Minimal-SAR RF Pulse Optimization in Parallel Transmission

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INTRODUCTION

Parallel transmission is an emerging technique that has great potential in many applications such as reducing selective RF pulse duration and improving B1 and B0 field inhomogeneity in high fields [1-3]. A potential issue in parallel transmission is elevated RF power deposition which is characterized by the specific absorption ratio (SAR). In parallel excitation, the effect of electric field/tissue interactions and superimposed fields from all channels can create localized hot spots". When high acceleration factors are used, SAR will dramatically increase because of the shortened RF pulse durations. At high fields, this problem is even more serious because SAR can increases quadratically with the static field strength. However, its practical implementation must be strictly subject to the FDA SAR limit. Several methods have been proposed to address this problem, either by exploiting the extra freedom in parallel transmission pulse design, or by using variable-density k-space trajectory [2-8]. To facilitate the parallel transmission imaging, we extend a recent methodology and other previous work by using a Lagrange function to optimize the excitation gradient waveforms in the parallel RF pulse design [4]. A significant feature of the new method is that it can model and optimize the SAR directly when the patient specific information is available. The method can achieve a global optimum under the given excitation pattern constraint.

METHOD

In this algorithm, we derive SAR as a function of gradient, with the constraints of the same excitation profile and pulse duration.

$$SAR(G) = \min_{\mathbf{g_{new}}} \sum_{q=1}^{Q} \left\{ \frac{1}{P} \sum_{p=1}^{P} \left[\frac{\sigma(\mathbf{r}_p)}{2\rho(\mathbf{r}_p)} \mathbf{EB}(\mathbf{r_p}, q) \mathbf{g}_{new}(q) / \mathbf{g}(q) \right] \right\} \text{ subject to } \sum_{q=1}^{Q} [\mathbf{g}(q)/\mathbf{g}_{new}(q) - 1] = 0 \text{ and } |\mathbf{g}_{new}(q)| < G_{\max}$$

where $\mathbf{EB}(\mathbf{r_p}, q) = \left[\left| \sum_{l=1}^{L} \mathbf{E}_{l,x}(\mathbf{r}) \mathbf{b}_{1,l}(q) \right|^2 + \left| \sum_{l=1}^{L} \mathbf{E}_{l,y}(\mathbf{r}) \mathbf{b}_{1,l}(q) \right|^2 + \left| \sum_{l=1}^{L} \mathbf{E}_{l,z}(\mathbf{r}) \mathbf{b}_{1,l}(q) \right|^2 \right]$ This problem is separable and is equivalent to minimize a Lagrange function. A global optimal can be obtained by taking the derivative of gradient. Then the trajectory will be adjusted to conform to the gradient constraint and slew rate constraint. The corresponding RF pulse sequences are computed using the method in [3].

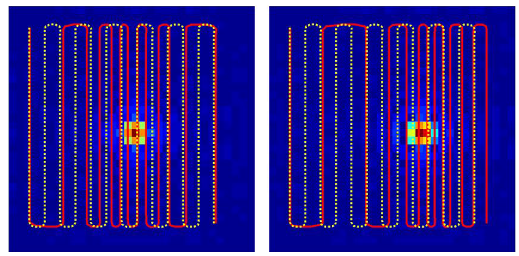

Figure 1. EPI excitation trajectories overlapped on the k-space spectrum of two oval patterns in simulation I (left) and simulation II (right). The yellow line is the conventional EPI; the red line is the optimized EPI.

SIMULATION RESULTS

A four-channel transmit coil and a 3D head model with known dielectric properties and tissue density were modeled at 4.7 Tesla (200 MHz) using xFDTD 6.3 bio-pro package (Remcom Inc. State College, PA). More details of the simulation are described in [7]. In particular, ideal RF current sources at 200 MHz were used as feeding source for coil decoupling. The xFDTD output gives the steady state 3D **E** fields and **B** fields produced by constant current excitations.

The proposed algorithms were implemented using Matlab (The Mathworks, Inc, Natick, MA) on a 2.39 GHz Dell laptop of 512 MB memory. Two excitation patterns were designed to simulate two field inhomogeneity scenario. Simulation I: In the first scenario, we aim to achieve B1 homogeniety within an oval region of the head. The oval has a radius of 5 cm. Simulation II: In the second scenario, oval the excitation pattern was modulated with a phase term, so that the corresponding k-space spectrum is shifted by $\pi/6$. This excitation pattern was designed to demonstrate the optimization performance when the k-space energy concentration has shifted away from k-space center.

For both simulations, the FOV is 32 cm, discretized over a 64x64 grid. When designing both conventional EPI and optimized k-space trajectory, maximum gradient and gradient slew rate are 5 gauss/cm and 15 gauss/cm/ms separately. Both k-space trajectories are designed to achieve a field of excitation (FOX) of 16 cm, 8 cm and 5.3 cm, which corresponds to a reduction factor R = 2, 4 and 6. A Bloch simulator was used to get the excited patterns (http://www-mrsrl.stanford.edu/). The optimized excitation k-space trajectories are shown in Fig.1. The excited patterns in Simulation I are shown in Fig. 2. The SAR maps from the conventional and the proposed method are shown in Figs.3 and 4.Note the significant reduction in SAR.

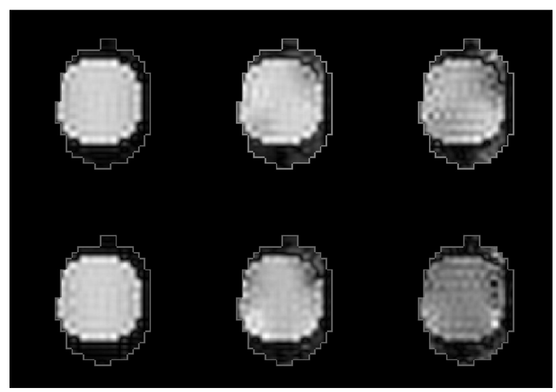

Figure 2. Excited patterns using: (upper row) conventional EPI; (bottom row) optimized EPI trajectory, for acceleration factors R = 2, 4 and 6 (From left to right)

DISSCUSSION A method was presented to design multi-channel RF pulses and gradient waveforms to achieve reduced-SAR for a given excitation pattern and pulse duration in parallel excitation. The simulation results show that the automatically adjusted excitation trajectories can adapt to the spectrum –of the excitation patterns. Future studies are required to validate the method for practical applications, and to improve the computation speed.

REFFERENCES: [1] Katscher U., et al., MRM 2003;49:144-150; [2] Zhu Y., et al., MRM 2004;51:775-784; [3]Grissom W., et.al, MRM 2006; 56:620-629; [4]Liu Y., et al., ISMRM 2007; [5]Xu D., et al., ISMRM 2007; [6]Wu X., et al., ISMRM 2007; [7] Yip CY., et al., ISMRM 2007;[8] Connoly S., et al., JMR 1988;78:440-458; [9] Boyd S., et al., Convex Optimzation, 2004.

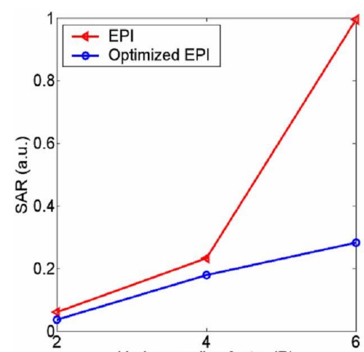

Figure 3. SAR comparison for conventional EPI and optimized EPI under acceleration factors R = 2, 4, 6

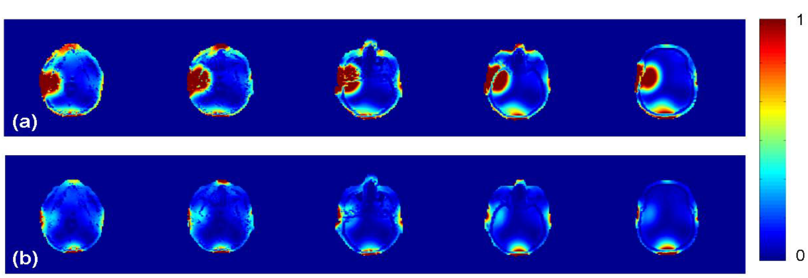

Figure 4. SAR maps of five slices from: (a) conventional design; (b) new design.