Conductivity Effects on RF Surface Coils used for MR-Guided HIFU of the Prostate

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Introduction

In an endorectal high-intensity focused ultrasound (HIFU) treatment system the US transducer is surrounded by water to effectively couple the US energy into the adjacent prostate tissue. To provide temperature feedback during HIFU treatment, a local RF coil for the acquisition of temperature-sensitive MR data is required. This coil is in close proximity to the US transducer which creates unwanted shielding effects, and the coil is loaded by the dielectric US coupling medium. To optimize the SNR, the embedded coils are often tuned within the magnet bore under tissue loading conditions which is impracticable for clinical applications. The purpose of this study is to determine the effect of the conductivity of the surrounding medium on coil performance in order to predict the changes in the coil quality factor and the resonance frequency for correction of the coil parameters.

Materials and Methods

The effect of dielectric loading on a coil has been described previously (1): A surface loop coil can be generically treated as an inductance L and resistance R_1 in series, which are tuned and matched with capacitances C_t and C_m. When placed in proximity to a dielectric medium losses are induced that can be described by a parasitic capacitance C_p and a series resistance R_2 between the coil and the dielectric (cf. equivalent circuit in Fig. 1). The impedance of the inductance branch and the parasitic elements can be described as

$$Z_{eq} = \frac{(Z_1 + Z_2)(Z_3 + Z_4)}{Z_1 + Z_2 + Z_3 + Z_4} \qquad \text{where: } Z_1 = j\omega L,\ Z_2 = R_1, Z_3 = \frac{1}{j\omega C}, Z_4 = R_2$$

We obtain for the real and imaginary part of Z_{eq}:

$$Re(Z_{eq}) = \frac{R_1R_2(R_1 + R_2) + \frac{R_1}{(\omega C)^2} + R_2(\omega L)^2}{(R_1 + R_2)^2 - \left(\omega L - \frac{1}{\omega C}\right)^2}, \qquad Im(Z_{eq}) = -1\frac{\frac{R_1^2}{\omega C} + 2R_1R_2\omega L + R_2^2\omega L - \frac{(\omega L)^2}{\omega C} + \frac{\omega L}{(\omega C)^2} - \frac{2R_1R_2}{\omega C}}{(R_1 + R_2)^2 - \left(\omega L - \frac{1}{\omega C}\right)^2}$$

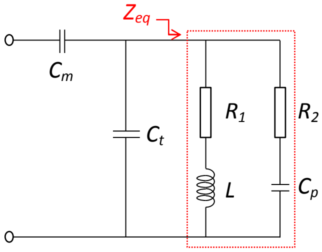

Fig. 1: Coil model with parasitic capacitance.

The conductivity σ of the medium is influencing the resistance R_2, which can be written as $R_2 = \sigma/(\epsilon'\omega^2 C)$, with $C = C_p$, and $\epsilon' = Re(\epsilon)$. Where ϵ is the permittivity of the material.

For comparison with the theoretical model, a coil model was implemented and simulated using the FEM software package (HFSS, ANSYS, Inc.). The rectangular coil 8x4x0.035cm was placed in a conducting medium, and the conductivity was varied. The change in reflected power was observed to assess the coil performance. The coil was tuned in distilled water, and then the conductivity was varied. The change in the coil quality factor Q and the resonance frequency ω were calculated.

Results and Discussion

As expected, for a high unloaded quality factor even small differences in conductivity lead to measurable changes in Q and ω, whereas a low initial Q is virtually unaffected by changes in σ. Figure 2a shows a comparison between the Q changes calculated with the FEM model and the equivalent circuit model. Both calculations predict a reduction of Q with increasing σ, however the FEM model yields values nearly double that of the equivalent circuit model. The change in resonance frequency with respect to conductivity is shown in Figure 2b. One can see that there appear to be discontinuities in the FEM model curves. This may happen due to sparseness of the sampling. The data still tracks quite well, in both cases. At a conductivity of greater than approx. 10^{-3} the two models start to deviate. When the conductivity exceeds this threshold the circuit model starts to become invalid. When the Q is no longer considered “high” many additional parameters must be considered to make the simple model valid.

Since an RF coil in a HIFU system is directly exposed to the surrounding material, and tuning and matching can become tedious, if the influences of different loading conditions are not taken into account. In particular, the conductivity of the surrounding medium has a strong influence on the coil resonance frequency, and thus needs to be re-tuned. In this work we analyzed the detuning of the coil using a simplified circuit model, which is able to account for the salient features of the coil behavior. Automatic tuning of coils has been proposed to compensate for different loading conditions; however, this requires additional tuning hardware which complicates the coil design. Based on these calculations it should be possible to characterize the change in resonance frequency based on prior conductivity assessments, which would greatly simplify the design and optimization of endorectal coils in HIFU treatment devices.

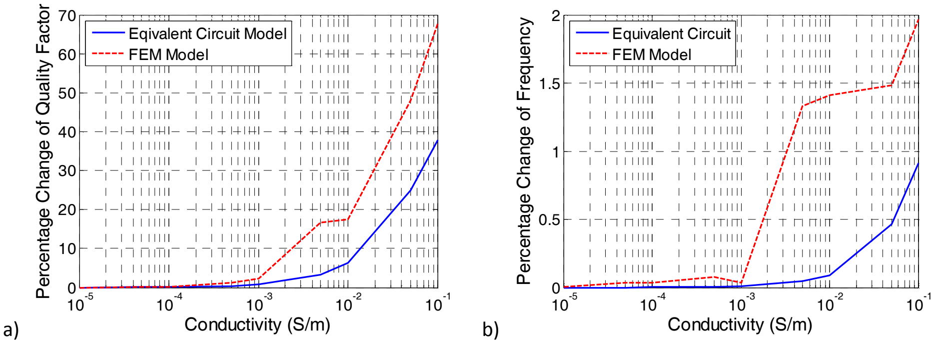

Fig. 2: The effect of conductivity on the quality factor (left) and resonance frequency (right) of the coil using the FEM model and an equivalent circuit model.

Acknowledgements

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References

[1] J. Mispelter, et al. NMR Probeheads for Biophysical and Biomedical Experiments, 2006