

Ultra-Short Gradient Coil Design

Beibei Zhang$^{1,5}$, Blaine Chronik$^{2,5}$, Brian Rutt$^{1,2,3,4,5}$

Depts. of $^1$Electrical and Computer Engineering, $^2$Physics and Astronomy, $^3$Diagnostic Radiology and $^4$Medical Biophysics, University of Western Ontario, $^5$Imaging Research Labs, The John P. Robarts Research Institute, London, Ontario, Canada N6A 5K8

Introduction

The development of ultra-short MRI systems is an important goal for interventional, cardiac and head-only applications. We have conducted a design study to assess the performance trade-offs for ultra-short, symmetric gradient coils, where the performance parameters of interest are gradient efficiency, coil inductance and region of uniformity (ROU) size/position relative to coil dimensions.

Methods

We used the constrained current minimum inductance (CCMI) target field method developed in [1] for the design of short gradient coils. This algorithm solves for the current distribution of minimum inductance satisfying a set of constraints. We imposed outer current/closure constraints to define finite coil length, and set field constraints to define the central ROU. The configuration of the constraints is shown in Figure 1.

Field constraints (crosses) were placed close to the coil surface (at $c = 0.8a$ to $0.9a$ for coil radius $a$), and spaced closely together (spacing $d = 0.065a$ to $0.085a$) to prevent instability in the resulting current density. Current constraints (short vertical lines) were placed from $-3.2a$ to $-1.2a$ and from $1.2a$ to $3.2a$, and current closure constraints (dashed vertical lines) were placed at $-1.2a$ and $1.2a$; these current and closure constraints produced ultra-short coils of aspect ratio 1.2:1. For each choice of “boundary zone” $\Delta$, (distance between the edge of the coil and the outermost field constraint), we optimized ROU extent by varying the field radius $c$ and field spacing $d$. Coil performance was then assessed according to the resulting efficiency $\eta$, inductance $L$, ROU length $\rho$, and distance from coil edge to the 50% ROU edge, $\delta$, for a fixed wire density.

Results and Discussion

Maximum ROU extent was achieved with $c = 0.8a$, $d = 0.085a$, and $\Delta = 0.3075a$. The corresponding gradient uniformity plot is shown in Figure 2. The vertical lines at $\pm 24\text{cm}$ indicate the edges of the coil. The 10%, 30%, and 50% ROU contours are displayed in the plot. Notice that there are secondary ROUs of considerable size within the fringe field, largely outside the coil. This interesting observation suggests the possibility of operating the coil in dual mode – for head/neck imaging, for example, this may allow brain imaging in the central ROU and neck imaging in the outer ROU.

Figure 2. Percent deviation from gradient uniformity

To investigate coil optimization for head-only imaging, we explored the trade-off between boundary zone size (controlled by changing $\Delta$ and assessed by measuring the resulting $\delta$) and coil performance, with other parameters held constant ($a = 20\text{cm}$, $c = 16\text{cm}$, $d = 1.7\text{cm}$ wire density = $1000\text{m}^{-1}$). Table 1 illustrates the rapid fall in efficiency as we demand $\delta$ values below $0.6a$ ($12\text{cm}$), and that for a 35% decrease in $\Delta$, we only achieve an 11% decrease in $\delta$. For $\Delta$ less than $0.3a$ ($6\text{cm}$), the CCMI design algorithm failed to converge. The length and efficiency of the secondary ROU are also displayed in the table.

Table 1. Coil parameters versus $\Delta$

<table>
<thead>
<tr>
<th>$\Delta$ (cm)</th>
<th>$\delta$ (cm)</th>
<th>$\rho$ (cm)</th>
<th>$\eta$ (mT/m/A)</th>
<th>$\Omega$ (cm)</th>
<th>$\eta$ (mT/m/A)</th>
<th>$L$ ($\mu\text{H}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.6</td>
<td>12.1</td>
<td>23.8</td>
<td>0.349</td>
<td>15.1</td>
<td>0.246</td>
<td>802</td>
</tr>
<tr>
<td>8.7</td>
<td>11.8</td>
<td>24.4</td>
<td>0.245</td>
<td>15.1</td>
<td>0.180</td>
<td>547</td>
</tr>
<tr>
<td>7.8</td>
<td>11.4</td>
<td>25.2</td>
<td>0.205</td>
<td>15.0</td>
<td>0.154</td>
<td>470</td>
</tr>
<tr>
<td>7.0</td>
<td>11.0</td>
<td>26.0</td>
<td>0.168</td>
<td>15.1</td>
<td>0.129</td>
<td>399</td>
</tr>
<tr>
<td>6.2</td>
<td>10.8</td>
<td>26.4</td>
<td>0.134</td>
<td>15.1</td>
<td>0.105</td>
<td>349</td>
</tr>
</tbody>
</table>

Conclusion

The CCMI algorithm allows rapid and thorough investigation of the design space for ultra-short gradient coils. For a 1.2:1 aspect ratio gradient coil, it is extremely expensive to decrease the unusable boundary zone $\delta$ below $0.6a$. Dual ROU coils may allow simultaneous imaging inside / outside the gradient coil.

References and Acknowledgements


The authors acknowledge financial support from MRC Canada.