Near-Field Wave Impedance Matching with High-Permittivity Dielectric Materials for Optimum Transmittance in MRI Systems

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Introduction: Dielectric pads with high permittivity ε_r, located adjacent to human tissues, are used increasingly in MRI systems to enhance the transmission of the B_1 field in the region of interest (ROI) [1-3]. Numerical simulations and experiments have shown that for 3T MRI systems materials with permittivity ε_r larger than 250 can provide high transmittance of the B_1 field in the body, with consequent higher SNR, and higher transmit efficiency: this behavior seems to indicate that the role of the dielectric pad is to better match the human tissue and the power source. Each permittivity value ε_r of the dielectric pad determines the matching between the power source and the subject. Since matching can be analyzed by quantifying the reflectivity and the transmittivity of the electromagnetic fields at the interfaces among different materials, a simple method which maximizes the matching may be used to determine the value of permittivity of the pad that guarantees the optimum transmit efficiency. Hence, we propose a method that maximizes the matching by analyzing the wave impedance of the fields generated by a magnetic loop through different materials with a simple 1D analytical model. The permittivity values that maximize the matching in this simplified model are compared with the permittivity values that maximize the B_1 field in 3D simulations to investigate the correlation between matching and high permittivity dielectric pads.

Method: The spatial distribution of the wave impedance Z of a magnetic dipole, with respect to the distance r from the source in the direction of maximum propagation, is equal to $Z(r) = -\eta\left(\frac{j}{\beta r} + \frac{1}{(\beta r)^2}\right) / \left(\frac{j}{\beta r} + \frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3}\right)$ where j is the imaginary unit, $\eta = \sqrt{\frac{\mu}{\epsilon}}$, μ the permeability, σ the electrical conductivity, $\beta = j\omega\sqrt{\mu\epsilon}\sqrt{1 - j\frac{\sigma}{\omega\epsilon}}$, and ω the angular frequency.

The fields generated by the magnetic dipole propagate through three different layers (Fig.1) having three different electrical properties. The first layer is air and represents the distance (6 mm) between the coil and the dielectric pad; the second layer is a dielectric pad having thickness 20 mm, and the third layer a homogeneous phantom where the transmitted field needs to be maximized. The operating frequency is 300 MHz. The continuity of the wave impedance is imposed by using the method presented in [5], where both reflection and transmission coefficients are computed in a near field multi-layer propagation scenario. This simple analytical method is used to quickly span multiple values of permittivity and conductivity of the layer representing the dielectric pad. The curve showing the transmit efficiency is then compared with the curve representing the average B_1^+ in the phantom respect to different electrical properties of the dielectric material, obtained with several full-wave 3D numerical simulations (Xfdtd). The geometry of the 3D simulations is shown in Fig.2.

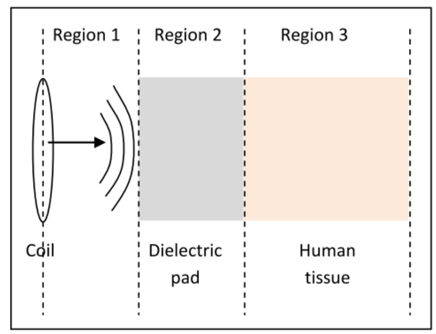

Figure 1: Geometry of the 1D model

Results and discussion: the two curves showing respectively the transmit efficiency with the 1D model and the B_1^+ average in the phantom by changing both the permittivity ε_r and the conductivity σ of the dielectric pad are shown in Fig.3 and Fig.4. The predicted values of optimum permittivity are very similar, ε_r =330 for the 1D analytical model and ε_r =300 for the 3D numerical model, despite the simplicity and speed of the unidimensional model presented here. In addition, the high correlation between the optimum values predicted by the two methods confirm that pads with high dielectric materials enhance matching between source and phantom. In fact, since we are operating in a near field scenario, optimum matching condition is not obtained with permittivity values intermediate between the ones of the first and third layer, since that relationship is only valid in far-field scenarios, but with permittivity values much higher than the other two layers.

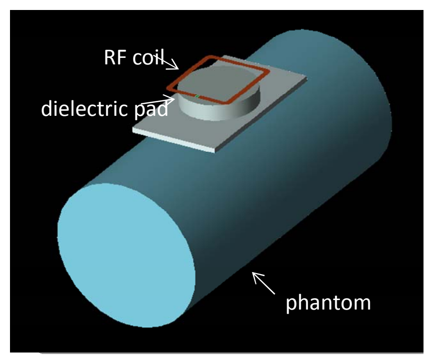

Figure 2: Geometry of the 3D model

References:
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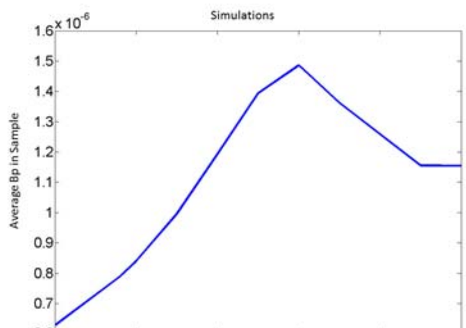

Figure 3: Average B_1 plus in the phantom by varying the conductivity and the permittivity of the dielectric pad with 3D simulations. For each conductivity value the permittivity varies from 1 to 500, and an optimum value of ε_r =300 has been found.

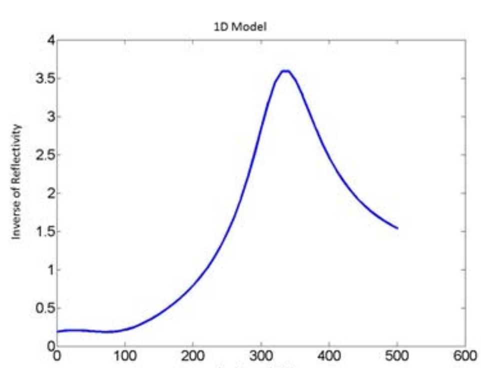

Figure 4: Ratio square of the incident field over the reflected field at the interface air/dielectric by varying the conductivity and the permittivity of the dielectric pad with the simplified analytical 1D model. For each conductivity value the permittivity varies from 1 to 500, and an optimum value of ε_r=330 has been found.