Non-invasive in vivo Loss Tangent Imaging: Thermal sensitivity estimation at the Larmor frequency

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Purpose: Medical thermotherapy such as hyperthermia treatments uses thermal sensitivity difference between tumor and normal tissue. Some factors to determine the thermal sensitivity are the electrical tissue properties which represent energy propagation and energy loss. The loss tangent is a parameter of a dielectric material that measures the ratio of energy dissipated to energy stored. The loss tangent is a measure of the electromagnetic wave energy transformed to heat energy. It is generally assumed that the thermal sensitivity used in hyperthermia treatment has a positive tendency to the loss tangent hence its knowledge can be beneficial. We propose a nondestructive loss tangent imaging method using magnetic resonance electric properties tomography (MREPT) approach[1,2], which is a non-invasive estimation method of probing electrical properties.

$$\alpha \approx \cos^{-1}\left(\frac{1-\sqrt{1-2(r-n)r(n-1)}}{2(n-r)}\right),\ where\ r=\frac{s_2}{s_1},\ n=\frac{TR_2}{TR_1} \quad (1)$$

$$\varepsilon_r(x) \approx \mathrm{Im}\left(\frac{\nabla^2 H_1^+(x)}{j\mu\omega^2\varepsilon_0 H_1^+(x)}\right) \quad (2)$$

$$\sigma(x) \approx \mathrm{Re}\left(\frac{\nabla^2 H_1^+(x)}{j\mu\omega H_1^+(x)}\right) \quad (3)$$

$$\tan\delta(x) \approx \frac{\sigma(x)}{\omega\varepsilon(x)} \quad (4)$$

Methods: Sequence: In this work, we used a multi-echo actual flip angle imaging (AFI) method[3] to acquire the complex B_1^+ map, both magnitude and phase. Here, to obtain high SNR for both B_1^+ magnitude and phase, the flip angles are adjusted as follows: first FA: α°, second FA: 2α°. Using a similar approach to AFI[4], the magnitude of B_1^+ can be reconstructed by Eq. 1.The S_1 and S_2 are initial gradient echoes acquired at both TR_1 and TR_2, respectively. The second TR has a multi-echo readout scheme so that the B_1^+ phase (TE=0 phase) can be retrieved by linear fitting the phase values.

Loss tangent imaging: The conductivity (σ) and permittivity (ε_r) are measured from complex B_1^+ map using the Helmholtz equations (2) and (3). The loss tangent (tan δ) can be estimated by the ratio between electrical conductivity and permittivity (Eq. (4)) where μ is permeability, and ω is the angular frequency. In the MREPT process, we used a smooth mollifier which was a Gaussian filter with kernel size 3 and standard deviation 1 to reduce the noise.

Experiments: To demonstrate the performance of our proposed methods, a phantom was made as shown in Fig. 1(a). Four regions were filled with varying concentrations of copper sulphate ($CuSO_4$) and sodium chloride (NaCl) to generate different permittivity and conductivity values. Axial images of the phantom were acquired on a 3.0T Siemens Tim Trio MRI scanner using a transmit-receive head coil. Using the double angle multi-echo AFI, fourteen slices were obtained in 3D with resolution =2.0x2.0x4.0 mm^3, TR_1/TR_2= 20/100ms, first echo time = 3.55 ms, echo spacing = 3.55 ms, FA_1/FA_2 = 40/80°, FOV = 256x256 mm^2, number of echoes = 3, NEX = 3 leading to a total scan time of 10 minutes 45 seconds.

Table 1. Estimated electrical properties

($CuSO_4$, NaCl)(%)	σ (S/m)	ε_r	tan δ
(0.1, 0.1)	0.26	78.56	0.48
(0.5, 0.5)	1.27	70.65	2.59
(0.1, 0.5)	1.01	74.42	1.93
(0.5, 0.1)	0.53	71.73	1.14

Results: The estimated electrical properties are represented in Table 1. Quantitative electrical property values match well with known values of conductivity and permittivity. The loss tangent value is also provided. Figure 1 shows phantom results. As expected, the conductivity and permittivity images (Fig. 1(e) and (f)) have strong correlations with the ion concentrations. However, differences between $CuSO_4$ and NaCl concentrations are not clearly shown. The loss tangent image represents distinct contrast to each specific region.

In the conductivity image, processing error is occurred at the phantom boundaries. The process to acquire permittivity image is much sensitive to the noise.

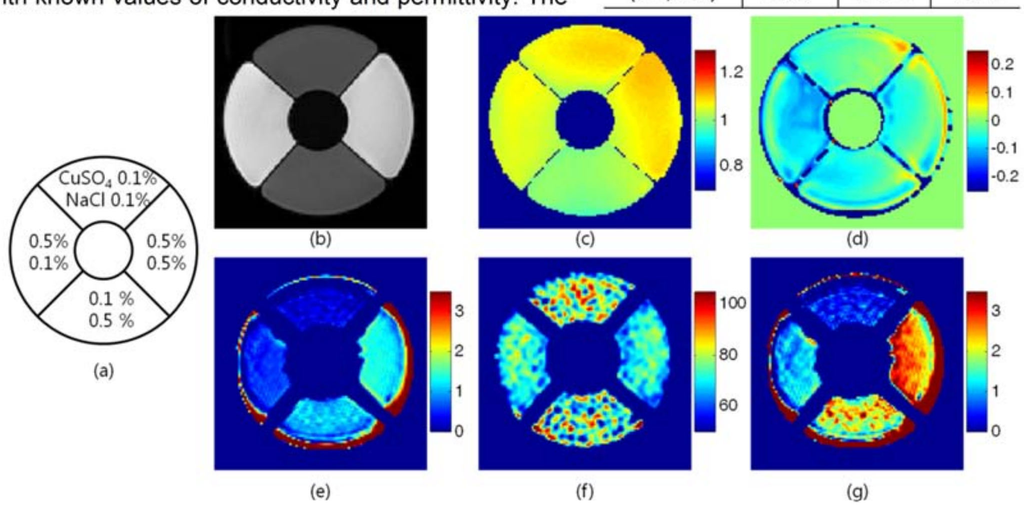

Figure 1. (a) Designed phantom with different concentration of $CuSO_4$ and NaCl, (b) Magnitude image (S_2), (c) B_1^+ magnitude, (d) B_1^+ phase (TE=0 phase), (e) Conductivity image, (f) Relative permittivity image, (g) Loss tangent image

Discussion and Conclusion: The loss tangent image can be estimated from the complex B_1^+ map using MREPT algorithm. The loss tangent image shows new contrast that represents the interaction between the human tissue and the electromagnetic fields. We propose the possibility of loss tangent imaging to estimate the thermal sensitivity of tissues. It may be a usable marker for medical laser applications such as RF ablation and microwave ablation.

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