Automated Pulse Sequence Design for Minimal SAR in Parallel Transmission

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INTRODUCTION

Parallel transmission techniques have great potential in several applications such as reducing selective RF pulse duration and correcting B1 and B0 field inhomogeneity in high fields [1-3]. However RF power can increase significantly in parallel transmission, particularly with high reduction factors. Thus, its practical implementation is subject to the FDA SAR limit. Several methods have been proposed for this problem, either by exploiting the extra freedom in parallel transmission pulse design, or by using variable-density k-space trajectory [2-7]. In [7], both RF pulses and the excitation k-space trajectory were jointly optimized to minimize a cost function which incorporates both excitation error and RF power. In this abstract, we extend the methodology initially developed for 1-D single channel RF pulse design [8] to use a Lagrange function to optimize the gradient waveforms to achieve minimal SAR. As a result, multi-channel 2-D selective excitation pulse sequences are optimized in term of minimal SAR for a given excitation pattern and same pulse duration.

METHOD

The pulse sequenze design starts with a conventional gradient for constant-density k-space trajectory (EPI or spirals), and the corresponding RF pulses are computed using the method in [3]. Then the gradient and RF waveforms are iteratively adjusted to achieve minimum SAR. Specifically, after incorporating the equal excitation pattern facsimile conditions [8], local averaged SAR within an region of interest (ROI) can be derived as $SAR \propto \sum_{n=1}^{N} f\left(g(n)\right)$, where $f\left(g(n)\right) = \left|\operatorname{avg}_{\mathbf{r}\in \mathrm{ROI}} \sum_{l=1}^{L} B_{1,l}(n)\mathbf{E}_l(\mathbf{r})\right|^2 g(n)/G(n)$, where $B_{1,l}$, $\mathbf{E}_l, l = 1\ldots,L$, are the initial RF pulse and the E field of the l-th channel, $G(n), g(n)$, $n = 1,\ldots,N$ are the initial and optimized gradient vectors for the n-th time. The SAR is minimized under the constraints of the same pulse duration i.e., $\sum_{n=1}^{N}\left(G(n)/g(n)-1\right)=0$, and of that all components of g is below the maximum gradient amplitude. To find the optimal gradient waveforms, a Lagrange function is formed as $L(g,\lambda,\mu)=\sum_{n=1}^{N} f(g(n))+\lambda_n\left(G(n)/g(n)-1\right)+\mu_n\left(g(n)-G_{\max}\right)$ where λ and μ are the Lagrange multipliers [9]. For a 2-D EPI trajectory, the solution is $g_x(n)=\min\left\{\operatorname{Re}\left(cG(n)/\left|\operatorname{avg}_{\mathbf{r}\in ROI}\sum_{l=1}^{L} B_{1,l}(n)\mathbf{E}_l(\mathbf{r})\right|\right), G_{\max}\right\}$, where the constant c can be solved iteratively until both constraints are satisfied. This algorithm can be modified to minimize the maximal local SAR by changing $\operatorname{avg}_{\{\mathbf{r}\in ROI\}}\{\bullet\}$, to $\max_{\{\mathbf{r}\in ROI\}}\{\bullet\}$.

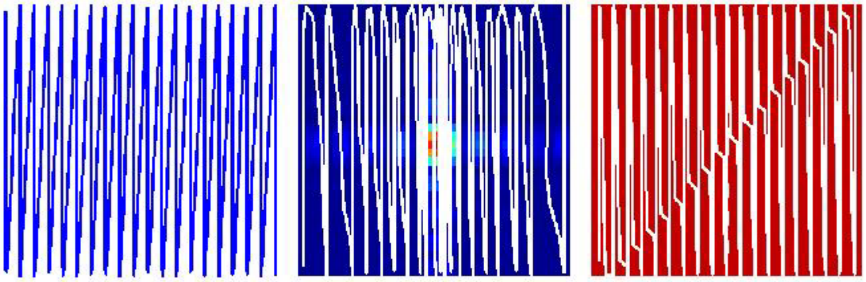

Figure 1. Excitation trajectories: (Left) EPI; (Middle) optimized EPI overlapped on the spectrum of a large square pattern; (Right) optimized trajectory for a small square pattern.

SIMULATION RESULTS

The B and E transmit sensitivities of a 4-channel transmit coil with a 3D head model were simulated at 4.7 Tesla using xFDTD (Remcom Inc. State College, PA). Each of the elements (rung) is modeled as a slotted TEM cavity resonator. The rung has the size of radius=140 mm, length=250 mm, and width=20 mm. The radius of the shield is 165mm. Ideal RF current sources are used for inter-coil decoupling. Two square patterns with the size of ($100\text{x}100\text{mm}^2$ and $10\text{x}10\text{mm}^2$) were excited using the conventional and proposed methods. The initial RF pulses and constant-density EPI trajectory were initially designed to achieve a FOX of 380 mm and spatial resolution of 10 mm. A Bloch simulator was used to get the excited patterns (http://www-mrsrl.stanford.edu/). Figure 2 shows the excited large square pattern, without detectable degradation. Figure 3 shows the RF waveforms from channel 1 before and after the pulse sequence optimization. Table 1 lists the corresponding pulse durations and the normalized SAR values. Both the RF amplitudes and SAR were significantly reduced. The average SAR was reduced to 30%-50% by using the optimized pulse sequences, for both accelerate (R=2) and non-accelerated (R=1) excitations.

Table 1. Pulse durations and normalized SAR before and after pulse sequence optimization (for the large pattern)

	Pulse Duration	SAR
EPI, R = 1	1.9 ms	0.19
Minimal SAR EPI, R = 1	1.9 ms	0.09
EPI, R = 2	1 ms	0.39
Minimal SAR EPI, R = 2	1 ms	1

DISSCUSSION A method was presented to design multi-channel RF pulses and gradient waveforms to achieve minimal SAR for a given excitation pattern and pulse duration in parallel excitation. The simulation results show that the automatically adjusted excitation trajectories become denser in k-space center where most of the spectrum power is located which agrees with [7]. Future studies are required to validate the method for practical applications, and to improve the computation speed.

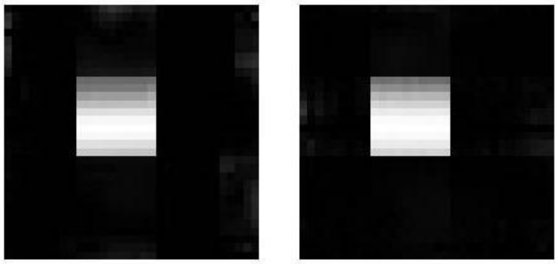

Figure 2. Excited patterns using: (Left) EPI; (Right) minimal SAR EPI trajectory (Fig1 middle).

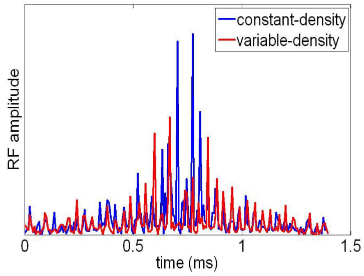

Figure 3. RF waveform from channel 1 before and after SAR optimization

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.