Journal of Magnetic Resonance 195 (2008) 76–84

Contents lists available at ScienceDirect

Journal of Magnetic Resonance

journal homepage: www.elsevier.com/locate/jmr

High-flip-angle slice-selective parallel RF transmission with 8 channels at 7 T

Kawin Setsompop [a,*], Vijayanand Alagappan [b], Adam C. Zelinski [a], Andreas Potthast [c], Ulrich Fontius [d], Franz Hebrank [d], Franz Schmitt [d], Lawrence L. Wald [b,e], Elfar Adalsteinsson [a,e]

[a] Department of Electrical Engineering and Computer Science, MIT, 77 Massachusetts Ave., Building 36, Room 766, Cambridge, MA 02139, USA
[b] A. A. Martinos Center for Biomedical Imaging, Department of Radiology, MGH, Harvard Medical School, Charlestown, MA, USA
[c] Siemens Medical Solutions, Charlestown, MA, USA
[d] Siemens Medical Solutions, Erlangen, Germany
[e] Harvard-MIT Health Sciences and Technology, MIT, Cambridge, MA, USA

ARTICLE INFO

Article history:
Received 15 March 2008
Revised 22 August 2008
Available online 30 August 2008

Keywords:
Parallel transmission
High flip-angle
Slice-selective excitation
RF inhomogeneity
Multidimensional pulse

ABSTRACT

At high magnetic field, B_1^+ non-uniformity causes undesired inhomogeneity in SNR and image contrast. Parallel RF transmission using tailored 3D k-space trajectory design has been shown to correct for this problem and produce highly uniform in-plane magnetization with good slice selection profile within a relatively short excitation duration. However, at large flip angles the excitation k-space based design method fails. Consequently, several large-flip-angle parallel transmission designs have recently been suggested. In this work, we propose and demonstrate a large-flip-angle parallel excitation design for 90° and 180° spin-echo slice-selective excitations that mitigate severe B_1^+ inhomogeneity. The method was validated on an 8-channel transmit array at 7 T using a water phantom with B_1^+ inhomogeneity similar to that seen in human brain *in vivo*. Slice-selective excitations with parallel RF systems offer means to implement conventional high-flip excitation sequences without a severe pulse-duration penalty, even at very high B_0 field strengths where large B_1^+ inhomogeneity is present.

1. Introduction

The presence of severe RF excitation field (B_1^+) inhomogeneity at high magnetic field strength [1,2] poses a serious challenge for the use of standard slice-selective excitation. The B_1^+ inhomogeneity leads to non-uniform in-plane excitations resulting in an undesirable inhomogeneity for both Signal-to-Noise Ratio (SNR) and image contrast. Several RF design approaches have been suggested to mitigate this inhomogeneity, including excitation k-space design [3–5], RF-shimming [6–8], and adiabatic pulses [9,10]. In this work, the focus is on extending the current excitation k-space design to higher flip angle, particularly in the context of parallel transmission where significant reduction in RF waveform duration can be achieved compared to conventional single-channel systems.

RF waveforms designed based on the Small-Tip-Angle approximation (STA) [11], along with the appropriate 3D k-space trajectories termed either "fast-k_z" or "spokes" trajectories [3–5], have been shown to be effective in correcting for mild B_1^+ inhomogeneity, such as that observed at 3T for brain imaging. With these trajectories, slice selection is achieved with a conventional sinc-like RF pulse during each k_z traversal (a "spoke"), and in-plane flip-angle inhomogeneity is mitigated by the appropriate choice of the complex-valued amplitude that modulates the RF waveform of the spokes which are positioned at an appropriately chosen set of k_x–k_y positions. However, with a more severe B_1^+ field variation, e.g., as observed in brain imaging at 7 T, the resulting RF waveform from this design method becomes too lengthy for practical use in conventional sequences with single-channel excitation. For example, in [12], an optimized 30-spoke excitation was designed for slice-selective B_1^+ mitigation at 7 T, resulting in a time-penalty of approximately 30-fold compared to a conventional sinc excitation.

Parallel transmission systems with simultaneous independent control of RF waveforms from multiple channels [13–16] offer means to accelerate k-space based RF waveforms resulting in shorter excitation duration. With parallel transmission, "spoke"-based trajectories can be use to mitigate highly inhomogeneous B_1^+ fields, such as are observed in brain imaging at 7 T, to produce highly uniform slice-selective excitation with relatively short excitation durations [17–20]. Nonetheless, a major drawback for the k-space based parallel transmission design is its reliance on the STA approximation, and its failure to adequately perform at large flip angles.

Recently, several promising large-flip-angle design methods for parallel transmission have been proposed [21–26], with experimental verification performed for 2D spiral excitation in [26], and for spoke-based B_1^+ mitigation design in [24]. Nonetheless, the spoke-based experiment was only performed under a relatively mild B_1^+

* Corresponding author.
E-mail address: kawin@mit.edu (K. Setsompop).

1090-7807/$ - see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.jmr.2008.08.012

inhomogeneity constraint with a brain imaging setup at 3T using an oil phantom. In the current work, we describe a new design method for large-flip-angle, spoke-based B_1^+ mitigation. The method draws on our earlier work [20,24] and on the work by Xu et al. [26] to provide a much improved B_1^+ mitigation capability using short duration RF waveforms. The new design method was demonstrated with large-flip-angle parallel excitation for 90° pulses and 180° spin-echo slice-selective pulses on an 8-channel transmit array at 7 T in the presence of B_1^+ inhomogeneity that matches the typical worst-case 3:1 range seen in human brain *in vivo*.

2. Theory

2.1. Parallel transmission RF design overview

Our goal is to design slice-selective 90° and 180° spin-echo excitations which produce a spatially uniform within-slice flip angle distribution using a highly inhomogeneous multi-channel parallel transmission system designed for the head at 7 T. We propose a two-stage design to achieve this goal: an initial (linear) approximation design and a (nonlinear) Bloch equation based iterative optimization design. In the initial approximation, the RF and gradient waveforms are designed based on the linear class of large-tip-angle (LCLTA) method [26,27] with the incorporation of a magnitude least square optimization (MLS) criterion [20,28] that substantially improves the excitation profile performance. This design method provides a fast algorithm to create large-flip-angle excitation that yields superior performance to the standard STA design. Nonetheless, the LCLTA design utilizes a linear approximation of the nonlinear Bloch equation, resulting in expected imperfections in the excitation profile when the pulses are driven to yield large flip angles. In the second part of the design, a Bloch equation based iterative optimization [24] is used to achieve the ultimate performance through a refinement of the first-stage design. In this optimization, the solution from the initial approximation process is used as an initial guess for an iterative optimization process that loops through a numerical solution of the Bloch equation to provide improvement to the excitation profile. Substantial reduction in computation time during the second design stage is achieved by the application of a local cost function evaluation combined with a spinor-domain based Bloch equation simulation [29].

2.2. Initial approximation design

The initial approximation design step utilizes the LCLTA design for parallel transmission proposed Xu et al. [26], with an extension of MLS optimization from [20]. Briefly, and following the notation in [26], the multidimensional excitation calculated for L coils using the LCLTA design is written as

$$\theta(r) = \gamma \sum_{l=1}^{L} S_l^*(r) \int_0^T B_1^{(l)*}(t) e^{-ik(t)\cdot r}\, dt, \tag{1}$$

where S_l^* and $B_1^{(l)*}$ are the spatial transmit sensitivity profiles and the RF voltage waveforms for coils indexed by l, with $*$ denoting complex conjugation, r the spatial variable, and $\theta(r)$ the target flip angle about the x axis after excitation. The term $k(t)$ represents the excitation k-space trajectory defined as $k(t) = -\gamma \int_t^T G(\tau)\, d\tau$, where γ is the gyromagnetic ratio, and G is the gradient, and T is the duration of the gradient waveform. After discretization in space and time, this expression can be written as a matrix equation, $\theta = Sb$, where the matrix S contains (the complex conjugate of) the transmit sensitivity profiles modulated by the Fourier kernel due to the k-space traversal, θ is the target flip angle in space, and the vector b contains (the complex conjugate of) the RF waveforms. With this formulation, the RF pulses can be designed by solving the MLS optimization

$$b = \arg_b \min\{\||Sb| - \theta\|_w^2 + \beta\|b\|_2^2\}. \tag{2}$$

Here, the optimization is performed over the region of interest (ROI) implied by a weighting, w, and the term $\beta\|b\|_2^2$ embodies the Tikhonov regularization that is used to control the integr ated RF power. The MLS optimization, as represented by $|Sb|$ in Eq. (2), is used instead of the standard Least Square (LS) optimization to limit the optimization to the magnitude of the flip-angle, allowing for flip-angle phase variation (i.e., variation in the axis of rotation). This has been found to achieve substantial gains in excitation magnitude performance over conventional LS optimization with little penalty in the image phase [20].

An inherently refocused spoke-based k-space trajectory similar to the ones described in [30] was used in this work to satisfy the "linear class" assumption for LCLTA design. In designing the spokes trajectory, we made use of the fact that the profiles of the coils do not differ from each other much along the z direction. As a result, we do not expect to achieve any excitation variation or acceleration in z, and simplified the design by restricting the RF pulse shape of all coils to a Hanning-windowed sinc in k_z. Consequently we only needed to calculate the amplitude and phase modulation for each of the sinc spokes. This design method have been demonstrated to perform well for low-flip-angle B_1^+ mitigation on our 8-channel setup at 7 T [20].

2.3. Bloch equation iterative optimization design

The aim of the iterative optimization is to improve on the excitation profile resulting from the initial linear approximation. The iterative optimization problem is stated as

$$\begin{aligned} &b = \arg_b \min\{\||m_{\text{actual}}(b)| - m_{\text{desired}}\|_w^2 + \beta\|b\|_2^2\} \\ &\text{s.t.}\|b\|_\infty < \text{RF voltage limit} \end{aligned} \tag{3}$$

where m_{actual} is the actual transverse magnetization profile created by the RF pulses obtained via Bloch equation simulation, and m_{desired} represents the desired transverse magnetization profile. Similar to the initial approximation design, an MLS condition is used to allow spatially-varying in-plane phase and to improve the magnitude design. To simplify the calculation the optimization is again limited to the complex amplitude of the sinc spokes. Furthermore, in this design stage, as part of Eq. (3) a hard limit on the maximum RF voltage is specified to accommodate hardware limits on the maximum voltage amplitude.

Powell optimization [31] is chosen as the method for the iterative optimization of Eq. (3). Similar to Conjugate-gradient methods, the Powell method is a direction-set method where line minimizations are performed successively along a set of directions [31]. However, unlike the conjugate-gradient methods, the gradient or derivative of the cost function is not used in updating this set of directions during the optimization. Without the gradient information, more iterations may be required for the algorithm to converge. Nonetheless, in cases where gradient evaluation is expensive, such as here, Powell optimization can be more efficient than conjugate-gradient search. In using Powell optimization to solve Eq. (3), the initial bases at the start of the optimization are set to be either the real or imaginary part of the amplitude of the sinc spokes, and the line minimizations are performed along the bases in a bounded region that is within the maximum RF voltage constraint.

To improve computational speed, the optimization is tailored to take advantage of the spin domain representation of the RF