MINIMUM OUT-OF-SLICE ERROR SMS RF PULSE DESIGN WITH DIRECT PEAK, POWER, AND IN-SLICE ERROR CONSTRAINTS

SYDNEY N. WILLIAMS[1], JEFFREY A. FESSLER[2], AND DOUGLAS C. NOLL[1]
DEPARTMENTS OF (1) BIOMEDICAL ENGINEERING AND (2) ELECTRICAL ENGINEERING AND COMPUTER SCIENCE,
UNIVERSITY OF MICHIGAN, ANN ARBOR, MI, USA

BIOMEDICAL ENGINEERING
UNIVERSITY OF MICHIGAN

INTRODUCTION

Simultaneous multislice (SMS) imaging accelerates MRI but is limited by peak RF amplitude and RF power deposition which scales roughly linearly with the multiband factor (MB), or number of slices [1]:

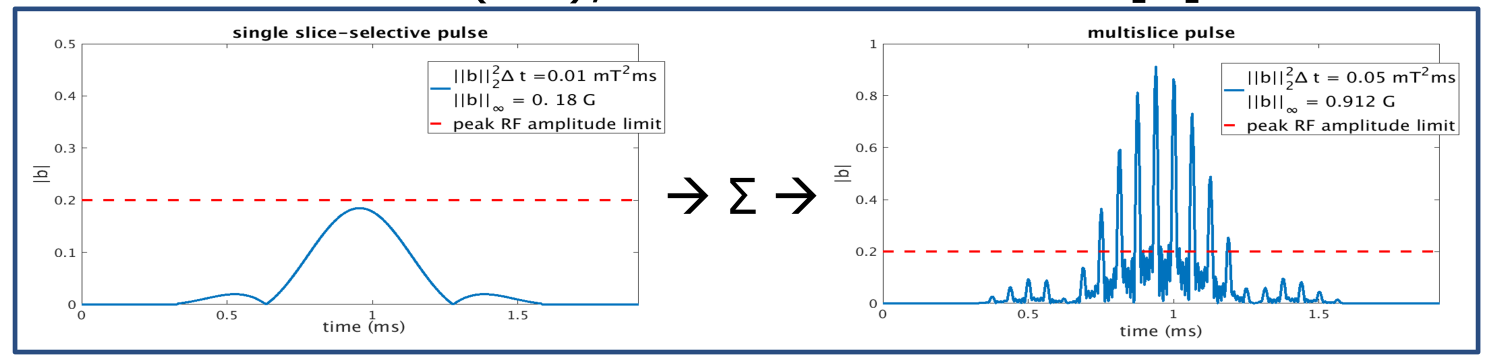

Figure 1. A single slice-selective pulse is phase modulated and summed to form a 5MB multislice pulse with increased peak amplitude and power.

Techniques for SMS pulse design have been proposed to reduce or penalize peak amplitude [1,2], RF integrated power [3], or both [4]. In [5], we introduced a method for designing small-tip angle (STA) SMS pulses directly constraining peak amplitude, which eliminated the need for parameter tuning. Here, we re-formulate the design problem to minimize the out-of-slice excitation error while keeping the physical constraints on RF integrated power and peak amplitude.

METHODS

Standard Approach: SLR SMS

- Slice-selective pulses are often a filter design problem via the Shinnar Le-Roux (SLR) algorithm [6], where in-slice and out-of-slice ripple are design parameters.
- To compare with our constrained design, we create SLR SMS pulses, using both least-squares (LS) and Parks-McClellan (PM) filters.
- Slices have optimized phase scheduling from [1] to reduce peak RF amplitude.

Our Approach: Constrained RF Pulse Design

- The design target pattern **d** is set to contain a target magnitude flip angle and phase pattern based on the phase scheduled SLR SMS pulse.
- In additional to physical constraints, we minimize the out-of-slice error with a set in-slice error constraint.
- Constrained mimization is solved in CVX [7].

METHODS (CONTINUED)

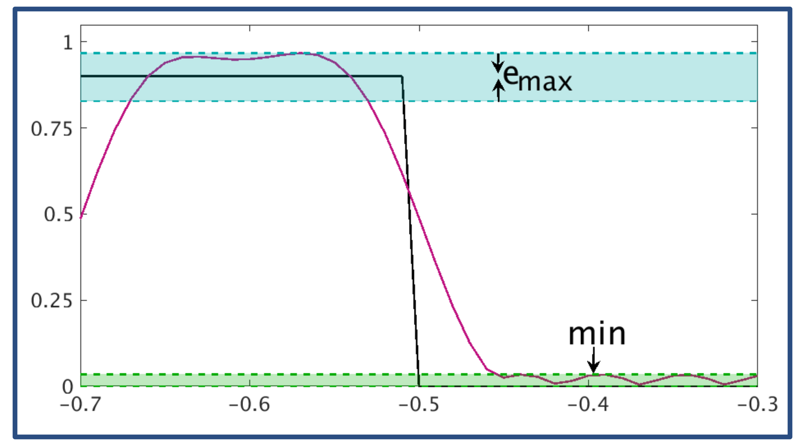

Figure 2. With an in-slice error constraint e_{max} in blue, we minimize the maximum out-of-slice error in green

We formulate this constrained problem as

$$\hat{\mathbf{b}} = \underset{\mathbf{b}}{\text{argmin}} \; ||\mathbf{A}\mathbf{b}-\mathbf{d}||_{\infty,\mathbf{W}_{\text{out}}} \quad \text{s.t.} \; ||\mathbf{b}||_\infty \le b_{\max}, \; C_{\text{SAR}}||\mathbf{b}||_2^2 \Delta t \le p_{\max}, \; ||\mathbf{A}\mathbf{b}-\mathbf{d}||_{\infty,\mathbf{W}_{\text{in}}} \le e_{\max} \qquad \text{[Eq. 1]}$$

where

- **A** is the STA approximation system matrix [8]
- **d** is the target SMS magnetization pattern
- $\mathbf{W}_{in,out}$ are the in-slice and out-of-slice regions, defined by the fractional transition width of an SLR pulse designed using the method in [6]
- Δt is the dwell time
- C_{SAR} is a measured constant converting integrated RF power to W/kg
- b_{max}, p_{max}, and e_{max} are the maximum RF peak amplitude, RF power, and in-slice-excitation error limits

We also update the phase pattern through 10 iterations of the constrained design pattern (Eq. 1) in a relaxed method akin to magnitude least squares [9]:

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Data: Solve for constrained STA RF pulse with initial target pattern
      having constant flip angle magnitude and Wong optimized phase
Result: Outer iteration updates phase with STA approximation before
        RF pulse is re-solved
begin
  d^1 = α e^{√−1 ∠m_{STA,SLR}}
  for i = 1 : no. phase updates do
    Constrained optimization,
    Equation 1 → b^i
    m^i_STA = A b^i
    for j = 1 : no. slices do
      φ^{i,j} = mean(∠m^{i,j}_STA)
    end
    d^{i+1} = |d^i| ∘ e^{√−1 φ^{i,j}}
  end
end
Algorithm 1: Constrained RF Pulse Design with Phase Updates
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[Eq. 2]

RESULTS

In total, we designed the two SLR pulses (with LS and PM filters) and two minimum out-of-slice error constrained RF pulses without phase updates (just Eq. 1) and with phase updates (10 iterations of Eq. 2) for a 0.95 ms MB=8 pulse with a flip angle of 23.1°.

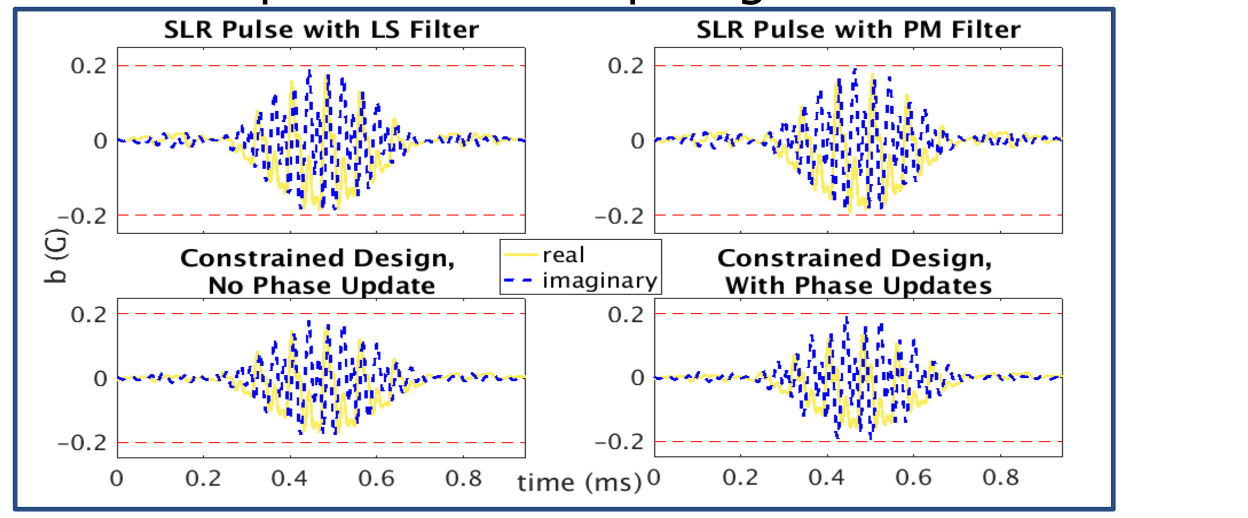

Figure 3. RF waveforms for four RF pulse designs; real and imaginary components in left column, magnitude in right.

We compared these pulses quantitatively via Bloch simulation:

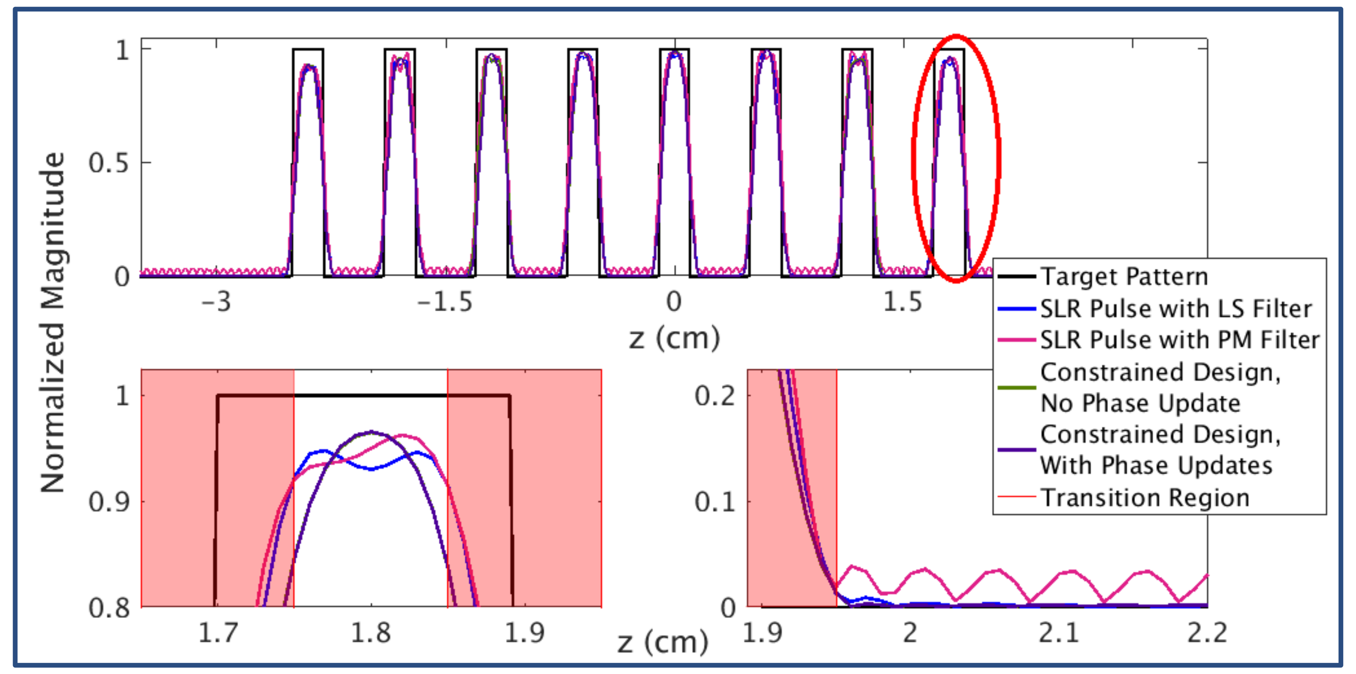

Figure 4. Bloch simulated magnetization magnitude with zoomed slice profiles of right-most slice

Pulse	$\|\|b\|\|_\infty$ (G)	$\|\|b\|\|_3^2 \Delta t$ (G^2ms)	Max In-Slice Err.	Max Out-of-Slice Err.
SLR wit LS	0.20	7.0E-3	0.25	0.4E-2
SLR with PM	0.20	7.0E-3	0.25	1.4E-2
Const. Eq.1	0.18	6.0E-3	0.25	**0.1E-2**
Const. Eq. 2	0.20	6.0E-3	0.25	**0.1E-2**
Constraints:	0.20	1.3	0.25	N/A
Short Const. Eq. 1	0.20	6.0E-3	0.25	0.4E-2
Short Const. Eq. 2	0.20	6.0E-3	0.25	0.4E-2

Table 1. Performance metrics for 4 0.95 ms SMS RF pulses, constraints, and metrics for *shorter* (0.8 ms) constrained pulses

RESULTS (CONTINUED)

Then, we used these pulses in a 2D experiment with the SPGR sequence and measured slice profiles:

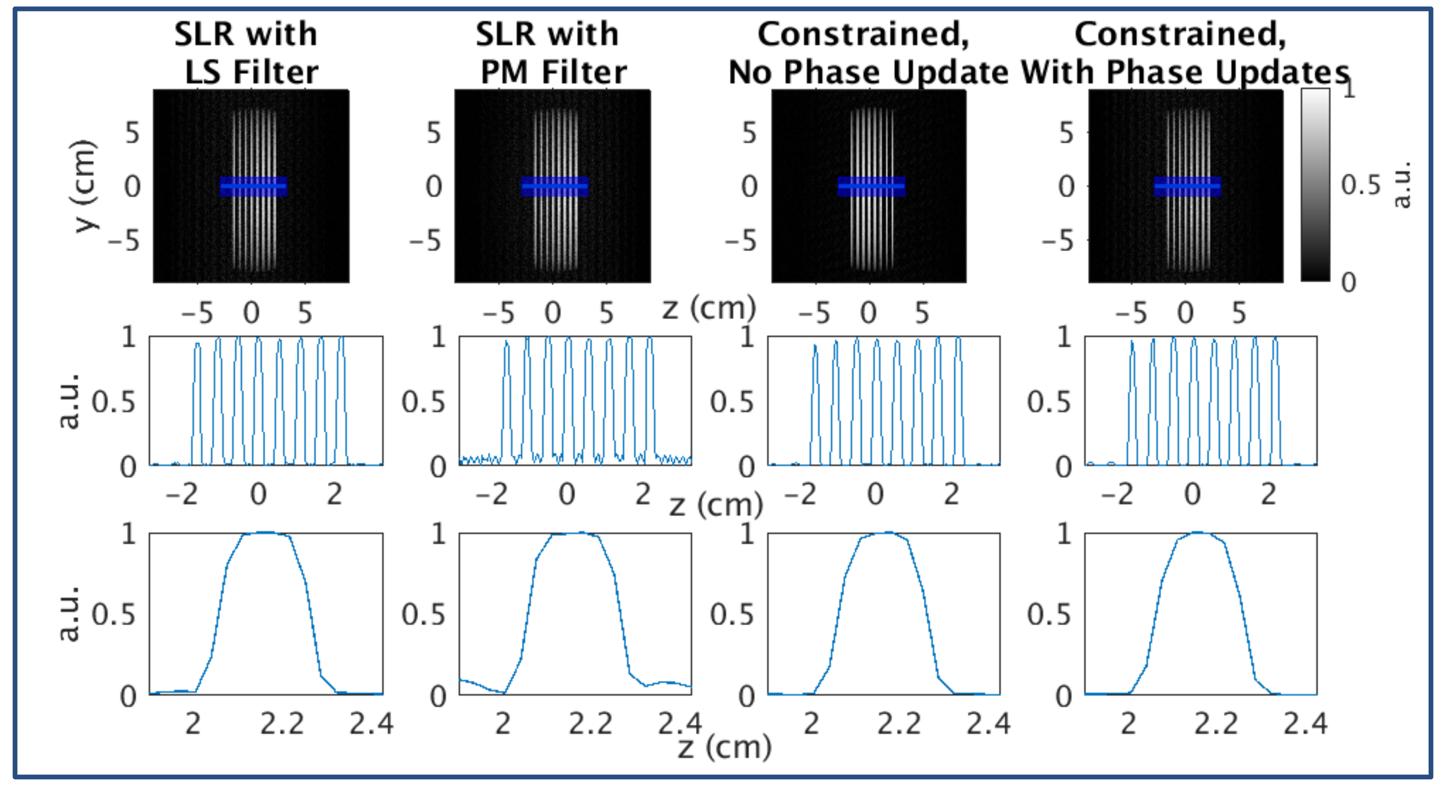

Figure 5. 2D images (top) and averaged line profile (middle) with zoomed right-most slice (bottom) for 4 RF pulse designs

CONCLUSIONS

Our constrained SMS pulse design enforces physical and in-slice excitation error RF constraints and minimizes the amount of out-of-slice error. Unlike other design methods, our method doesn't require parameter tuning yet achieves better out-of-slice error than the standard SLR SMS pulse. Similarly, we also can design shorter constrained pulses (0.8 ms) for the same out-of-slice error. We also investigated additional phase updates in our design but only saw negligible reductions of out-of-slice error.

REFERENCES

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CONTACT INFORMATION

Sydney Williams
Ph.D. Candidate Biomedical Engineering
sydneynw@umich.edu

MEDICAL SCHOOL UNIVERSITY OF MICHIGAN | MICHIGAN ENGINEERING UNIVERSITY OF MICHIGAN