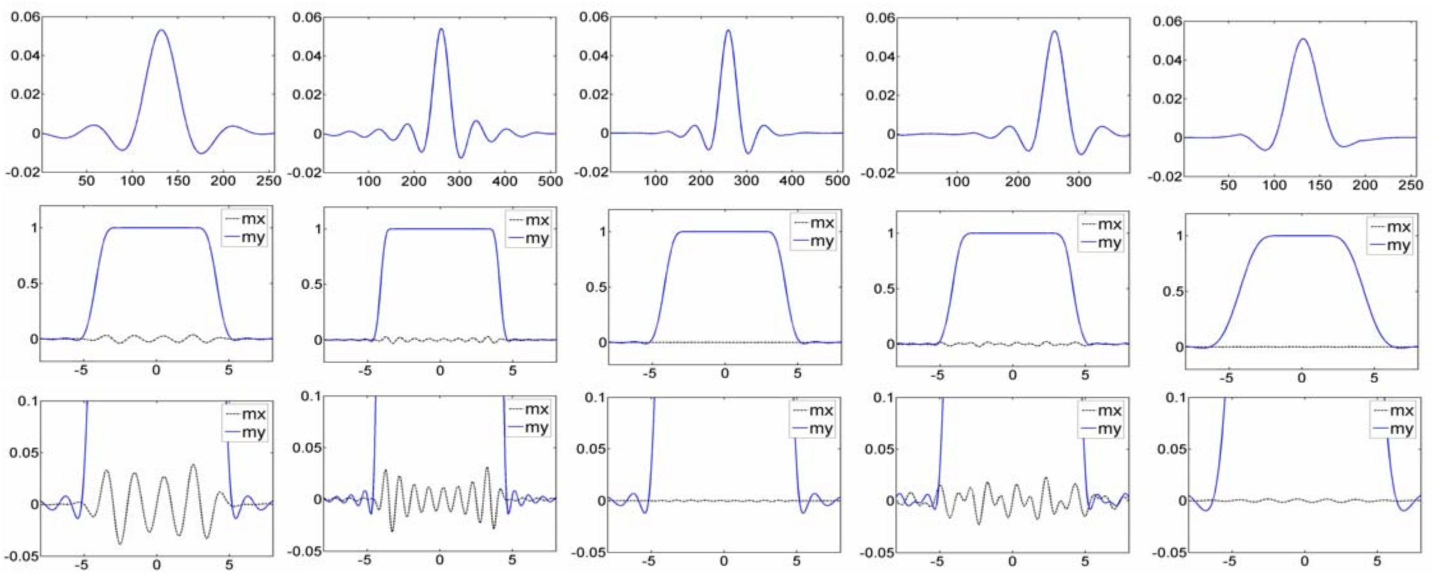

Fig. 1 RF pulses and simulated 1D excitation profiles, using the improved inverse SLR algorithm (linear phase corrected, use equal-ripple filter in the beta profile design, with δ_1=0.01, δ_2=0.01, flip angle=90 degrees). Top row: RF pulses; middle row: real and imaginary excited profiles; bottom row: zoom-in images of the middle row. a) N=256, A_l=A_r=0, TBW=8; b) N=512, A_l=A_r=0, TBW=16; c) N=256, A_l=A_r=0.5, TBW=8; d) N=256, A_l=0.5, A_r=0, TBW=8; e) N=128, A_l=A_r=0.5., TBW=4.

Conclusion

Simulation results show that the zero-padding techniques can effectively suppress the residual phase after the beta profile phase precompensation. Three modes of zero-padding are suggested in this work as well. The choice of these modes in practice is a trade-off among effectiveness of phase suppression, echo time and pulse selectivity. Future work includes physical experiments using this RF pulse design, in the applications where perfectly refocused excitation is desired.

Reference

1. Bernstein et al., Handbook of MRI pulse sequences, 2004: pp.43-58.
2. Frahm et al., J. Magn. Reson., 1987 (72): pp.502-508.

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