Rapid B1 field calculation using integral equations for RF shimming

H. Yoo[1,2], A. Gopinath[1], and T. Vaughan[1,2]
[1]Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN, United States, [2]Department of Radiology, Center for Magnetic Resonance Research, Minneapolis, MN, United States

Introduction: Magnetic resonance imaging (MRI) is an important tool in clinical diagnosis and high field MRIs provide better signal to noise ratios (SNR) with transmission line (transverse electromagnetic (TEM)) coils. High field RF coil design with the human subjects is challenging due to the wavelength effect and coupling. The TEM coils are close to the human subject and strong coupling occurs between the coil and the human subject. To obtain the RF B_1 field in the phantom and human body, the combined field integral equations (CFIE) including the TEM coil are solved. In this method of moments solution, triangular patches on the surface are used with the Rao-Wilton-Glisson (RWG) basis functions. In this paper, the single TEM coil is modeled for the 9.4T (400MHz) MRI system and subsequently, the electromagnetic scattering fields with the human phantom model are solved. Numerical results are rapidly obtained and accurate B_1 fields are evaluated in the phantom for the 9.4T MRI system. The rapid B_1 field solutions will be used for RF shimming initially with phantoms and subsequently in the human head to optimize image quality.

Method: To calculate electromagnetic scattering from the human head phantom, the combined field integral equations are solved by the method of moments and the equivalent surface current method to reduce computational time. For dielectric scatterers, the combined field integral equation (CFIE) formulation may be used to find the equivalent currents on the enclosing interfaces. In order to transform the combined integral equation into a matrix equation, the surface of the objects has a triangular patch model with Rao-Wilton-Glisson (RWG) basis functions. The following matrix equation is obtained for electromagnetic scattering by homogeneous lossless and lossy dielectric objects:

$$\begin{bmatrix}[Z] & [C]\\ -[C] & [Y]\end{bmatrix}\begin{bmatrix}[J]\\ [M]\end{bmatrix}=\begin{bmatrix}[V]\\ [H]\end{bmatrix} \qquad [1]$$

where [Z], [Y], and [C] are the impedance, admittance, and off-diagonal submatrices, respectively. [V] and [H] are elements of electric and magnetic field excitation while [J] and [M] are the electric and magnetic current coefficients to be determined.

Simulation results: The half-wavelength TEM coil element with the center feed modeled at 400MHz for 9.4T MRI systems was used in these simulations. Subsequent simulations will use shunt capacitors loaded and end fed elements will be used. In Fig. 1, the dimension of the coil is shown and the substrate dielectric constant, ε_r=2.18 is used. To find a resonant frequency, input impedance and return loss (S11) are plotted in Fig. 2. At approximately 400MHz, the input resistance is about 75Ω and the input reactance is nearly zero. After modeling the TEM coil at the resonant frequency, elements of field excitation in Eq.[1] are calculated, then the equivalent current coefficients can be determined over the phantom. The phantom is a sphere, which is 10cm in radius and is filled with brain-equilvalent (ε_r=58, σ=0.6). The TEM coil is positioned 10mm away from the phantom (Fig 3), and Fig. 4 shows the transmit B_1 fields in the axial slice of the center of the phantom with excitation of one element.

Conclusion: The combined integral equation (CFIE) method to analyze the B_1 fields using TEM coils in high field MRI systems has been demonstrated. The CFIE method provides good modeling flexibility and solution accuracy for coils and phantoms by using triangular patches and the RWG basis functions. After modeling the TEM coil at the resonant frequency and obtaining the equivalent current unknowns over the phantom, the internal fields in the phantom were calculated. Numerical results show rapid, efficient and accurate B_1 fields after normalization for the 9.4T MRI system. In this paper, the single TEM coil with the phantom is presented. The method is to be extended to human models for RF B_1 shimming for multi channel coils in high field MRI systems due to its exceptional computational rapidity.

References: (1) Rao et al, IEEE Trans Antennas and Propagation 30, 409 (1982) (2) Umashankar et al, IEEE Trans Antennas and Propagation 34, 758 (1986) (3) S. Makarov, Antenna and EM modeling with MATLAB, Wiley (2002) (4) Wang et al, Phys. Med. Biol. 51, 3211 (2006) (5) R. Harrington, Field Computation by Method of Moments, IEEE (1993) (6) Vaughan J et al, MRM 2001:24-60 (7) Vaughan J et al, MRM 2006:1274-1282 (8) Vaughan J, U.S. patent 6,633:161, 2003

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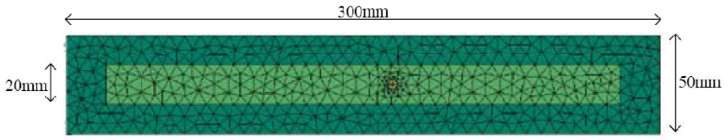
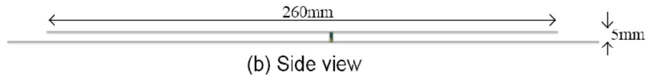


(a) Top view



(b) Side view

FIG. 1. TEM coil model.

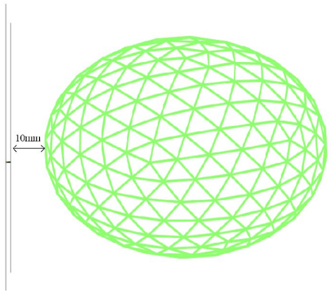
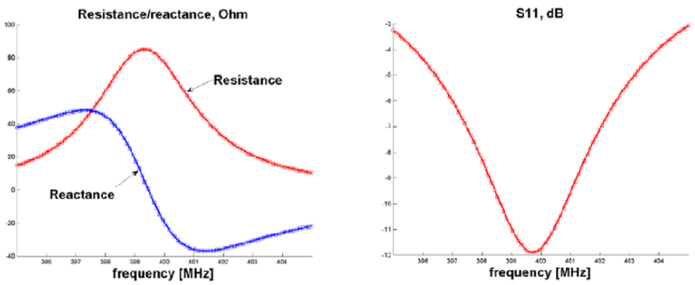


FIG. 3. TEM coil and phantom model



(a) Input impedance (b) Antenna retrun loss (S11)

FIG. 2. Input impedance and return loss (S11)

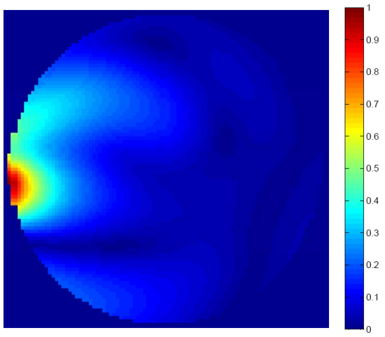


FIG. 4. $|B_1^+|$ result in the phantom