Theoretical determination of the dielectric constant for passive RF shimming at high field

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Introduction: Optimal image quality for MRI at high fields requires a homogeneous RF (Bf) field among others; however, dielectric properties of the human body result in severe Bf field inhomogeneity. These are resulted from constructive and destructive RF interactions of complex wave behaviour, which become worse with increasing Larmor frequency. Placement of a shim object with high-dielectric constant adjacent to the body has been proposed as a method for reducing Bf inhomogeneity by altering wave propagation within the volume of interest [1, 2, 3, and 4]. Selecting the appropriate permittivity and the quantity of material for the correction of Bf field is essential. While previous work determined primarily empirically the dielectric properties of the shim object, this work introduces a theoretical framework for calculating the requisite dielectric constant of the passive shim material and verifies the accuracy using simulated field maps.

Theory and Methods: The human head is approximated by a cylinder with radius r1 of 20 cm. The head lies inside a TEM coil with inner and outer radii r2 and r3 of 28 and 34 cm, respectively. The head and coil are coaxial (Fig. 1). The relative permittivity and conductivity of brain is εr = 58 and σ = 0.3S/m, respectively; and both the brain-to-coil and inner-to-outer coil spaces are filled with air with permittivity ε0 [2]. It is assumed that Bf field propagates along the B0 direction. The general solution of the propagating electromagnetic wave has a unique solution at each region with unknown amplitudes. After applying the boundary conditions to wave solutions in each region, the characteristic equation can be determined [5]. The characteristic equation can further be simplified by substituting the first terms in series expansion of the Bessel function. The simplified characteristic equation is

\[ f(k_{\rho 0}, k_{\rho}, k_{\omega 0}, k_{\omega}, k_z) = r_1^2 - k_{\rho 0}^2 \cdot k_{\rho}^2 \cdot \left( k_z^2 - k_{\omega 0}^2 \right) \cdot \left( r_2^2 - r_1^2 \right) \cdot \alpha + k_{\omega 0}^2 \cdot (2k_{\rho 0}^2 \cdot (r_3^2 - r_1^2) + k_{\omega 0}^2 \cdot (r_3^2 + r_1^2) - k_{\rho 0}^2 \cdot k_{\rho}^2 \cdot \alpha - k_{\omega 0}^2 \cdot \alpha) = 0 \]  

Here k, k0, k, and kρ are the brain, air, axial and radial propagation constants respectively. The k and kρ characterize the RF field amplitude distribution within the brain, where α and α′ are given below.

\[ \alpha = -2 \cdot (r_1^2 + \pi \cdot r_1) / \pi^2 \cdot r_1 \cdot r_3^2 \cdot k_{\rho 0} \]  

\[ \alpha' = -2 \cdot (r_1 + \pi \cdot k_{\rho 0} \cdot r_3) / \pi^2 \cdot r_1 \cdot r_3 \cdot r_2^2 \cdot k_{\rho 0} \]  

The values of k and kρ depend on the dielectric properties within the brain and brain-to-coil region.

\[ k_0^2 = k_0^2 - k_z^2 \]  

\[ k_{\rho 0}^2 = k_{\rho 0}^2 - k_z^2 \]  

Loading with high dielectric material into the brain-to-coil air region significantly influences on the propagation characteristics of the head coil which is demonstrated by changes in propagation constant. The loading with high dielectric material into the brain-to-coil air region significantly influences on the propagation characteristics of the head coil which is demonstrated by changes in propagation constant. The modified characteristic function can be factored to express the kz as a function of the kρ. Based on this relationship between radial and axial propagation constants, it is possible to maximize kz and minimize kρ. Additionally, the modified characteristic function can also be expressed as a function of kz and effective dielectric constant (ε) in the body-to-coil region, i.e. g(kz, ε). The range of required effective ε and corresponding kz can then be determined when the modified characteristic function g(kz, ε) approaches zero. Once the maximal kz has been determined, the requisite effective ε for Bf passive shimming can be determined.

Results: Based on the relationship between k0 and k (Fig. 2A) the minimum k0 of 0.34 cm−1 is obtained at the maximum k of 1.82 cm−1 for a 4T magnet. Additionally, at the first maximum of k0, the radial wave length of λρ = 2π / kρ is about 18.5 cm which is comparable to the size of the subject’s brain. According to Fig. 2B the appropriate magnitude range of the effective ε of 92 - 94 is determined corresponding to k0 of 1.82 cm−1 as g(kz, ε) reaches zero. Fig. 3 shows the simulated Bf field map after filling the body-to-coil region with (A) air and (B) a dielectric material with ε of 94 which is obtained according to Eq. (1). The Bf field map is normalized to the field amplitude at the center of the FOV with the assumption that the entire brain has a uniform dielectric constant. The results clearly show that the ripples of the Bf field distribution within the brain are significantly reduced as the ε within the body-to-coil region increased.

Discussion: We have demonstrated with simulation data, as shown in Fig. 3, that this method provides an effective solution for selecting an appropriate material to improve Bf field homogeneity within the human brain at 4T. This approach should be applicable to all fields. Experimental verification of the method is currently being conducted in vivo.