Improved Slice Profiles Using Low-Ripple Numerically Optimized SINC Pulses

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Purpose

A great deal of interest is associated with developing RF pulses which produce as close to ideal slice profiles as possible while remaining easily implemented on an MRI console. A number of methods have been proposed to compensate for the truncation effects on slice profile produced when using finite RF pulses. Examples include the Shinnar-Le Roux (SLR) (1) and discrete inverse scattering (2) algorithms. Presented here is a simple and flexible method for use with any RF pulse waveform to improve slice profile through numerical optimization offering greatly reduced rippling.

Methods

All RF pulses were calculated using the Python 2.3 scripting language with Numpy, Scipy and Matplotlib third-party add-ons on a standard PC computer. Similar in principle to the design of BURP pulses (3), the RF waveform of duration *T* takes the form:

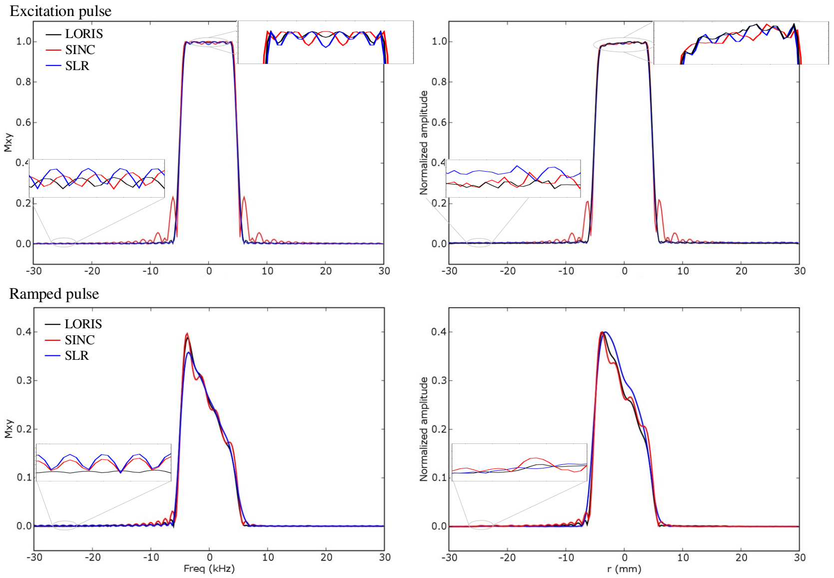
$$\gamma B_1(t) = \frac{2\pi}{T}\left(A_0 + \sum_{i=1}^{N} A_i \cos\left(\frac{2\pi i t}{T}\right) + B_i \sin\left(\frac{2\pi i t}{T}\right)\right) \qquad [1]$$

Design of symmetric pulse with time-bandwidth product TB begins with setting the initial set of coefficients A_N to the first several coefficients of the discrete cosine transform of the equivalent SINC waveform (the coefficients B_N are set to 0 for symmetric pulses). This set of coefficients is then optimized using a quasi-Newton algorithm minimizing the difference between the target slice profile ($M_{xy} = 1$ in the passband and $M_{xy} = 0$ in the stopband regions) and the slice profile calculated via Bloch simulation. After optimization, the number of coefficients *N* is increased by one and the process repeated until no further improvement is obtained. The resulting low-ripple SINC (LORIS) waveform is symmetric with linear phase.

Ramped LORIS pulses were synthesized by fitting the A_N coefficients (real transmit channel) and B_N coefficients (imaginary transmit channel) to a trapezoidal target profile as above, where M_{xy} decreases from 30° to 15° in the passband and is 0 in the stopband. For comparison, a 30°-to-15° ramped SLR pulse in the time domain was generated by applying a ramp in the frequency domain for a TB 8 small tip angle 0.5% equiripple SLR pulse.

RF waveforms were implemented on a 0.2 Tesla TMX MRI console (4). Slice profiles were obtained on a uniform $CuSO_4$-doped cylindrical phantom using a gradient echo sequence for excitation pulses and a spin echo sequence for the refocusing pulses with the readout applied in the slice-select direction. The nominal slice thickness was 10 mm with a 60 mm projection length. All pulses were 4 ms in duration and 256 points acquired.

Figure 1. Top: Comparison simulated (left) and measured slice profiles (right) for a TB 8 SLR (equiripple, 0.5%), SINC and low-ripple SINC (LORIS) excitation (upper) and 2:1 ramp ratio TB 8 LORIS, SINC and SLR ramped (lower) rf pulses.



Results

Simulated and measured slice profiles for a TB 8 LORIS pulse is shown in Figure 1. The decreased rippling obtained using the LORIS waveform resulted in better performance (as measured by sum-of-squares error) in both the stopband (excitation: 0.0016 vs. 0.0018; refocusing: 0.00009 vs. 0.0002) and passband (excitation: 0.0036 vs. 0.0096; refocusing: 0.0078 vs. 0.0088) than equiripple SLR pulses. Similar results were obtained for LORIS refocusing pulses (passband: 0.0078 vs. 0.0088 for a TB 8 0.5% equiripple SLR pulse; stopband: 0.00009 vs. 0.0002).

Both ramped LORIS and SLR TONE pulses both produced ramped profiles, but the LORIS TONE pulses better resembled the target slice profile in both the passband (0.0025 vs. 0.0050) and stopband (0.0014 vs. 0.0059) than the SLR TONE pulse.

Discussion

The number of coefficients defining the LORIS waveform tends to increase with increasing TB product. Both the theoretical and measured slice profiles of the LORIS excitation pulses are significantly closer to the ideal slice profile. Side lobes characteristic of SINC pulses are essentially absent in LORIS slice profiles. Slice profiles of refocusing LORIS pulses are greatly improved over those from SINC pulses at the expense of increased B_1 peak amplitude, and hence greater SAR (as are SLR pulses). However, since the nominal slice thickness using LORIS pulses is maintained, the need to decrease the slice select gradient strength to compensate when SINC pulses are used is unnecessary. Performance of both the excitation and refocusing LORIS pulses was improved relative to equiripple SLR pulses. In addition, SLR pulses cannot be optimized to include relaxation effects.

In the method outlined here, pulses can be tailored to include relaxation with additional relaxation terms to the Bloch simulation and the weighting of the stopband can be changed by scaling the error function in that region. Waveforms for generating irregular target slice profiles, such as ramped slice profiles or multiple-slice excitation, can be created through proper design of the target function.

Conclusions

The use of pulses developed with this method allows for improved slice profiles. While similar in performance to SLR pulses, the decreased rippling in the stopband region of LORIS pulses allows use of smaller interslice gaps in multi-slice imaging, providing better volume localization in spectroscopy. Since the actual slice width obtained using the optimized refocusing pulse is maintained, increased S/N is expected for spin echo-based sequences over the use of SINC pulses. The method described here has increased flexibility allowing the design of pulses that the SLR transform is unable to produce easily, such as ramped pulses for angiography.

References

1. Pauly J, et al, *IEEE Trans Med Imaging* **10**, 53 (1991).
2. Magland J and Epstein CL, *J Magn Reson* **172**, 63 (2005).
3. Conolly S, Nishimura D and Macovski A, *IEEE Trans Med Magn* **MI-5**, 106 (1986).
4. King SB, et al, *ISMRM Annual Meeting*, Seattle, p. 1351 (2006).