Simulating the SNR of High-Field RF Coils by the Surface Integral-Equation Method

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Introduction: Full-wave electromagnetic simulations have gained much popularity in high-field RF coil design. As the wavelength becomes comparable with the size of the phantom and RF coils, dielectric resonance and wave attenuation effects make RF coil design depend more on the knowledge of the actual electromagnetic field distribution inside phantom, which can only be sought by the rigorous solution of Maxwell's equations. In this work, we developed a surface integral-equation (SIE) approach for evaluating the SNR of RF coils. Compared with the FDTD method, SIE method is much better at resolving complex and very fine geometric structures that are commonly encountered in MRI coil design.

Methods: The SIE approach seeks for the solution of equivalent currents instead of the field directly. It starts from decomposing the total field as the combination of the incident and the scattering fields as the following

$$\vec{E}_0 = \vec{E}^{inc} + \vec{E}^s_{10} + \vec{E}^s_{00}$$
$$\vec{H}_0 = \vec{H}^{inc} + \vec{H}^s_{10} + \vec{H}^s_{00}$$

In coil design, the incident field is the feed of RF coils. The scattering field is expressed in terms of vector potentials A and F as

$$\vec{E}^s_{ij} = \frac{\nabla(\nabla\cdot\vec{A}_{ij}) + k_j^2\vec{A}_{ij}}{j\omega\epsilon_j} - \nabla\times\vec{F}_{ij}$$
$$\vec{H}^s_{ij} = \nabla\times\vec{A}_{ij} + \frac{\nabla(\nabla\cdot\vec{F}_{ij}) + k_j^2\vec{F}_{ij}}{j\omega\mu_j}$$

and the vector potentials are related to the equivalent electric and magnetic currents on surfaces by Green's function as

$$\vec{A}_{ij}(\vec{r}) = \int\int_{S_i'} \vec{J}_i(\vec{r}')G_j(\vec{r},\vec{r}')ds'$$
$$\vec{F}_{ij}(\vec{r}) = \int\int_{S_i'} \vec{M}_i(\vec{r}')G_j(\vec{r},\vec{r}')ds'$$

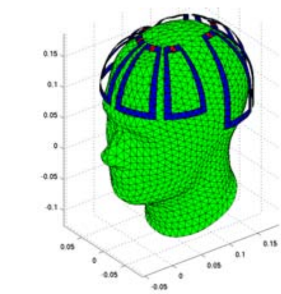

Figure 1: The computer model of the human head and RF coils.

The scattering field expression is derived in each region. By enforcing field continuity on the interface between different media, a set of coupled equations are established with the equivalent currents as the unknowns. The electromagnetic field distribution is calculated after solving the equivalent currents. Because the SIE approach formulates equations on surfaces, much less number of unknowns is involved comparing with the FDTD method. Furthermore, complex and fine geometric structures bring no additional computational overhead because the local mesh size can be as small as desired.

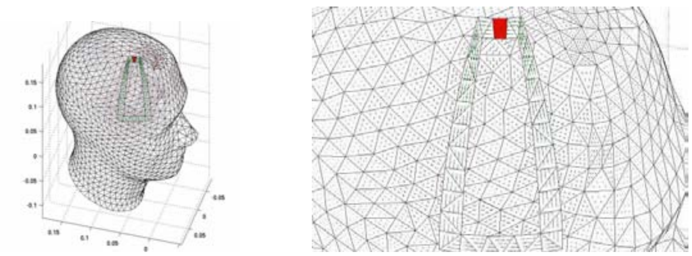

Figure 2: Left: Equivalent current distributions on one coil and the phantom surface. Right: the zoomed view.

Results and Discussion: An in-house computer program was implemented with the standard ANSI C++ language and compiled on Linux system. We applied the method to study the SNR of an eight-channel coil array for brain imaging at 7.0 Tesla. The coils and the human head are modeled with triangular patches as shown in Fig. 1. The human head model is based on the Specific Anthropomorphic Mannequin (SAM) model 2). The SAM model is constructed in such a way that 90th-percentile of adult male head, which were measured by the U.S. Army, are within its dimensions. The phantom is filled with brain equivalent (εr=45.3 and σ=0.87 at 300 MHz). As we see, the geometry of both coils and the head can be *exactly* modeled without using the staircase approximation as in FDTD. The mesh consists of 3320 triangular patches, which result in 9808 unknowns. On a 2 GHz AMD Opteron 246 processor with 2 GB memory, it took about 4 minutes to solve the current distribution (the result of one coil element is shown in Fig. 2.). The field distribution is calculated from the current distribution and thereafter the phase-sensitive combined SNR maps. The results on three observation slices are shown in Fig. 3. It is observed that due to the shorter wavelength effect, the SNR map is distorted. This agrees well with previous results obtained by the FDTD method 3). If the same problem is simulated by the FDTD method with the same resolution, at least 100 million unknowns would be involved.

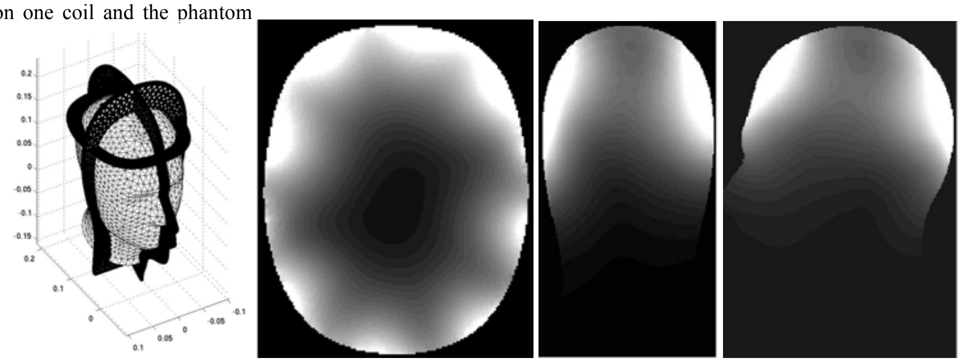

Figure 3: Left: the axial, coronal and sagittal observation slices where the combined SNR is calculated. Mid-left: the axial SNR map. Mid-right: the coronal SNR map. Right: the sagittal SNR map.

Conclusion: We developed a surface integral-equation approach for simulating the SNR of RF coils. Numerical results show its accuracy of geometric modeling and the efficiency. This method is useful in general RF coil design at high-field.

References: 1) R.F. Harrington Field computation by method of moments. IEEE Press, 1993. 2) IEEE standard 1528-2003. 3) Ledden P. et al, ISMRM, Honolulu, 2002. p 324.