Designing RF Refocusing Pulses for Parallel Transmit Spin Echo Sequences

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INTRODUCTION

Parallel transmission of RF pulses [1, 2] has shown great potential in B_1 inhomogeneity correction at high fields [3]. Most of the existing applications of parallel transmission, however, have been restricted to only gradient echo due to lack of systematic design of parallel transmit refocusing pulses. The difficulty of designing such pulses lies in that 1) the large flip angle nature of refocusing pulses requires addressing the Bloch equation nonlinearity, 2) the refocusing pulses need to "pancake" flip a spin ensemble (rather than a single spin) where each spin can have different initial phase in the transverse plane, and 3) parallel transmission in general does not favor a spatially constant nutation axis due to the complex nature of B_1+ maps. In this paper, we propose an optimal control [4, 5] based method for designing parallel transmit refocusing pulses that addresses all the above difficulties. Bloch simulation results show that refocusing pulses designed by the proposed method can produce homogeneous refocusing and are expected to enable spin echo applications of parallel transmission.

PROPOSED METHOD

We consider conventional spin echo sequences with a single refocusing pulse per repetition time. Note the design of such refocusing pulse is independent of the design of its preceding excitation pulse. We therefore assume that the excitation pulse has been applied and spins have been flipped into the transverse plane. As the Bloch equation is linear with respect to its initial conditions [4], to consider a collection of spins with different initial phases of transverse magnetization, it is sufficient to consider only two magnetization vectors $\mathbf{m}(t)$ and $\mathbf{n}(t)$ with orthogonal initial directions: $\mathbf{m}(0) = [1, 0, 0]^T$ and $\mathbf{n}(0) = [0, 1, 0]^T$, where the magnetization vectors are normalized to equilibrium magnetization. Denote $b_l(t)$ as the RF pulse waveform of the lth transmission channel, $l = 1, 2, \ldots, L$, and $\theta(\mathbf{r})$ as the phase angle of the nutation axis for spins at spatial location $\mathbf{r}$. The desired final magnetizations are then $\mathbf{m}_{des} = [\cos 2\theta(\mathbf{r}), \sin 2\theta(\mathbf{r}), 0]^T$ and $\mathbf{n}_{des} = [\sin 2\theta(\mathbf{r}), -\cos 2\theta(\mathbf{r}), 0]^T$, respectively. The pulse design problem is to choose $\theta(\mathbf{r})$ and design $b_l(t)$ such that the final magnetization $\mathbf{m}(\mathbf{r}, T)$ and $\mathbf{n}(\mathbf{r}, T)$ (where the italic "T" denotes pulse duration) are as close to $\mathbf{m}_{des}$ and $\mathbf{n}_{des}$ as possible. Note that the above explicit dependency on $\theta(\mathbf{r})$ can be removed by the following equivalent formulation:

$$\text{Choose } b_1(t), \ldots, b_L(t) \text{ to minimize } J = \sum_{\mathbf{r}} \left\{ [m_x(\mathbf{r},T) + n_y(\mathbf{r},T)]^2 + [m_y(\mathbf{r},T) - n_x(\mathbf{r},T)]^2 + m_z^2(\mathbf{r},T) + n_z^2(\mathbf{r},T) \right\} + \lambda \sum_{l=1}^{L} \int_0^T |b_l|^2 \, dt, \quad (1)$$

where subscripts x, y, and z denote individual components of $\mathbf{m}$ and $\mathbf{n}$. The first term of Eq. (1) forces the final magnetization vectors to approach $\mathbf{m}_{des}$ and $\mathbf{n}_{des}$ (note the θ dependency is implicitly included) and the second term is an RF power regularization term with λ being the weighting factor balancing the two terms. Both $\mathbf{m}$ and $\mathbf{n}$ are subject to the Bloch equation. The above formulation is an optimal control formulation, which does not permit a closed form solution in general [4, 5]. However, the first order necessary condition for the optimal $b_l(t)$ can be found in a way similar to the method in [5], and a first order gradient descent method is implemented to obtain the optimal $b_l(t)$ numerically. Details of the first order necessary conditions for optimality and the algorithm implementation are omitted for limited space.

RESULTS

Bloch simulation results of dual channel transmission of 180° refocusing pulses for B_1 inhomogeneity correction are shown in Fig. 1. The B_1+ maps are acquired using a dual channel transmission 3T GE Signa scanner with a torso phantom (boundary of the phantom shown as white dotted line). FOV is 48 × 48 cm^2 and the matrix size is 64 × 64. A 3-turn unaccelerated inherently refocused spiral trajectory [6] is used to cover the excitation k-space. Three design methods are compared: The first two methods use a design similar to the conventional optimal control design [5] except for simultaneously considering two magnetization vectors $\mathbf{m}$ and $\mathbf{n}$ with orthogonal initial directions. The first method assumes $\theta(\mathbf{r})$ to be zero everywhere (column a). The second method chooses $\theta(\mathbf{r})$ to be the phase of the overall B_1+ (individual B_1+ maps with appropriate phase delays summed across all channels), mimicking the body coil quadrature mode (column b). The third method is the proposed design (column c) that chooses the optimal phase to achieve the best performance (i.e. minimizing Eq.(1)). The first row in Fig. 1 shows $\theta(\mathbf{r})$. Note the significant difference between the optimal and quadrature phase. To measure the refocusing homogeneity, we plot two quantities $[m_x(T) + n_y(T)]$ and $[m_y(T) - n_x(T)]$ in the second and third rows, respectively. Note both quantities should be kept close to zero for a well-designed refocusing pulse. Such closeness is measured by the mean square error (MSE) and standard deviation (STD). For the method with zero phase, both quantities are very high (MSE = 85.5, STD = 0.38 for row 2 and MSE = 74.3, STD = 0.34 for row 3). This is because B_1+ maps at different locations point in different directions; forcing nutation axes to have zero phase everywhere is thus overly constrained. For the method with quadrature phase, both quantities become much smaller (MSE = 0.50, STD = 0.029 for row 2 and MSE = 0.51, STD = 0.029 for row 3) because the phase of B_1+ map is taken into account in this design (although θ is chosen heuristically). The proposed method starts with the pulse used in b and further optimizes the pulse by the formulation in Eq. (1). The method implicitly finds the optimal phase that gives the best magnetization profile. As shown in column c, both quantities are further closer to zero (MSE = 0.47, STD = 0.028 for row 2 and MSE = 0.22, STD = 0.020 for row 3), indicating better refocusing homogeneity.

CONCLUSION

A new optimal control based method is proposed to design parallel transmit refocusing pulses for spin echo sequences with a single refocusing pulse per repetition time. The method addresses the nonlinearity of refocusing pulses by including Bloch equation in the formulation, designs pulses that refocus a spin ensemble by considering two magnetization vectors with orthogonal initial directions, and optimizes the phase angle of the nutation axis to achieve homogenous refocusing performance. Simulation results have shown that parallel transmit refocusing pulses designed by the proposed method produce better homogeneity than pulses designed by conventional methods.

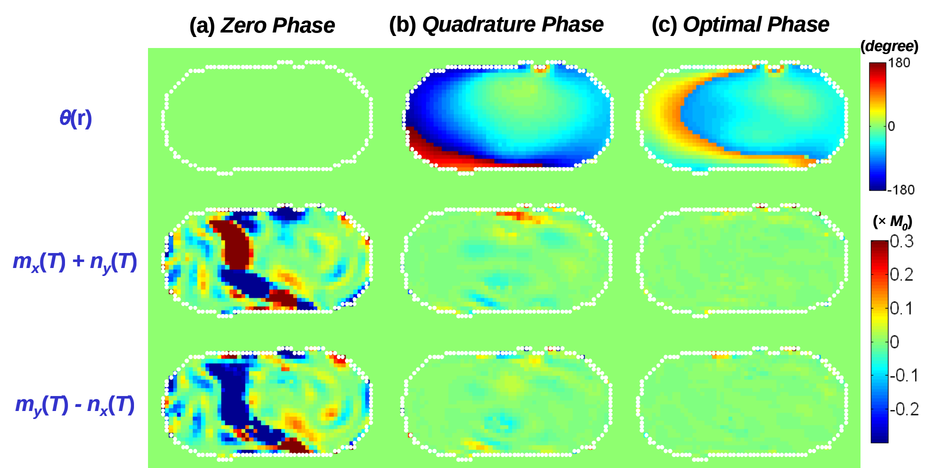

Fig. 1. Bloch simulation of dual channel transmission of refocusing pulses designed by three methods for B_1 inhomogeneity correction. The first row shows the phase angle of the nutation axis in the transverse plane. The second and third rows show two quantities that measure refocusing homogeneity. (a) Conventional optimal control design with $\theta(\mathbf{r}) = 0$, which does not refocus spins well in many locations. (b) Conventional optimal control design with $\theta(\mathbf{r})$ being the quadrature phase, which achieves much improved homogeneity. (c) The proposed design that optimizes $\theta(\mathbf{r})$ to produce the most homogeneous magnetization profile. See text for details.

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