Generalization of CEST Saturation Pulses designed by Optimal Control: A Pulse Pair Approach

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INTRODUCTION:

Optimal Control (OC) has recently been applied to enhance CEST saturation pulses, improving contrast and robustness for specific saturation times and B1RMS compared to conventional methods like Gaussian, Block Pulse Train (BPT), and Adiabatic Spin Lock (aSL) saturation [1,2]. However, these trains require optimization of the entire sequence. While combining pulse trains can increase total saturation time (Tsat), they do not match the versatility of single pulses, such as Gaussian pulses, which can adapt to varying Duty Cycles (DC) and Tsat. Consequently, this work investigated whether optimized single pulses could offer similar flexibility, while maintaining their excellent performance.

METHODS:

Pulse design: Pulses were optimized using the Optimal Control framework described in [1]. The cost function was initially designed for a single repetitive pulse. To improve the smoothness of the water peak, a second pulse shape was subsequently permitted. The optimization constraints included a 100 ms single pulse duration (tp) and a 12.5 ms inter-pulse pause. The optimization target was a 1 s continuous wave (CW) spectrum.
Experiments: Performance of various saturation methods was assessed using phantom measurements on a Siemens Vida 3 T scanner, with sequences implemented in pulseq CEST [3,4]. The phantom, containing 87 mM creatine in a 500-ml glass sphere, was subjected to 15 pulses of 100 ms each, with 50 ms pauses. After B0 correction using the WASABI protocoll the MTRasym at the creatine was used for CEST image generation. [5].

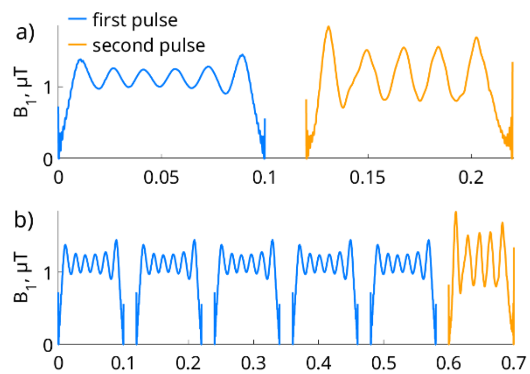

Figure 1: (a) Pulse pair designed by Optimal Control. (b) proposed use case, repeating first pulse and finishing with second.

RESULTS:

A pulse pair designed for the N-1 approach can be seen in Fig. 1 (a) and two variants of how to implement the pulses are shown in Fig. 1 (a,b). The approach of optimizing only identical pulses introduced some wiggles in the water peak. Figure 2(a) shows CEST images from phantom measurements with 15 pulses at 75% DC, and the profiles through the sphere in (b). OC, aSL, and Gaussian saturation are homogeneous, whereas BPT introduces severe artifacts. OC saturation yields about 13% higher CEST contrast at the sphere's center than aSL and over 35% more than Gaussian.

DISCUSSION AND CONCLUSION

In this work, we introduce a new generation of saturation pulses developed using OC to surpass previous limitations and enhance flexibility. Our novel pulse pair approach allows the first pulse to be applied repetitively to achieve desired Tsat and DC, concluding with the second pulse. Phantom measurements demonstrated superior performance and versatility compared to conventional saturation strategies.

Our OC-based pulse design framework generalizes well across various physical and experimental parameters. Utilizing the first pulse alone introduces minor wiggles in the water peak. While these wiggles are not severe, using the first pulse alone remains a feasible approach. However, incorporating the second pulse at the end of the sequence yields a smoother spectrum from 0.8 to -0.8 ppm. The complementary nature of the pulses facilitates robust, high-contrast, and versatile saturation trains.

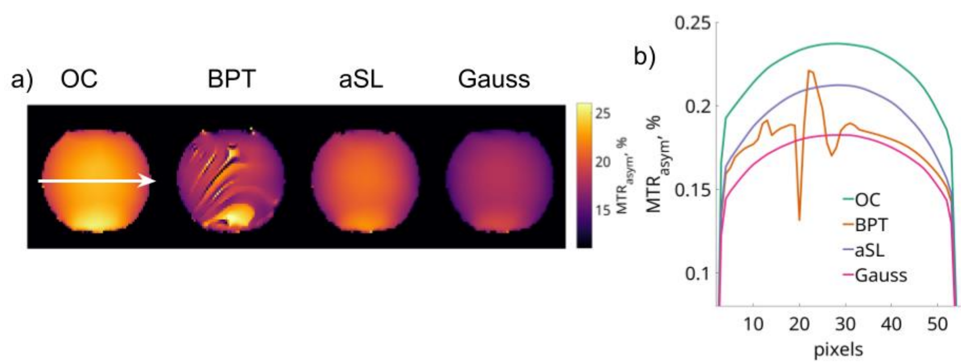

Figure 2: (a) CEST phantom images with creatine contrast. (b) horizontal slice indicated by the white arrow. Images were measured with 15 pulses (14 first pulses and one second pulse)

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