A New Analytical Approach to RF Coils at High Frequency: The Spiral Coil Example

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Introduction: RF inhomogeneity continues to be a major challenge in today's high-field MRI. Among various RF coils designed to address this problem, a spiral coil [1, 2] has been constructed to improve field homogeneity for 4T imaging. We present an efficient analytical modeling of the spiral coil for theoretical insight as to why and how the spiral coil works, and its improved uniformity compared with a birdcage coil. We first show that the analytical results are consistent with (the limited) experimental results reported and (preliminary) numerical simulations. We then further demonstrate that an optimal spiral coil can improve RF field homogeneity for higher frequencies up to 400MHz.

Methods: A conventional birdcage model and an ideal spiral coil model are illustrated in Figure 1. The birdcage model has eight straight axial conductors evenly distributed on a cylinder with diameter 25cm and length 30cm. The spiral coil is formed by twisting the conventional birdcage so that all straight axial conductors now become spirals [1, 2]. The orientation angle of the spirals (α in Figure 1) is 20.5° (7.3°) so that the axial current phase variation is approximately 0.21rad/cm (0.63 rad/cm) for 170MHz (400MHz). There are no end rings in the spiral model. To simplify the calculation, a constant dielectric is assumed over all space with no conductivity (the errors of these approximations are estimated with numerical simulations). To calculate the RF field, we divide the conductors of both models into a number of short current-carrying elements. For each of these elements, a simple but powerful approach for determining the vector potential is $\delta\boldsymbol{A}(\boldsymbol{r})\approx\mu_0\boldsymbol{I}(\boldsymbol{r}_0)\cdot\delta l\cdot\exp(ik|\boldsymbol{r}-\boldsymbol{r}_0|)/4\pi|\boldsymbol{r}-\boldsymbol{r}_0|$ where $\boldsymbol{r}_0$ and δl are the element position and length, respectively, $\boldsymbol{I}$ is the current on the element, and k is the wave number. The birdcage (spiral) coil has only axial (both axial and azimuthal) elements. We sum the element contributions to obtain the total vector potential and RF field (curl of the vector potential).

Results and Discussion: The RF field distribution is calculated for both birdcage and spiral coils with the above methods. The dielectric constant is chosen to be 56 to simulate human tissue. Both coils are driven in quadrature for circularly polarization. There is no phase or amplitude variation of the current along one single conductor for both models, and, with the same amplitudes for each spiral, the relative current phase is chosen to yield the familiar birdcage sinusoidal azimuthal dependence. Figures 2 and 3 show the RF field distribution in the central axial plane for both models at 170MHz and at 400MHz. The conventional birdcage model has a 61% drop in the RF field strength at 7.5cm from the center while the spiral coil has a lower value of 35% at 170MHz, while at 400MHz the drop is 62% for the conventional birdcage model and 45% for the spiral birdcage model. These results, consistent with previous numerical simulations, support the experimental results reported in references [1, 2] and predict that spiral coils can be applied for higher frequencies. In fact, by properly choosing the orientation angle of the spirals, a phase variation along the axial direction can be introduced to match the wave number (k) of the wave propagation in the dielectric. As a result, the oscillation of the RF field demanded by Maxwell equations can be approximately restricted to the axial direction and the homogeneity in the transverse plane is thereby improved. This possibility has been discussed in other experimental [3] and theoretical work [4]. In particular, we have found that the optimal spiral coil can produce a sine-like oscillation in one RF field component and a cosine-like oscillation in the other along the axial direction (with the results validated with a full numerical computation). While the end ring effect is still to be studied, the RF field magnitude is found to be more uniform along the axial direction than that of a birdcage coil. Motivated by these encouraging results, we conclude that such an analytical approach can serve to optimize the number of elements and spiral orientation angle and provide input for a full validation via electromagnetic numerical software.

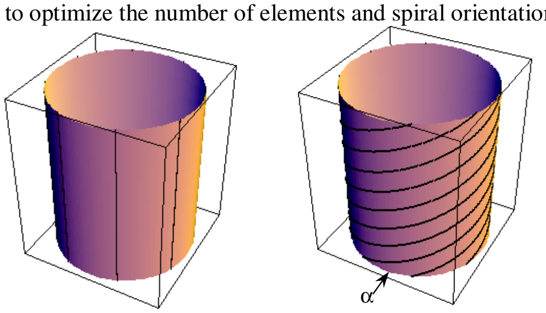

Figure 1: Models of a conventional birdcage coil (left) and a spiral coil (right).

References:
[1] Alsop D, Connick T and Mizsei G, MRM, vol 40: 49-54, 1998
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[3] Foo TKF, Hayes CE and Kang YW, MRM vol 23, 287-301: 1992
[4] Chen X, Eagan TP, Baig TN and Brown RW, Proc. Intl. Soc. Mag. Reson. Med. 15 (2007), 1069

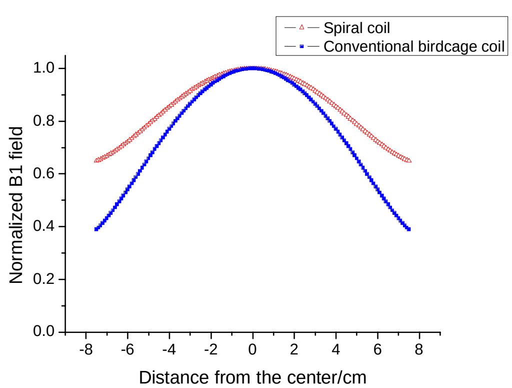

Figure 2: Normalized B1 field profile in the central axial plane for the spiral coil (red) and the traditional birdcage coil (blue) at 170MHz.

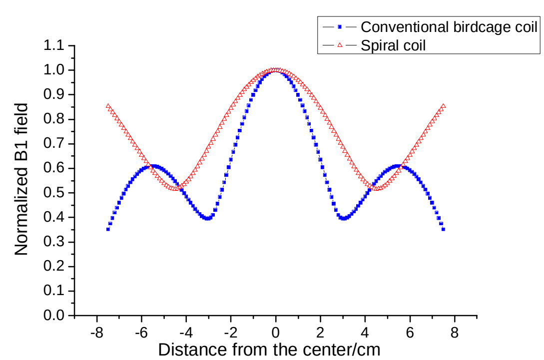

Figure 3: Normalized B1 field profile in the central axial plane for the spiral coil (red) and the traditional birdcage coil (blue) at 400MHz.