Simulation on Passive RF Shimming with High Permittivity Dielectrics in Ultra-High Field

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INTRODUCTION: In ultrahigh field human MR imaging systems (≥7.0T), RF field homogeneity is difficult to achieve. The RF field distribution is highly dependent on sample electrical properties, geometry, and relative position to the coil [1]. As demonstrated by studies at 4.0T [2] and 7.0T [3], adjustment of the RF field distribution inside a sample and the coupling between the sample and the coil can be effectively facilitated with placement of high permittivity (ε) materials in an RF coil [2-3]. In this report, the physical basis and characteristics of this phenomenon are investigated numerically using the Finite Difference Time Domain (FDTD) method. The results provide a fundamental understanding and guidance for RF field engineering utilizing high ε dielectric materials in ultrahigh field MRI.

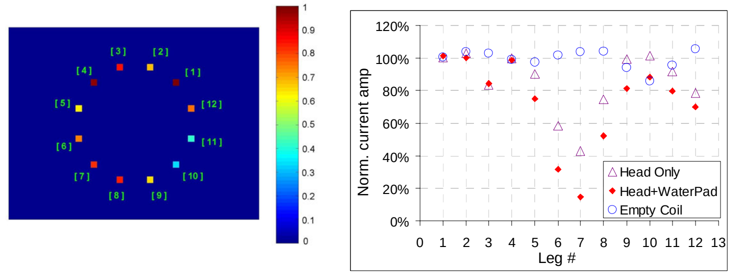

Figure 1. Coil current distribution in 12 legs. The numbers in bracket in the left figure are the leg #, which correlate to the leg # in the right figure.

METHODS: Full-wave B_1 field profiles were calculated by the FDTD method. The calculation was performed with a 3D model incorporating the National Library of Medicine (NLM) Visual Human Project's digitized male head within a 12-element TEM resonator [4] . For conductive dielectric materials, such as human brain tissues, the RF field inside the sample is perturbed by induced conductive current ($\mathbf{J}_C$) and displacement current ($\mathbf{J}_d$) proportional to the electric field (**E**):

$$\mathbf{J}_c = \sigma \mathbf{E} \qquad \mathbf{J}_d = \varepsilon \varpi \mathbf{E}$$

where σ is the conductivity of the sample and ϖ is the angular frequency. The RF field with and without a high ε (water) pad next to the forehead in the coil resonating at 300MHz (7.0T) and 64MHz (1.5T) have been simulated with a 2-source quadrature driven and an ideal 12-source driven TEM coil.

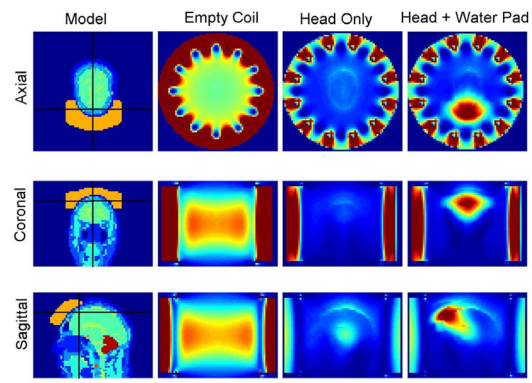

Figure 2. Head model and signal intensity distributions in the axial, coronal, and sagittal planes of an empty coil, head only, and head with high ε pad at 300MHz. The signal intensity is normalized in each case. Red color presents the strongest signal.

RESULTS: The current distribution in the coil with a 2-source quadrature drive is perturbed by loading the human head and adding a high ε pad (Figure 1). B_1 field (Figure 2) with an ideal coil current distribution using 12-source drive yields a similar pattern to the 2-source quadrature drive case. All of the signal intensity maps with or without high ε pad have been normalized by the same value. For quantitative analysis of the origin for the field changes, the corresponding x, y, and z components of $\mathbf{J}_c$ and $\mathbf{J}_d$ distributions on a mid-sagittal plane are shown in Figure 3. A strong $\mathbf{J}_d$ in the high ε pad and nearby brain areas is observed in all three directions in Fig. 3.

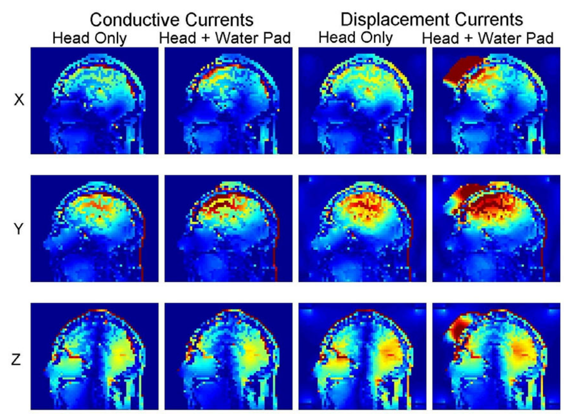

Figure 3. Conductive current and displacement current distribution on sagittal profile. X, Y, and Z represent the components in a Cartesian coordinate system at 300MHz. All are of the same scale. Red color presents the strongest current density.

DISCUSSION: In addition to the effects of changing the coil current pattern, which manipulates the B_1 field, the placement of the high ε pad alters B_1 field in other ways as demonstrated in the case with the ideal 12-source drive. In Fig. 2, the signal intensities in the region far from the high ε pad are identical in both cases (with or without the pad). This indicates that the high ε pad increases the signal intensity in the nearby region instead of simply shifting the bright spot from center to the high ε pad. Figure 3 illustrates that the high ε pad enhances both conductive current and displacement current at the nearby brain region. More importantly, it holds very strong displacement current inside the pad where there is no conductive current. Generally, the conductive current leads to a rapid decay of the RF field in the tissue preventing RF field penetration, while the displacement current acts as a secondary field source facilitating the RF wave propagation. The strong displacement current in the high ε pad and nearby region is the major contributing factor enhancing the signal intensity. At 64MHz, the effects of high ε pad are limited because $\mathbf{J}_d$ decreases with frequency. A stronger effect is expected at even higher frequencies. The information presented is important for designing strategies and devices for producing desirable RF distributions with high ε materials in ultra-high field MRI.

REFERENCES: [1] Vaughan et.al. MRM 2001; 46:24-30; [2] Alsop et.al. MRM 1998; 40:49-54; [3] Yang et.al. Proc. ISMRM IX 2001; p1096; [4] Collins et.al. MRM 2001; 45:684-691.

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