Numerical Optimization of Minimum Phase RF Pulses for UTE Imaging

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Introduction

Ultra-short TE imaging (UTE) introduces new challenges for excitation pulse design, as sampling must begin in as short a time possible after excitation – making slice select rewinder gradients difficult to 'fit' into UTE sequences. Typical UTE relies on a half-excitation pulse to minimize residual slice select phase, followed by radial k-space readouts. This solution has been shown to work well[1], but at the cost of poor slice profiles, and at a doubling of acquisition time (as all acquisitions are collected with slice gradients in regular and reversed polarity).

We present results from a numerical optimization for short, self-rewound, slice selective RF pulses with near-zero phase across the slice.

Methods

Pulse optimization is performed via a purely numerical approach, allowing for limits on total and peak RF power and arbitrary constraints on the slice profile. The pulse design is cast as a finite-dimensional, non-linear, non-convex constrained optimization problem. The open-source optimization package IPOPT[2] is used to solve the problem, using first and second derivative information. Optimization times are on the order of several seconds for short pulses (here: 100-200us RF duration).

A spoiled gradient echo type sequence was used to test the pulses. This consists of a slice select gradient with RF pulse played out on the ramp down, followed by radial sampling of k-space and gradient spoiling. Testing of the sequence was performed on a 30mm diameter cylindrical Lego and water phantom, in a Varian 9.4T 31cm small animal imager. The plastic Lego bricks have an approximate T2 of 300us[3].

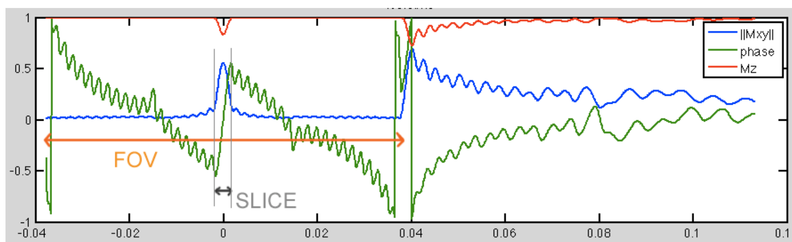

Figure 1: Example optimized slice profile. *y-axis: Mxy, phase, and Mz normalized to +/-1. x-axis: distance in FOV (m) -- 3mm slice thickness, 8cm FOV.* Very little phase across the slice and flat stop-band response is visible. Signal outside of the design FOV is an expected tradeoff .

Discussion

In this type of numerical optimization, the pulse response is designed only over a specific range (FOV). As displayed in Figure 1, behaviour outside of the design FOV is erratic at best (compared to 'smooth' FIR/FT or Shinnar-Le-Roux[4] methods). This means that it is advantageous to optimize pulses for each protocol (or even patient) to gain performance.

To minimize excitation time, the RF pulses were designed to be played out over a linear ramp down of the slice select gradient. Ramping at maximum slew rate limits the total available time-bandwidth for the RF, and thus imposes a limit on the minimum slice thickness.

Figure 2: Axial slice of Lego™ phantom at 9.4T. *Left:* TE: 8us after RF excitation *Mid: TE: 2ms Right:* Difference image. The lego, plastic container tube, and plastic coil former are visible. The top brick is partial-volumed with water, leading to its brighter signal in the two left images.

Future work

The behaviour of spins during RF excitation for species with very short T2 is complicated, with decay happening during excitation in some cases. Simulations of spin behaviour on a per-RF-waveform basis will lead to more accurate ideas of the 'true' TE being sampled.

Conclusion:

A numerical optimization method to design minimum phase RF-pulses for UTE imaging has been demonstrated. This is a promising direction, as it provides good excitation profiles in half the time of standard UTE acquisitions.

References:

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Acknowledgements: Work funded by CIHR and NSERC operating grants