Conservative Electric Fields Can Dominate Sample Loss in High Field Microimaging

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INTRODUCTION: Recently there has been compelling evidence that sample loss can be a significant factor in SNR for high field microimaging in MRI (1). Because the magnetically-induced electrical fields and related power loss within the sample are expected to be negligible in comparison to power loss in the coil (1, 2), it has been proposed that conservative electric fields and related power loss in the sample may have a significant role (1). Here we perform Full-Maxwell numerical calculations of the electromagnetic fields within a solenoid under several different loading conditions and analyze the results to evaluate the contribution of conservative electric fields (E_c) and magnetically-induced electric fields (E_i) to the total electric fields (E_{total}) within a solenoidal microimaging coil. The methods we present may be valuable for other MR applications as well.

METHOD : We modeled a solenoid coil based on a design for microimaging at 600MHz/14T (3). The result resembles 8 turns of 0.15mm-diameter round wire, with a solenoid diameter of 1.0mm, a coil length of 2mm, and a distance per turn of 2.31 mm (Figure 1). All simulation work was performed using commercially available software (xFDTD; Remcom, Inc; State College, PA) driving the coil with a constant voltage source in series with a 50Ω resistor. Analysis of results was performed in Matlab (The MathWorks, Inc., Natick, MA). The calculation procedure to obtain the E_c and E_i consists of 1) calculating the total E-field and the current density using xFDTD software; 2) calculating the magnetic vector potential (**A**) using the current density (**J**) in the wire; 3) calculating $\mathbf{E}_i$ using **A**; 4) calculating $\mathbf{E}_c$ using the total E-field and $\mathbf{E}_i$ ($\mathbf{E}_c = \mathbf{E}_{total} - \mathbf{E}_i$); 5) normalizing all fields so that $B_x = 4\mu T$ at the coil center.

RESULTS: In this case, the conservative E-field was much stronger (by more than an order of magnitude) than the magnetically induced E-field in the empty coil (Figures 2 and 3). The conservative E-field within the sample is reduced with the addition of conductive and dielectric samples, but still remains significantly larger than the magnetically-induced E-field (Figure 3).

DISCUSSION: For $\mathbf{E}_c$, the x-component is dominant because the scalar potential was directed in the coil-winding direction (along the x-axis: Fig. 1). Whereas for $\mathbf{E}_i$, the z-component (circumferential direction; perpendicular to plane shown in Figures 2 and 3) was dominant because (following Faraday's Law) $\mathbf{E}_i$ is perpendicular to magnetic flux density (B), which is oriented in the x-direction. The order of magnitude of $\mathbf{E}_c$ shown here is in agreement with rough analytical approximations based on the voltage across the solenoid and the solenoid length. The values for $\mathbf{E}_i$ shown here are in agreement with analytical approximations based on Faraday's law. The conservative electric field presented here is in agreement with the total electrical field pattern presented in a previous work (4) – further evidence that the contribution of conservative electric fields can be dominant in solenoidal microimaging coils.

The method of analysis utilized here should be useful as long as no significant wavelength effects are present (for the accurate calculation of **A** from **J**), and as long as **J** in the wires is much greater than **J** in the sample. It may therefore also be useful as an alternate method to one previously presented (5) in examining fields within loaded gradient coils or very low-frequency RF coils for human imaging.

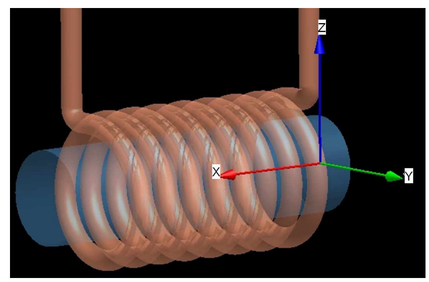

Figure 1 Solenoid coil and sample geometry for the simulation.

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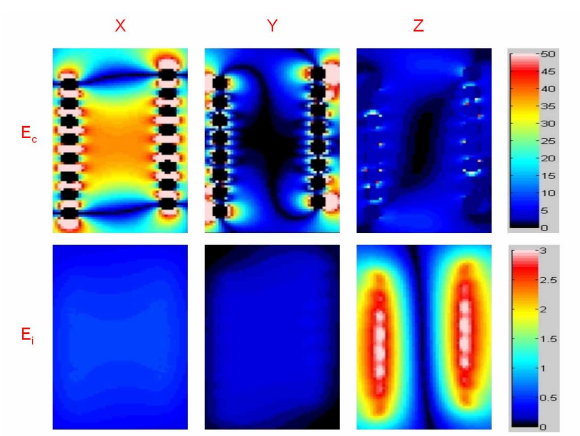

Figure 2 Magnitudes of X, Y, and Z-oriented components of Conservative E-field (E_c, top) and Magnetically-induced E-field (E_i, bottom) in the empty solenoidal microcoil driven to 4μT at 600 MHz. On plane shown, X is axial direction, Y is radial, and Z is circumferential. Linear color scale from 0 to 20 V/m for E_i and from 0 to 400 V/m for E_c.

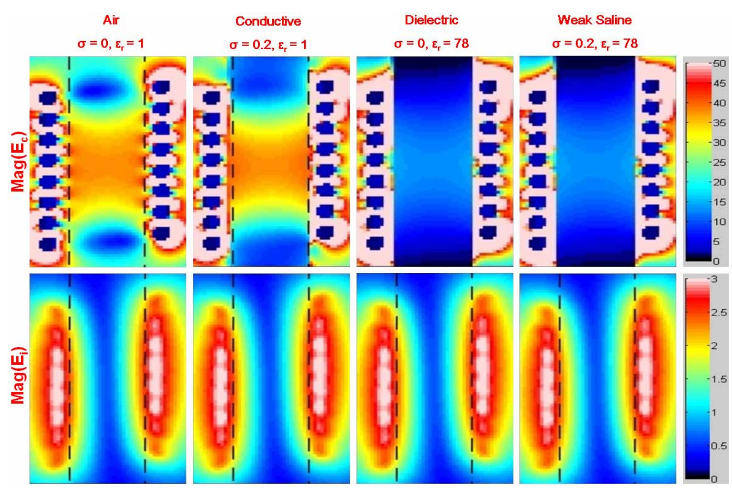

Figure 3 Approximate total magnitude of Conservative electric field (E_c, top) and Magnetically-induced electric field (E_i, bottom) when loaded with a cylindrical sample containing various materials. Linear color scale from 0 to 3 V/m for E_i and from 0 to 50 V/m for E_c.