shimming with SAR reduction in high-field MRI

H.W. Son \(a\), Y.K. Cho \(a\), A. Gopinath \(b\), J.T. Vaughan \(b\), C.H. Lee \(c\) & H. Yoo \(d\)

\(a\) School of Electronics Engineering, College of IT Engineering, Kyungpook National University, Daegu, Korea
\(b\) Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN, 55455, USA
\(c\) School of Technology Management, Ulsan National Institute of Science and Technology (UNIST), Ulsan, Korea
\(d\) Department of Biomedical Engineering, School of Electrical Engineering, University of Ulsan, Ulsan, Korea

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In high-field magnetic resonance imaging (MRI) systems, parallel excitation with a multi-channel transmitter and receiver has been widely investigated to mitigate $B_1^+$ inhomogeneity. Multi-channel RF coils employed in the parallel imaging may alleviate the non-uniformity in the $B_1^+$ field and each element can be independently controlled by adjusting the phase and amplitude of the excitation. In this paper, convex optimization for each coil elements to homogenize $B_1^+$ and to reduce $E$ fields is proposed. Improved homogeneity and reduced specific absorption rate over the whole field of view is achieved.

1. Introduction

High-field magnetic resonance imaging (MRI) systems with static $B_0$ fields have higher signal to noise ratios and higher resolution in the images.[1,2] With increasing interest in using high-field MRI systems, parallel excitation with a multi-channel transmitter and receiver has been widely investigated to mitigate $B_1^+$ inhomogeneity.[3,4] At high fields, reducing specific absorption rate (SAR) levels is also required to accelerate anatomical and functional applications.[5] Traditional volume RF birdcage coils used in medical clinics with single-channel excitation do not provide the additional degrees of freedom required to change the $B_1^+$ field distribution. Multi-channel RF coils employed in the parallel imaging may alleviate the non-uniformity in the $B_1^+$ field and each element can be independently controlled by adjusting the phase and amplitude of the excitation.[6]

In this study, we describe an efficient method for both $B_1^+$ field homogeneity and SAR reduction. To demonstrate the technique, 16-channel transmission line coil elements were modelled together with a human head phantom at 300 MHz for the 7-T MRI system and $B_1^+$ fields and $E$ fields are obtained by finite difference time domain numerical simulations using the SEMCAD X.[7] The coils support transverse electromagnetic (TEM) modes and each coil comprises 16-transmission line elements that can be microstrip elements. Convex optimization method is used to determine the magnitude and phase of the excitation for each coil elements to homogenize $B_1^+$ and to reduce...
fields. The need to obtain rapid solutions is important to minimize the scan time in the MRI systems; therefore, convex optimization is a good method. In this paper, the proposed method achieves improved homogeneity and reduced SAR over the whole field of view (FOV).

2. Method

To calculate the $B_1^+$ and $E$ field, distribution of each of RF coil elements in the 16-channel transceiver array and the input power of the RF resonators is normalized to 1 watt in the simulations. The primary objective of this study is to mitigate destructive $B_1^+$ interferences resulting in inhomogeneity and decrease the SAR in the entire FOV. Since $B_1^+$ and $E$ fields are proportional to $w$, which is linear amplitude and phase of the each generated element, the total field representation for the positively polarized transmitted field with $w$ at each element is written as $\sum B_1^+ w$.

subject to $B_1^+ w = 1$, $c =$ centre of FOV where $E_f$ and $B_1^+ c$ represent $E$ in the FOV and at the centre of the FOV, respectively. The total SAR can be expressed as $\text{SAR} = \frac{\sigma}{\rho} |\sum E w|^2$ where $\sigma$ and $\rho$ represent the conductivity and mass density of the object, respectively. Once the problem can be formulated in a convex way, the optimal solution is globally minimized. In addition, the convex technique is very fast to get the optimal solutions. Before the shimming technique is applied, each RF coil element has an identical input power parameter. A phase shimming technique, which makes each element phase of $B_1^+ c$ identical, is also used and compared to the proposed method. The convex optimization process can be performed in approximately 2 s.

Figure 1. 16-channel transmission line (TEM) head coil model (a) with a realistic head model on axial view (b).
3. Result

A figure of 16-channel transmission line head coil model with individual elements is shown in Figure 1(a). The amplitude and phase of the currents driving individual coil elements may be varied to develop the desired $B_{1+}$, $E$ and SAR values. Duke model from Virtual Family Models is used to simulate a realistic head model (Figure 1(b)). Figure 2 shows the comparison of $B_{1+}$, $E$ and SAR between no shimming, phase shimming and proposed shimming methods in an axial slice of the head model. Before shimming, there are destructive $B_{1+}$ interferences and high SAR in the periphery of the head. To alleviate $B_{1+}$ inhomogeneity, the phase shimming is used and it provides more homogenous $B_{1+}$ and lower SAR.

The proposed convex optimization method concerning $E$ fields also results in better $B_{1+}$ distributions and SAR is more reduced. When $B_{1+}$, $E$ and SAR values are calculated, all the values are normalized to their maximum values, respectively. Corresponding

![Comparison of $B_{1+}$, E and SAR on axial views with no shimming (a), phase shimming (b) and proposed shimming (c).](image)

STD=0.1464, MEAN=0.1246
STD=0.0248, MEAN=0.0968
STD=0.0962, MEAN=0.1392

STD=0.1239, MEAN=0.1670
STD=0.0811, MEAN=0.1050
STD=0.0837, MEAN=0.0659

STD=0.1117, MEAN=0.1555
STD=0.0486, MEAN=0.0635
STD=0.0681, MEAN=0.0427
standard deviation (STD) and mean value (MEAN) are calculated and the decrease of the mean SAR ranges from 0.139 to 0.043 (70% reduction). Improvement factor (IF) and homogeneity factor (HF) are defined as follows:

\[ IF = \frac{\text{MEAN}(B^+_1)}{\text{MEAN}(\text{SAR})} \]

\[ HF = \frac{\text{STD}(B^+_1)}{\text{STD}(\text{SAR})} \]

The proposed method provides better results and the comparison of IF and HF is shown in Table 1.

### Table 1. Comparison of IF and HF.

<table>
<thead>
<tr>
<th></th>
<th>Before shimming</th>
<th>Phase shimming</th>
<th>Proposed shimming</th>
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<tbody>
<tr>
<td>IF</td>
<td>0.8951</td>
<td>2.5341</td>
<td>3.6417</td>
</tr>
<tr>
<td>HF</td>
<td>0.0141</td>
<td>0.0104</td>
<td>0.0080</td>
</tr>
</tbody>
</table>

4. Conclusion

A convex optimization method for \( B^+_1 \) shimming and effective SAR reduction has been introduced in parallel transmission. The results for 16-channel transmission coil elements at 7 T show that the convex optimization technique is more efficient in reducing SAR than a phase shimming method. In addition, homogeneous \( B^+_1 \) and SAR are obtained after the proposed method was implemented. This fast convex optimization in multi-channel transceiver coils can be considered as a good strategy to control the individual element excitation parameters for overcoming \( B^+_1 \) inhomogeneity and SAR limitations in high-field MRI.

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References


