Multi-dimensional refocusing pulses for parallel transmission by optimal control

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Introduction: Multi-dimensional 180° spatially selective radio frequency (RF) pulses are useful for spin inversions and refocusing while mitigating B1 homogeneity or recovering susceptibility-induced signal loss at high magnetic fields. The parallel transmission technique can be applied to reduce the pulse lengths and the specific absorption rate (SAR) of these pulses. The design of such large-tip-angle (LTA) pulses is difficult because the linearity assumed for the small-tip-angle (STA) approximation (1) is technically no longer valid for tip angle larger than 30°. The existing approaches for designing LTA pulses include the optimal control approach (2,3), the additive angle method (4), the small-perturbation approach (5), and the method of linear class of LTA (LCLTA) pulses (6, 7). Furthermore, designing a multi-dimensional refocusing pulse is more challenging because it requires a "pancake-flip" of the spins with different in-plane phases. In this work, we designed a 2D spiral refocusing pulse for parallel transmission using a two-process optimal control approach and demonstrated the performance of the pulse using Bloch equation simulations.

Theory: The optimal control approach for the design of refocusing pulses minimizes the RF energy $||B_1(t)||^2$ subject to the constraint that the pulse flips the Y component of the spins from +Y to –Y while leaving the X component intact. The objective function is

$$J(B_1) = \|M_x(T) - D_x\|^2 + \|M_y(T) - D_y\|^2 + \int_0^T \left\{ \|B_1(t)\|^2 + \lambda_1^T f_1(t) + \lambda_2^T f_2(t) \right\} dt \,, \qquad [1]$$

where B_1 is the RF pulse, M_x and M_y are the X and Y components of the magnetization, D_x and D_y are the desired X and Y components of the magnetization, λ are the Lagrange multipliers, and $f = \dot{M}(t) - M(t) \times B(t)$ is the Bloch equation. The optimization starts with an educated guess of the initial 180° pulse, which can be designed using the LCLTA method and refined using the optimal control approach. At the each iteration, the Bloch equation is integrated forward for the magnetization and backward for the Lagrange multipliers. The RF pulse is updated at the each iteration using the method of steepest descent.

Methods: Figure 1a shows the 2D spiral k-space trajectory designed with an under-sampling factor of two (gradient slew rate = 12.5 G/cm/ms, gradient amplitude = 4 G/cm). This limited the pulse length to 4.35 ms. The initial eight-transmitter 180° pulse was designed using the LCLTA method. The pulse was then further optimized for a more accurate excitation profile using optimal control theory and used as the initial pulse for designing the 2D refocusing pulse. The initial magnetization for the first control process was pointed in the +Y direction and the magnetization for the second process was pointed in the +X direction. The desired refocusing profile was the M_y component along the –Y direction within the center quarter of the FOX (field of excitation) and M_x remaining in the +X direction. Sixty iterations and two different step sizes were empirically chosen to ensure that the root-mean-square error between the actual profile from the Bloch simulation and the desired profile reached a local minimum.

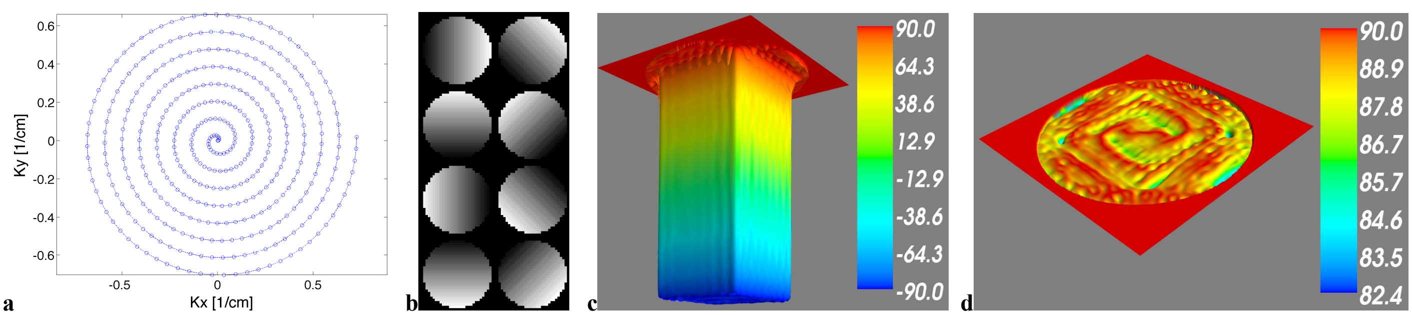

Figure 1 (a) The 2D k-space spiral trajectory with an under-sampling factor of two. **(b)** The simulated transmission sensitivity maps for eight channels. **(c)** The refocused M_y component. **(d)** The M_x component.

Results: Figure 2c shows the M_y component of the magnetization aligned along -Y (initially along the +Y). Note the 180° tip in the center quarter of FOX. Figure 2d shows that the M_x component of the magnetization remains aligned along the +X direction.

Discussion and Conclusions: A two-process optimal control approach was demonstrated to be useful for the design of multi-transmitter 2D spiral refocusing pulses. The limitation of this method is its long computational time (the pulse above required 5 minutes on a 2.8 GHz CPU). However, this limitation can be potentially overcome using modern high-performance graphics processing units to accelerate the integration of the Bloch equation. A potential application for this pulse is spin-echo imaging at high magnetic fields. The pulse can be implemented into a spin-echo sequence where the 2D spiral pulses can be used to refocus a region of interest within the slice excited by the slice-selection pulse.

References: (1) J. Pauly et al, JMR 1989;81:43-56. (2) S. Conolly et al, IEEE Trans Med Imaging 1986:MI-5:106-115. (3) D. Xu et al, MRM 2008;59:547-560. (4) W. A. Grissom et al, MRM 2008;59:779-787. (5) W. A. Grissom et al, IEEE Trans Med Imaging 2009;28:1548-1559. (6) J. Pauly et al, JMR 1989;82:571-587. (7) D. Xu et al, MRM 2007;58:326-334.

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