

Fast method to compute the electromagnetic field inside a model of the human head surrounded by a dielectric pad

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Target audience. Anyone interested in the understanding of what a dielectric padding does to the distribution of the electromagnetic field.

Purpose. To provide an analytical foundation elucidating the behavior of the magnetic field observed when dielectric material is used to enhance RF performance in MRI.

Introduction. High permittivity dielectric pads have recently become popular for their ability to locally enhance the B_1 field in the region of interest (ROI)[1-3], especially in tissues very close to the pad, and to ensure efficient transmission of RF energy into the body tissues. Commonly, it is challenging to have a strong signal in ROI close to the center of the head, and it is also hard to predict the effect of the use of dielectric materials in a deep ROI since those locations are far from the dielectric pad and their associated displacement currents. In this work, using a peculiar property of the Bessel functions, a fast exact analytical method is proposed to compute the electromagnetic field at the center of a model of the human head when the source RF field is produced by a single wire. The model can also be extended to include all of the effects of a dielectric material surrounding the head.

Methods. The analytical method is two-dimensional and based on the exact electromagnetic field radiated by a single wire antenna, which could represent, for example, one of the legs of a standard birdcage coil.

The human head is modeled as a uniform lossy dielectric circular cylinder, and is surrounded by a coaxial dielectric layer. This is a boundary value problem for the Helmholtz equation and can be solved exactly by applying the electromagnetic boundary conditions at the interfaces, *i.e.* the continuity of both the tangential component of the electric field and the magnetic fields. The electromagnetic fields inside the three regions (air, dielectric coating layer, and head) are represented as a series of modes expressed in terms of trigonometric and Bessel functions. For this geometry, it is possible to apply independently the boundary conditions for each mode and compute the corresponding expansion coefficients. At the center of the head, the electric field, oriented in the z direction parallel to the direction of the wires, can be expressed as $E_z = \sum_{n=-\infty}^{+\infty} a_n J_n(\beta_1 \rho) e^{jn\phi}$ where a_n are expansion coefficients, J_n are the Bessel functions of the first kind, β_1 is the wave number inside the inner cylinder, and ρ and ϕ are the polar coordinates where the field is computed. In particular, the electric and magnetic fields along the axis of symmetry of the structure are determined by simply the very first term of the pertinent series because of the Bessel function property that $J_n(0)=0$ for all $n \neq 0$. As a result, one obtains a simple closed formula relating the values of the electric and magnetic fields at the center of the structure to the parameters of the model, such as the thickness of the dielectric padding layer, its permittivity and the distance of the wire producing the RF field.

Results. The exact analytical results were applied to investigate the predicted value of the magnetic field along the axis of symmetry of the model of the head as a function of the dielectric permittivity of the padding at 300MHz. The results may be summarized as it follows. The presence of the dielectric layer causes a redistribution of the electromagnetic field and acts as a matching layer between the impedance of the air and of the head model[3]. In fact, in Figure 1, it is clear to see a correspondence between the maximum of the (power) transmission coefficient computed according to the 1D transmission line theory (red line) and the maximum of the normalized magnetic field at the center of symmetry (blue line) when varying the values of the permittivity of the dielectric layer. According to the fast 2D model, when the relative dielectric permittivity is around 19, the magnetic field along the axis has a maximum and the (power) transmission coefficient has an absolute maximum when the dielectric permittivity is around 28. We verified our results by carrying out full wave 3D simulations with a high resolution model of the human head (cell size 2.5 mm) using numerical field simulation software (XFDTD version 6.6 by Remcom). The normalized values of the results obtained with XFDTD agree quite well with the prediction of optimal permittivity obtained with the proposed simple model.

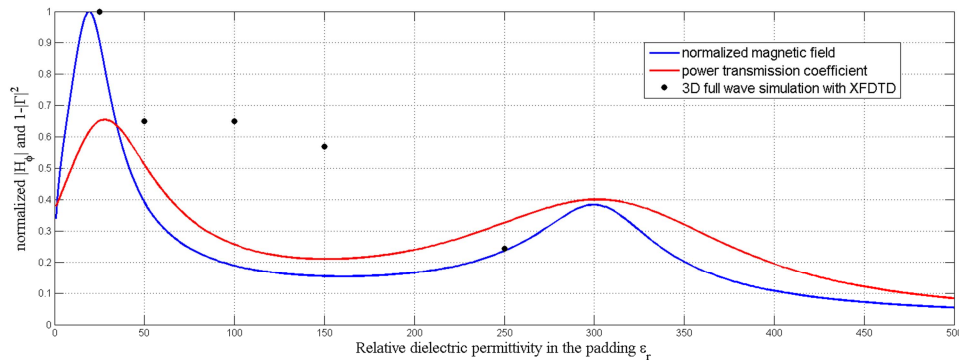


Figure 1. Power transmission coefficient (red line); normalized magnetic field along the axis of the head (blue line); 3D full wave simulation with XFDTD (black dots).

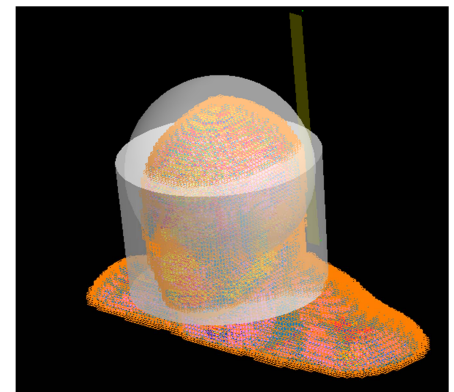


Figure 2. High-resolution human head and padding used for the simulation with XFDTD.

Head radius	Dielectric pad thickness	Distance of the source from the origin	Frequency
9 cm	3 cm	15 cm	300 MHz

Table 1. Parameter values for the numerical simulations.

Conclusions. The numerical results support the understanding that the dielectric materials can act as a matching layer between the impedance of the air and that of the human head. In addition, a simple 1D transmission line theory model for the computation of the (power) transmission coefficient provides results for the values of the relative dielectric constant of the padding that are very close to the ones obtained with a full scale 3D simulation with XFDTD.

References: [1] QX Yang et al. MRM 2011; 65(2) p. 358. [2] AG Webb, Concept Magn Reson A 2011; 38A(4) p. 148. [3] G Carluccio et al. ISMRM 2013, p. 4374.