A Novel MRI Based Electrical Properties Measurement Technique

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Targeted audience: This study is beneficial for coil producers and implant safety testers.

Introduction: Most of the Magnetic Resonance Imaging (MRI) studies require accurate knowledge of electrical properties of the phantoms. The coaxial transmission line measurement (CTLM) fixture, which was designed for measurement of electrical properties of viscous phantom materials at MRI frequencies, was previously presented by our group[1]. In this study, another method is proposed and the results are compared to gain confidence in the measurement. The new method depends on the phenomena of the lead tip heating inside a phantom during MRI scan. Electrical properties of a phantom are influential on the relationship between tip temperature increase and the lead length[2]. Modified Transmission Line Method[3] (MoTLiM), which is a method to solve RF induced currents on the leads, was used and the relationship between the lead length and the tip temperature increase was formulated as a function of conductivity and permittivity of the phantom. By changing the lead length the tip temperature increase was measured and the MoTLiM formulation was fitted to these data to find the electrical properties of the phantom. Afterwards the electrical properties of the phantom were measured with the CTLM fixture and the results that are obtained with both methods were compared for an error analysis.

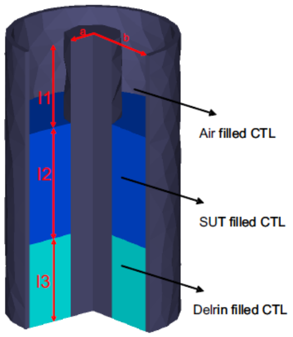

Figure 1: Coaxial Transmission line fixture

Methods: The tip heating of a lead under uniform E-field exposure was formulated using MoTLiM. In MoTLiM induced currents on the leads were formulated as in Equation 1 where s is the position along the lead, Z is the impedance per unit length and k_t is the wavenumber and $k_t = \omega\sqrt{\mu(\epsilon - j\sigma/\omega)}$ for a bare lead. Solving Equation 1 for uniform E-field and applying the boundary condition that the current is zero at $s = l_w/2$ and $s = -l_w/2$ where l_w is the length of the lead can be found as in Equation 2. Using MoTLiM a hypothetical voltage along the lead can be found under uniform E-field as in Equation 3. The temperature rise at the lead tip is caused by the dissipation of the localized power into the tissue which is around the tip of the lead. So the lead can be thought as a source and tissue can be thought as impedance. Thus the temperature rise can be found from the dissipated power on the tissue impedance and the dissipated power has a linear relationship with square of the hypothetical voltage at the point $s = l_w/2$. Therefore the temperature rise can be formulated as in Equation 4 where C is the constant shows the impedance of the tissue and the relationship between the dissipated power and the temperature increase. To find the electrical properties of the phantom material a bare copper wire was placed inside a cylinder which is filled with the phantom material as shown in Figure 2 and phantom placed in the center of a birdcage coil. This configuration ensures that the incident field on the wire is uniform. Then the temperature increase at the tip was measured (Optical Temperature Sensor, Neoptix Reflex-4 RFX134A) by changing the length (from 7cm to 55cm) of the wire. Later Equation 4 was used to estimate the wavenumber, k_t by finding the best fit to the measured temperature rise data. Lastly real part of k_t^2 was used to find permittivity ε_r and imaginary part of k_t^2 was used to calculate conductivity σ.

$$I(s) + \frac{1}{k_t^2}\frac{d^2 I(s)}{ds^2} = \frac{E^i(s)}{Z} \quad (1)$$

$$I(s) = \frac{E_0}{Z} - 2\frac{E_0}{Z}\frac{\sin(k_t\frac{l_w}{2})}{\sin(k_t l_w)}\cos(k_t s) \quad (2)$$

$$V(s) = 2\frac{E_0}{k_t}\frac{\sin(k_t\frac{l_w}{2})}{\sin(k_t l_w)}\sin(k_t s) \quad (3)$$

$$\Delta T = C|\frac{2E_0}{k_t}tan(k_t l_w/2)|^2 \quad (4)$$

The CTLM fixture is shown in Figure 1. To measure the electrical properties of a substance under test (SUT) or phantom material, a portion of the fixture was filled with SUT. This setup is easy to use with viscous materials, which is the common case for water based MRI phantoms, and less sensitive to the fringing field effects than the other techniques like open ended coaxial lines or parallel plate methods. In the case shown in Figure 1, our setup forms a system of serially connected three transmission lines with lengths l_1 (air), l_2 (SUT) and l_3 (Polyoxymethylene, POM). To measure the electrical properties of the material the impedance from bottom terminal of the fixture (Figure 1) was measured while keeping its top terminal open using a Network analyzer (Agilent, E5061A). The impedance measurements were carried out with different amount of SUT inside the fixture. Also the impedance values were calculated using the formulas of lossy transmission lines[4] for different amount of SUT in the fixture. Note that impedance is nonlinear function of ε_r and σ. The error between the calculated and measured impedance values were minimized by using ε_r and σ as parameters of the nonlinear minimization process.

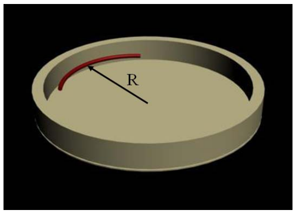

Figure 2: Gel filled phantom and position of the wire

Results: Conductivity and permittivity of different gel solutions (contents are shown in Table 1) were measured by using the CTLM fixture and also by fitting the measured wire tip temperature increase to Equation 4 and compared for 123 MHz (3 tesla). In Table 1 measured conductivity and permittivity of three different phantoms with two different methods are shown. The differences between estimated permittivity values are below 5% and the difference of conductivity values are below 34%.

Discussion & Conclusion: In this study temperature increase at the lead tip was formulated (Equation 4) using MoTLiM for estimating conductivity and permittivity of phantom materials. These electrical property values were also obtained by a CTLM fixture at MRI operating frequencies. It is shown that the CTLM fixture is good in predicting the permittivity of the phantoms however error in conductivity is slightly higher. These errors may come from both CTLM fixture and the MRI experiments. In the Equation 4 permittivity dominates the location of the resonance peaks whereas conductivity determines the sharpness (Q) of the resonance peaks. So as the Q of the resonance peaks are more sensitive to the errors in temperature increase measurements, misalignment of the optical probe can easily leads to higher errors while predicting the conductivity of the phantom. Also errors in measuring the gel length inside the CTLM fixture cause errors. In conclusion, a new method to measure electrical properties of gel phantom was proposed. Although the proposed method requires long MRI experiment, it can be used for verification of other electrical properties measurement techniques.

Solution	Measured with CTL (σ_{ctl}, $\varepsilon_{r,ctl}$)	Measured with MRI experiments (σ_{MR}, $\varepsilon_{r,MR}$)	Error ((σ_{MR}-σ_{ctl})/σ_{MR} ,($\varepsilon_{r MR}$-$\varepsilon_{r ctl}$)/$\varepsilon_{r MR}$)
14g HEC/L	0.14 S/m, 66	0.19 S/m, 63.16	27.9% , 4.49%
14g HEC/L 0.5g NaCl/L	0.26 S/m, 60	0.40 S/m, 62.75	28.2% , 4.38%
14g HEC/L 1g NaCl/L	0.36 S/m, 58	0.54 S/m, 60.22	33.8% , 3.70%

Table 1: Solution contents and their conductivity and permittivity values that are measured with CTL fixture and MRI experiments

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