Water-Content-Map Assisted Electrical Properties Reconstruction of Brain Tissue at 3T

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Target audience: This work is relevant to those interested in magnetic resonance electric property tomography

Introduction: High resolution and accurate estimations of tissue electrical properties (EPs) is a valuable information in several therapeutic and diagnostic applications. Current magnetic-resonance Electric Properties Tomography (EPT) methods consider only the information given by the transmit RF field (B_1^+) maps assuming an homogeneous permittivity (ε) and conductivity (σ) distribution, computing this tissue properties based on the Helmholtz equation[1]. However, this equation does not hold on boundary regions where different tissues coexist, leading to reconstruction errors. In addition, this approximation has further limitation of symmetry assumption in deriving transmit B_1^+ phase from the transceiver phase. It was demonstrated that there is a strong association of the dielectric properties of tissue with its water content based on the mixture theory[2]. In this work, we exploit those findings and consider recent physiological measurements of brain tissue to present a set of equations and corresponding methodology to compute EPT maps with improving accuracy and resolution.

$$\varepsilon_r = \varepsilon_w \frac{3\varepsilon_p + 2W(\varepsilon_w - \varepsilon_p)}{4\varepsilon_w - \varepsilon_p + 2W(\varepsilon_p - \varepsilon_w)} \quad (1)$$

$$\sigma = 0.5276W^2 + 0.845W + 0.6683 \quad (2)$$

$$W = \frac{1}{A + B/T_1} \quad (3)$$

$$I_r = \kappa \frac{1 - 2e^{-(TR_s - TE/2)/T_1} + e^{-TR_s/T_1}}{1 - 2e^{-(TR_l - TE/2)/T_1} + e^{-TR_l/T_1}} \quad (4)$$

$$W = 0.009777 I_r^2 - 0.1203 I_r + 0.8884 \quad (5)$$

Theory: The high correlation between the electrical properties of tissue and its fraction of water content (W, having values in the range [0-1]) has been demonstrated using the Maxwell mixture theory for both high- (W>0.65) and low-water-content tissues[2,3]. Using the mixture formula we can express the relative permittivity (ε_r) in terms of W as shown in Eq. (1), where ε_w is the relative permittivity of water and ε_p=2.5, the relative permittivity of the suspended particles (i.e. lipid or protein). Lately, more accurate measurements of body tissue parameters at body temperature have been performed in the range of MR frequencies[4-6]. As can be seen in Table 1, white matter (WM), gray matter (GM) and cerebral spinal fluid (CSF) are high-water-content tissues. We found that the literature values show a good agreement with Eq. (1) by using ε_w=84 (corresponding to the ε of CSF at 37°C at 128MHz). However, the mixture formula for conductivity does not work well for tissues having conductivities above the ionic conductivity of cytoplasm (~1.2 S/m) and results are inadequate in several aspects[2]. Alternatively, by performing a curve fitting between the literature values of the water content[5] and the conductivity[6], we found a good correlation between these two measurements, expressed by Eq. (2). We believe this relationship of water-conductivity is valid based on the fact that cell tissues contain conductive electrolyte solutions proportional to the (frequency-independent) conductivity of ions[2]. Recently, it has been verified that large-water-content tissues have longer T_1[7], and this relationship can be described by Eq. (3) where A and B are parameters computed according to the field strength[8]. This findings suggest that a good estimator for W can be obtained by acquiring T_1 maps of the tissue. Therefore, we use the literature values again to perform a least-square approximation of Eq. (3) to find more reliable parameters A (=0.9347) and B (=0.3572). In MRI, by dividing two spin-echo images having common parameters but TR, one with short TR (TR_s) and the other with long TR (TR_l), we can express an image ratio I_r, totally dependent on T_1 and a factor κ, as shown in Eq. (4). The proton density, T_2 and nonuniformity factors are eliminated in the division providing a ratio image with values in the [0-1] range, since the intensity of the image with long TR is always greater than the image of short TR, while the factor κ is usually about 1[9]. Even though no direct relationship between T_1 and the EPs has been demonstrated, an indirect relationship seems to exist by looking at Eqs. (1-4). We can calculate a transfer function using Eq. (3) and Eq. (4) by a change of basis to put W in terms of I_r. For the case of brain tissue, this relationship is expressed in Eq. (5) and the accuracy of this transfer function is shown in Fig. 1.

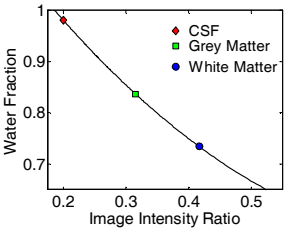

Fig. 1. Estimated relationship between the image intensity ratio and tissue water content.

Methods: To validate our approach, we performed in-vivo head experiments at 3T MRI of a healthy volunteer (male, 32 yr old) acquiring two spin-echo images (scan parameters: FOV=300mm, THK=5 mm, matrix size=128x128x3, TE=18ms, FA=90°, NEX=1) with short and long TR (TR_s=450 ms and TR_l=3 s, respectively) and we divided them to obtain the measured ratio image I_{ratio} and we applied adaptive filtering[10] to reduce the noise. The filtered I_{ratio} image was placed in Eq.(5) to compute W pixel-by-pixel. Finally, EPs maps were computed using Eqs. (1) and (2).

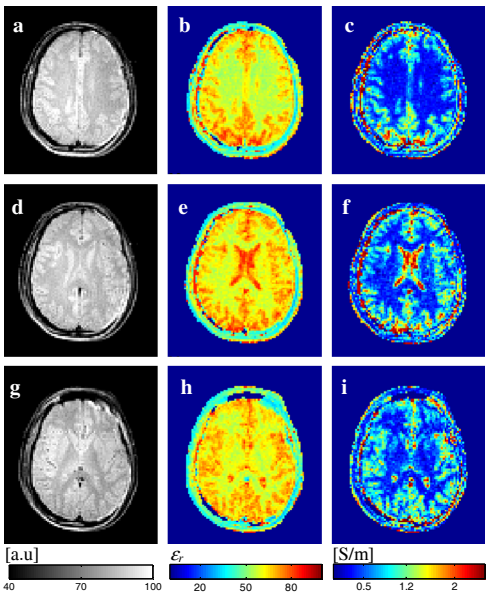

Fig. 2. (a,d,g) T_1-weighted images of the same brain at different and estimated (b,e,h) ε_r and (c,f,i) σ maps using the proposed EPT model.

		Literature			Estimated		
Parameter		**WM**	**GM**	**CSF**	**WM**	**GM**	**CSF**
T_1 (s)	[4]	1.11	1.47	1.55	1.12	1.40	1.53
W	[5]	0.74	0.843	0.988	0.76	0.85	0.98
σ (S/m)	[6]	0.34	0.59	2.14	0.36	0.61	2.12
ε_r	[6]	53	74	84	52.8	74.3	84

Table 1. Parameter values of the literature and the mean values of the estimated maps shown in Fig. 2.

Results and Discussions: The estimated EPs maps from the computed water content maps of 3 inter-leaved (5 mm) slices are shown in Fig. 2. The first column of Fig. 2 shows the T_1-weighted images obtained with TR_l while the second and third columns correspond to the permittivity and conductivity maps respectively. The mean EPs values and the other parameters, taken from the three slices at different homogeneous regions of 200 pixels, are summarized in Table 1. We found a good agreement between the estimated values and the literature for both permittivity and conductivity. This is not the case for B_1-related EPT methods where permittivity estimations are more challenging[11]. Although, the formulas presented here are optimized for brain tissues, the same concept can be applied to estimate EPs of other body regions. Since these formulae are based on live-tissue mechanisms, the formulae may not be applied to non-living (phantom) tissues.

Conclusions: We demonstrated that measuring the amount of electrolyte solution contained in brain tissue, represented by its water content, can be a decent predictor of the EPs distribution. Other advantages different from the performance of this approach can be enumerated. Among them, more number of slices can be estimated since this approach does not need information from neighboring pixels. Moreover, a faster and simpler implementation in clinical scanners is expected since does not requires dedicated sequences for B_1-mapping techniques. We believe that, by having an EPT model based on the biological characteristics of tissue, independent of the B_1^+ fields, this parallel approach can provide valuable information to other techniques relying on high resolution and more accurate EPT approximations.

References: [1] Voigt, et al. MRM **66** (2012) [2] Schepps et al. Phys. Med. Biol. **25** (1980) [3] Smith et al. Phys. Med. Biol. **30** (1985) [4] Lin et al. ISMRM **9** (2001) [5] Mansfield, et al. NY Academic (1982) [6] Gabriel, et al. Phys. Med. Biol. **41** (1996) [7] Ethofer, et al. MRM **50** (2003) [8] Fatouros, et al. J Neurosurg **90** (1999) [9] Mazzurana, et al. Phys. Med. Biol. **48** (2003) [10] Michel, et al. Biom. Eng. Onl. **10** (2011) [11] Michel, et al. Med Phys. **41** (2014)