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Optimization of low amplitude radiofrequency pulses for short-T₂ MRI

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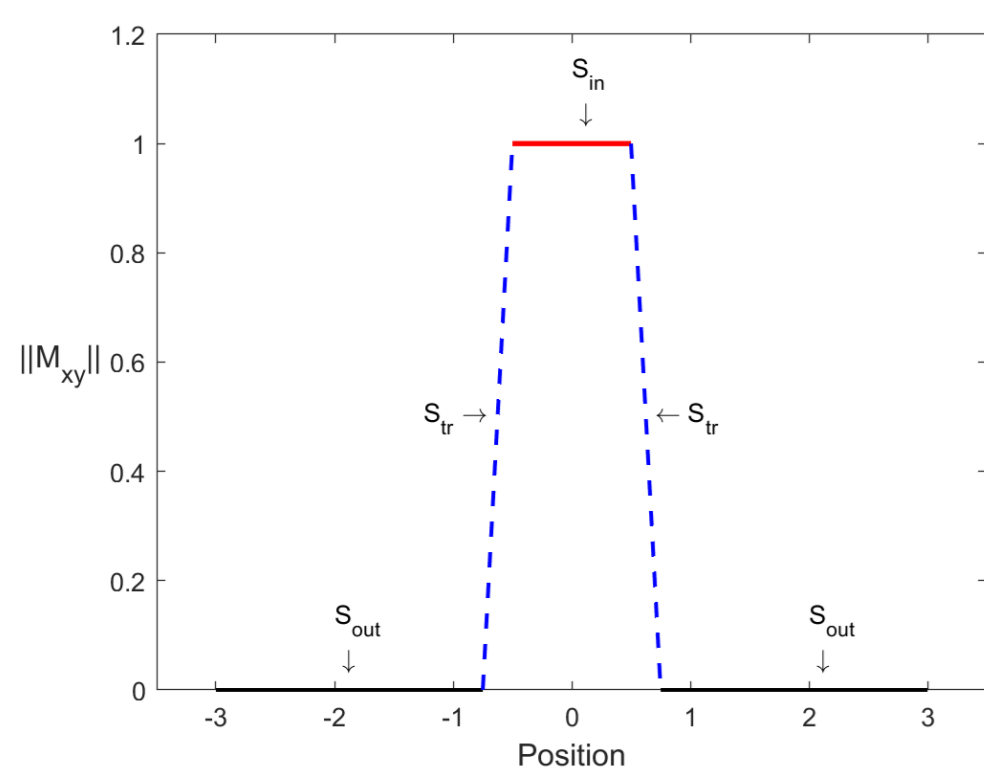
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Introduction



In nuclear magnetic resonance (NMR), selective radiofrequency (RF) pulses are applied to create signal in specific regions. When the T_2 time of the targeted species is short, signal loss occurs together with a degraded selectivity profile. The effect of relaxation can be limited by using pulses with a delayed peak amplitude, such as minimum-phase Shinnar-Le Roux pulses [3] (**mp-SLR**), and of the shortest possible duration. However, reducing the pulse duration implies the increase of the pulse amplitude and energy, which are submitted to practical constraints:

- i) the specific absorption rate (**SAR**), proportional to RF energy, is subject to **clinical thresholds** to limit patient heating,
- ii) RF power must be in compliance with the **material constraints** of the RF amplifier and coils used.

Since the early work of [1] and extended in the GRAPE algorithm in [2], optimal control (**OC**) has been used for RF pulse design in NMR. In the present case, the control is the RF pulse which rules the evolution of the magnetization following Bloch equations. This work presents an original approach to compute **selective excitation pulses for short T_2 species**. The objective is to achieve similar performance as mp-SLR pulses in terms of in-slice signal level and selectivity, while decreasing RF peak power and energy deposition.

Method (Optimal Control)

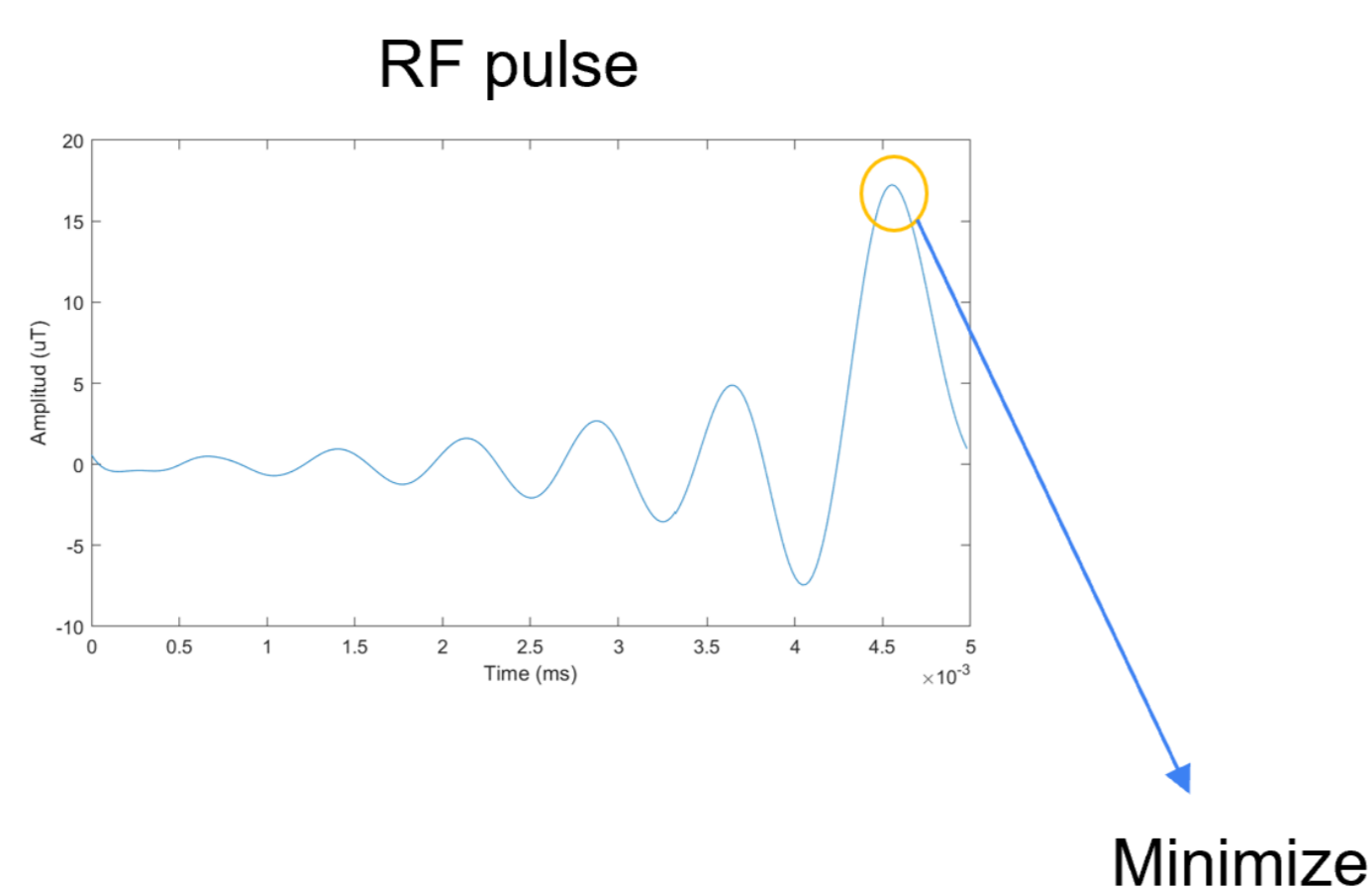
The OC problem is based on controlling the magnetization vector of the isochromats $M = (M_x, M_y, M_z)$ which dynamics is described by the following Bloch equations:

$$\begin{aligned} \dot{M}_x(t) &= -\frac{M_x(t)}{T_2} + \Delta\omega_0 M_y(t) \\ \dot{M}_y(t) &= -\frac{M_y(t)}{T_2} - \Delta\omega_0 M_x(t) + w_x(t) M_z(t) \\ \dot{M}_z(t) &= -\frac{M_0 - M_z(t)}{T_1} - w_x(t) M_y(t) \end{aligned}$$

- $\Delta\omega_0$ is the offset,
- w_x is the RF pulse (control variables).

The objective is to **minimize** the **max amplitude** of w_x defined as:

$$\min_{w \in L^\infty} \max_{t \in [0, \tau]} w(t)^2$$



where τ is the pulse duration. This is equivalent as minimizing the power ($P(w)$) necessary for the machine to apply the RF pulse w . The equation relies on :

$$P(w) = P_{ref} \left(\frac{\theta(w)}{\theta_{ref}} \right)^2 \left(\frac{\tau_{ref}}{\tau(w)} \right)^2 \left(\frac{I_{ref}}{I(w)} \right)^2 = K \cdot \max_{t \in [0, \tau]} w_x^2(t)$$

where I_{ref} , θ_{ref} and τ_{ref} respectively stand for the normalized integral factor, flip angle and duration of the reference pulse used for RF power calibration.

Selectivity constraints are imposed:

1. Produce at least as much signal as a given pulse (mp-SLR in this case) within the slice.
2. Keep the maximum ripple amplitude outside the slice below the reference maximal ripple amplitude.

Slice selectivity is evaluated by computing the passband signal (S), defined as the norm of the vector sum of isochromats situated within the passband; and the measurement of the maximal ripple amplitude in the stopband.

$$S = \frac{1}{|S_{in}|} \left| \sum_{k \in S_{in}} M_x^k(\tau) + i M_y^k(\tau) \right|$$

Experiments

Phantom Specifications: Water doped with NiSO₄ and Manganese (II) chloride, which T_2 was measured at 2ms.

Scan Specifications: Acquisitions were performed on a 11.7T Bruker MRI using the built-in RF profile sequence (TR = 2s, TE = 15ms, NA = 8) that is with the read gradient in the same direction as the gradient used for the slice selection.

Competitor: An mp-SLR pulse. The passband and stopband ripple amplitude of this pulse respectively set to 0.01% and 2%.

Parameters: All pulses are assumed to have a duration of 5 ms. Three values of Time-bandwidth Product (TBP) are used, they are 5, 10 and 15.

Results

For the targeted $T_2 = 2ms$, with respect to mp-SLR, the OC pulse pulses reduce the energy considerably by **36%**, **44%** and **43%** for TBP 5, 10 and 15 respectively. The power reduction is **27%**, **35%** and **34%** for the same TBP values. The passband signal is slightly higher for OC, while maximum stopband ripple amplitude is reduced (see Table 2).

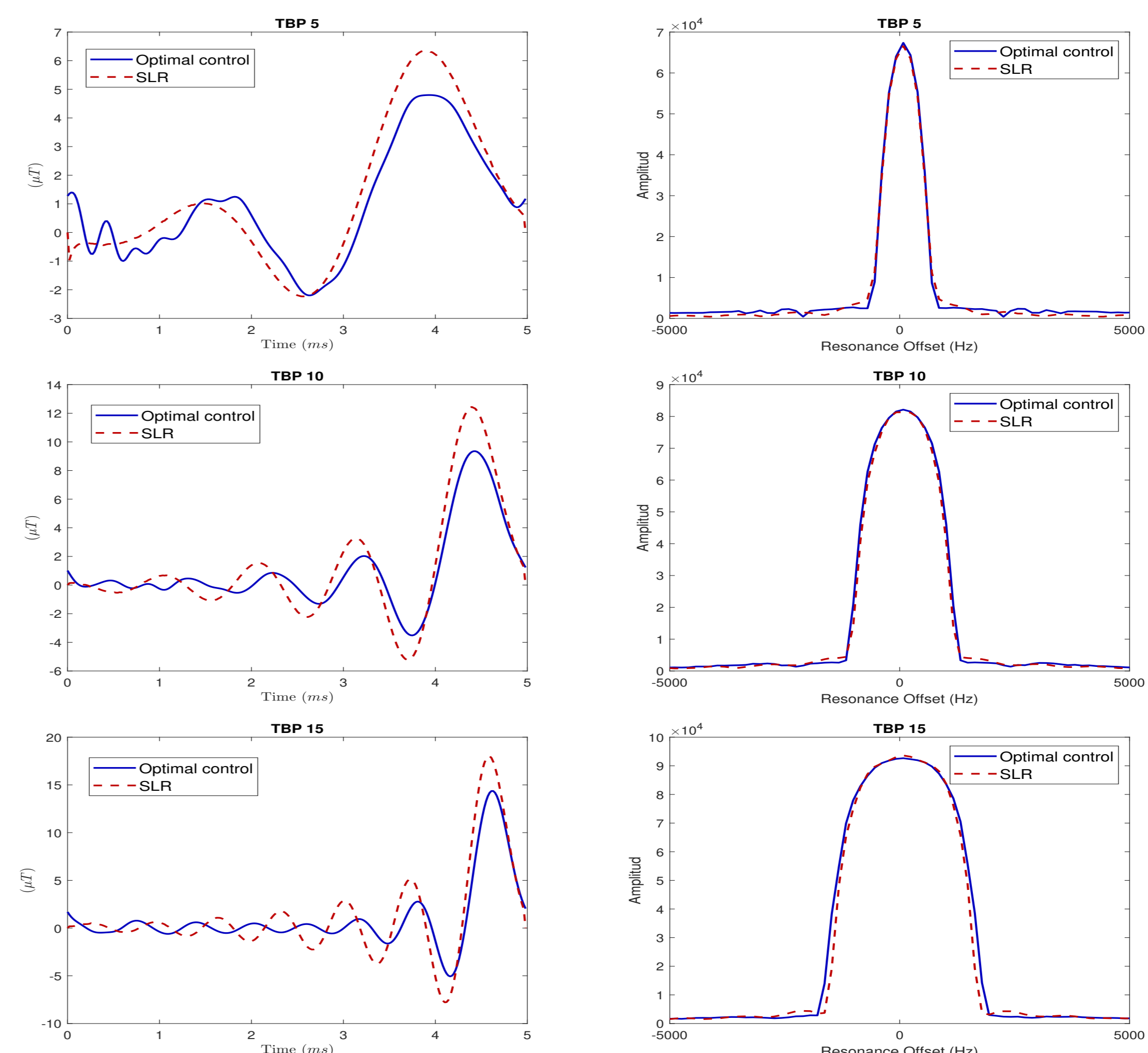


Figure 1: The first column of images depicts the pulses applied to the phantom for every TBP value. The subsequent column illustrates the respective acquired signal corresponding to the slice profile.

Method	TBP	Peak (μT)	Energy (kHz)	Power (W)	Passband signal (S)	Stopband Max Ripple
SLR	5	6.350	0.068	0.085	0.521	0.049
OC	5	4.800	0.043	0.062	0.523	0.021
SLR	10	12.442	0.149	0.362	0.634	0.030
OC	10	9.351	0.082	0.233	0.652	0.021
SLR	15	18.014	0.221	0.844	0.681	0.030
OC	15	14.360	0.125	0.552	0.723	0.021

Table 1: Comparison of the characteristics and slice selectivity performance of optimal control (OC) pulses, and mp-SLR.

Discussion & Conclusions

The proposed OC-based pulse design strategy has shown superior selective excitation abilities for short- T_2 species while reducing both the required RF peak amplitude and energy deposition with respect to mp-SLR pulses. Significant benefit could be obtained from this when RF amplitude is limited by the coil and/or RF amplifier, (a common clinical restricting factor). The methodology used can be simply adapted to other MRI problem such as B1-robust or spectroscopy. Future work will focus on showing the benefit of OC pulses for ultra-short T_2 (<0.5 ms).

Acknowledgments

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