Design of Linear Class Large-Tip-Angle Multidimensional RF Pulses for Parallel Transmit

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INTRODUCTION

Existing noniterative pulse design methods [1-3] for parallel transmit are based on the small-tip-angle (STA) approximation of the Bloch equation [4]. Therefore, these methods can design only excitation pulses with small flip angles (e.g., 30°, or at most 90°) and cannot design large-tip-angle (LTA) pulses (e.g., inversion/refocusing pulses). We propose a noniterative method to design LTA multidimensional RF pulses for parallel transmit, based on an extension of the linear class LTA (LCLTA) theory. The effectiveness of the proposed method in designing LTA pulses is validated by Bloch simulations and preliminary parallel transmit experiments.

PROPOSED METHOD

In [5], Pauly et al. show when certain assumptions are satisfied, a "linear class" of selective RF pulses can be designed using the following linear equation:

$$\theta(\mathbf{r}) = \gamma \int_0^T B_1^*(t) e^{-i\mathbf{k}(t)\cdot\mathbf{r}} dt \,, \qquad (1)$$

where $\theta(\mathbf{r})$ is flip angle at spatial location $\mathbf{r}$, γ is gyromagnetic ratio, T is pulse duration, $B_1(t)$ is the external RF pulse, "*" denotes complex conjugate, and $\mathbf{k}(t)$ denotes the chosen excitation k-space trajectory [4]. Equation (1) is a form of linearized Bloch equation neglecting T_1 and T_2 relaxation. It is more general than the design equation under STA assumption [1-3] in the sense that it allows for arbitrary initial magnetization and the flip angle between the initial and final magnetizations can be large [5]. When an array of L transmit coils are used, the effective B_1 field is a superposition of B_1 fields generated by individual coil element. Equation (1) thus becomes:

$$\theta(\mathbf{r}) = \gamma \sum_{l=1}^{L} s_l^*(\mathbf{r}) \int_0^T B_1^{(l)*}(t) e^{-i\mathbf{k}(t)\cdot\mathbf{r}} dt \,, \qquad (2)$$

where $s_l(\mathbf{r})$ represents transmit sensitivity of the lth coil and $B_1^{(l)}(t)$ denotes the RF pulse waveform to be designed for the lth coil, $l = 1,2,\ldots,L$. Equation (2) holds when the "linear class" assumptions [5] are satisfied. This requires one of the following conditions to be met. First, each $B_1^{(l)}(t)$ is small enough (which implies a small flip angle) and $\mathbf{k}(t)$ is inherently refocused, which means $\mathbf{k}(t)$ needs to start and end at the origin of the excitation k-space, and is Hermitian-symmetrically weighted about the origin (ensuring a real-valued flip angle). Second, if $B_1^{(l)}(t)$ is large (which implies a large flip angle), then it can be decomposed into a sequence of sub-pulses each producing a small rotation about the same axis, and correspondingly, $\mathbf{k}(t)$ can be decomposed into a sequence of inherently refocused sub-trajectories. Note there are various 2D "linear class" trajectories (e.g., the inherently-refocused spiral [5]). A 3D linear class trajectory is proposed in another abstract submitted to this conference.

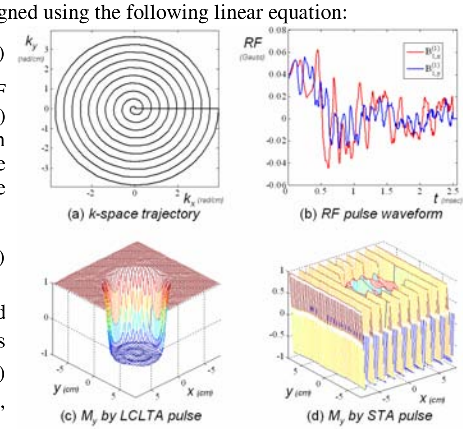

Fig. 1. Bloch simulation for an LCLTA 180° refocusing pulse. (a) Inherently refocused spiral trajectory. (b) One channel of the complex-valued pulse. (c) M_y component produced by the LCLTA pulse. (d) M_y component produced by an STA pulse (doubling the amplitude of a 90° STA pulse).

Equation (2) can be solved using a direct discretization method similar to the method in [3]. Specifically, we discretize t and $\mathbf{r}$ on both sides of Eq. (2) to convert it to a matrix form $\boldsymbol{\theta} = \mathbf{Sb}$, where $\boldsymbol{\theta}$ is a vector that contains the value of $\theta(\mathbf{r})$ at all spatial locations, $\mathbf{b}$ is a vector that contains the value of complex conjugate of $B_1^{(l)}(t)$ for all coils at all time points, and $\mathbf{S}$ is a matrix that contains the transmit sensitivity and the complex exponential terms in Eq. (2). Equation (2) is solved using direct matrix inversion or conjugate gradient method. Tikhonov regularization can be used to ensure good conditioning when inverting the matrix equation [3]. Taking the complex conjugate of $\mathbf{b}$ yields the desired pulse.

RESULTS

Bloch Simulation. An eight channel parallel transmit 180° refocusing pulse was designed to refocus an infinite cylinder (diameter = 8 cm) in an FOV of 16 × 16 cm^2. The transmit sensitivities were created by FDTD software to simulate a transmit array at 7 T main field strength. The trajectory (Fig. 1a) was an inherently refocused spiral [5] without acceleration. One channel of the complex-valued pulses is shown in Fig. 1b. The initial magnetization vector points to +y axis. Bloch simulation results show that this pulse produces good spatial selectivity (M_y shown in Fig. 1c; M_x is close to zero but not shown), while the pulse designed by the STA method (double the amplitude of a 90° pulse designed by the method in [3]) fails to produce an acceptable magnetization profile.

Experiments. A spin-echo experiment on a 1.5 T GE Signa scanner (GE Healthcare, Milwaukee, WI) with 8-channel parallel transmit capability [6] was carried out to evaluate the performance of another 180° refocusing pulse designed by the proposed method with a twofold accelerated inherently refocused spiral. The target profile was an off-centered cylinder (diameter = 6 cm). FOV = 30 × 30 cm^2, TE = 15 msec, TR = 100 msec. An eight-channel transmit-only head-coil array [6] was used to transmit RF pulses and a single channel body coil was used to receive signal. The method in [6] was adopted for B_1 mapping. The 90° excitation pulse (achieving the same spatial selectivity) using a twofold accelerated inward spiral trajectory was designed using the method in [3]. One channel of the transmit sensitivity and magnitude of the pulse waveforms is shown in Figs. 2a and b. The resulting spin-echo image and its 1D profile is shown in Fig. 2c. Clearly, this image has good spatial selectivity. The magnetization inside the off-centered cylinder is fairly uniform; the magnetization outside is suppressed well, except for a few locations (e.g., the one marked by the arrow), where noticeable artifacts occur. These artifacts are mainly due to the nonlinearity of the Bloch equation, and are addressed by an iterative method in another abstract submitted to this conference.

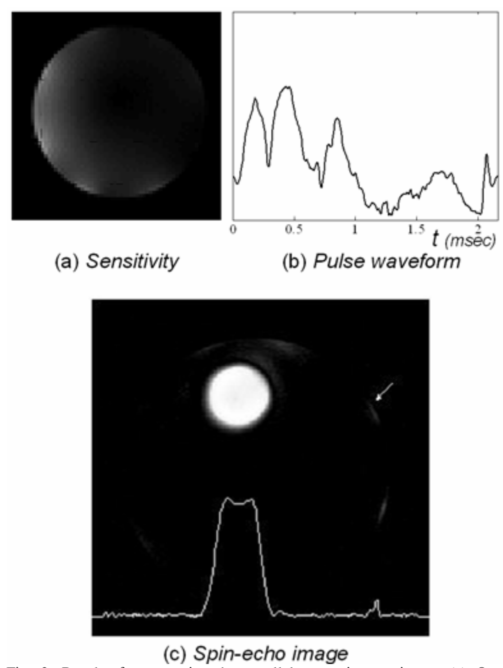

Fig. 2. Results from a spin-echo parallel transmit experiment. (a) One channel of transmit sensitivity. (b) One channel of the refocusing pulse (magnitude). (c). The spin-echo image and its 1D profile.

CONCLUSION

A noniterative method to design LTA multidimensional parallel transmit pulses is proposed, based on the linear class theory. Bloch simulation and preliminary experimental results show that this method is effective in designing LTA parallel transmit pulses (e.g., 180° refocusing/inversion pulses). The potential applications of the proposed method are spin-echo/inversion-recovery imaging with reduced field-of-view or B_1 inhomogeneity correction at high field.

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