Determining Electrical Properties Based on Complex B1-fields Measured in an MR Scanner Using a Multiple Transmit/Receive Coil: a General Approach

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Introduction Electrical Property Tomography (EPT) is a recently developed noninvasive technology to measure spatial maps of electrical conductivity and permittivity of biological tissues at radio frequencies used in MR scanners [1]. Because absolute B_1 phase cannot be directly measured in MR experiments [2], current EPT solutions have been proposed based on assumptions about the structure of imaged object and RF coil, phase distribution and main magnetic field, limiting their application to specific scenarios [3–5]. In this study, using a multi-channel transmit/receive coil, we introduce the framework of a new general approach for EPT, which does not depend on previously mentioned assumptions.

Theory Inside a piecewise homogeneous medium, based on the principle of reciprocity [6], the superposition of the Cartesian components (B_x and B_y) of B_1 field leads to the Helmholtz equation (1) [7], which associates electrical conductivity σ and relative permittivity ε_r with the complex B_1 field $\tilde{B}_{1j} = |\tilde{B}_{1j}| e^{i\phi_j}$. Here, $\tilde{B}_{1j}$ represents either transmit or receive complex B_1 field of channel j, ϕ is the absolute phase, ω is the Larmor angular frequency, and μ_0 and ε_0 are the permeability and permittivity of vacuum, respectively. Expansion of equation (1) into real and imagery parts and elimination of the common terms across channels, such as σ and ε_r, will lead to equation (2), where $|\tilde{B}_{10}|$ and ϕ_0 indicate the magnitude and absolute phase of a reference channel, and ϕ_{rj} is the relative phase between channel j and the reference channel. Grouping the unknown gradient of absolute phase $\nabla\phi_0$ from other measurable components as shown in equation (2), $\nabla\phi_0$ can be calculated voxel by voxel through solving a linear equation set consisting of multiple channels. Once the absolute phase is obtained, σ and ε_r can be calculated based on the Helmholtz equation (1).

$$-\frac{\nabla^2 \tilde{B}_{1j}}{\tilde{B}_{1j}\omega^2\mu_0} = \varepsilon_r\varepsilon_0 - i\sigma/\omega \quad (1)$$

$$\begin{cases} \left(\dfrac{\nabla|\tilde{B}_{1j}|}{|\tilde{B}_{1j}|} - \dfrac{\nabla|\tilde{B}_{10}|}{|\tilde{B}_{10}|}\right)\cdot\nabla\phi_0 = -0.5\nabla^2\phi_{rj} - \dfrac{\nabla|\tilde{B}_{1j}|}{|\tilde{B}_{1j}|}\cdot\nabla\phi_{rj} \\ \nabla\phi_{rj}\cdot\nabla\phi_0 = 0.5\left(\dfrac{\nabla^2|\tilde{B}_{1j}|}{|\tilde{B}_{1j}|} - \dfrac{\nabla^2|\tilde{B}_{10}|}{|\tilde{B}_{10}|} - \nabla\phi_{rj}\cdot\nabla\phi_{rj}\right) \end{cases} \quad (2)$$

Methods A phantom experiment was performed to validate the proposed method. The experiment was carried out in a Siemens MRI system with a 7T Magnet (Magnex Scientific, UK). A single-compartment cylindrical phantom (diameter of 8.7 cm and length of 20 cm) was built using a gel of saline solution, whose σ=0.34 S/m and ε_r=77 at 298 MHz were measured using a dielectric probe [5]. A 16-channel transceiver RF coil [8] was utilized for both transmission and reception. A hybrid multi-channel B_1 mapping technique [9], [5] using a 3D actual flip angle (AFI) map [10] and a series of 2D gradient-recalled echo (GRE) sequences was used to measure the magnitude and relative phase of receive B_1 fields with a resolution of 1.5x1.5x1.5 mm^3. Note that this method actually estimates the product of proton density (ρ) by receive B_1 fields $\rho\tilde{B}_{1j}^-$; given the uniform proton density of the phantom, here ρ is constant through space. The proton density weighted magnitude of receive B_1 fields $|\rho\tilde{B}_{1j}^-|$ and the relative phases ϕ_{rj}^- were used to solve equation set (2). For each channel utilized as a reference, one set of parametric maps of σ and ε_r can be calculated using the B_1 maps of three other channels. Then sixteen sets of σ and ε_r maps (one per channel used as a reference) were combined to form the final solution.

Results Shown in figure 1(a) is the relative phase of receive B_1 field measured between channels 4 and 15 in a transverse slice, while figure 1(b) shows the calculated relative phase between the reconstructed absolute phase maps of these two channels using two independent groups of four channels (group 1: channels 4 (reference), 8, 12 and 16; group 2: channels 3, 7, 11 and 15 (reference)). The average difference between the two maps is 0.08 radians and the correlation coefficient (CC) is 97.6%. In the region where the flip angle (FA) used in the AFI sequence was greater than 36° (providing better FA accuracy) over half of the slice, including a central profile (figure. 1(c-d)), the reconstructed σ is 0.33±0.08 S/m and ε_r is 78.2±5.4.

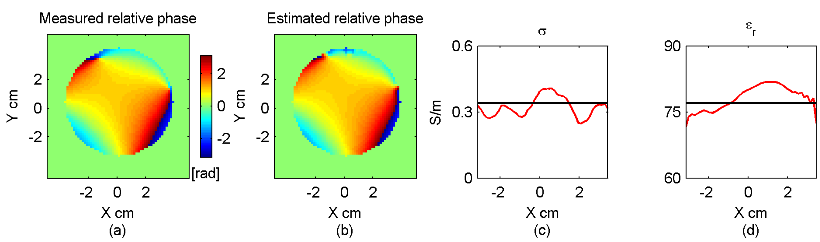

Figure 1. (a)-(b) Measured and estimated relative phase between channel 4 and 15 (c)-(d) Reconstructed profiles of electrical properties across the center of the phantom, red: reconstruction; black: probe measurement.

Discussion and conclusion In this study we proposed and validated experimentally the framework of a new general approach for solving EPT using measurable components of B_1 fields from multiple channels, which does not depend on assumptions about sample or coil geometry, phase distribution or field strength. This allows optimized RF excitation strategy of B_1 shimming and channel combination, and RF coil design for improved EPT estimation. This method can be applied at any magnetic field strength and is expected to be especially suitable for fast computation of patient-specific specific absorbing rate (SAR) during an actual scanning session at ultra high field. Different from some other multichannel methods [5], [11], [12], the current approach only requires measuring transmit *or* receive B_1 fields to derive absolute B_1 phases as well as electrical property maps; this can help reducing scanning time and motion induced artifacts for *in vivo* measurement.

Reference: [1] Katscher *et al., IEEE Trans Med Imaging* 2009, 28:1365 [2] Van de Moortele *et al.*, *MRM* 2005, 54:1503 [3] Voigt *et al.*, *MRM* 2011, 66:456 [4] van Lier *et al.*, *MRM* 2012 67:552 [5] Zhang et al. *MRM* 2012 (Online) [6] Hoult. *Concepts Magn Reson* 2000, 12: 173 [7] Wen, *Proc. SPIE* 2003, 5030:471 [8] Adriany *et al. MRM* 2008, 59:590 [9] Van de Moortele et al., *ISMRM* 2007, 1676 [10] Yarnykh, *MRM* 2007, 57:192 [11] Katscher *et al., MRM* 2012 (Online) [12] Sodickson et al., *ISMRM* 2012, 387 **Acknowledgement** NIH R01 EB006433, R01 EB007920, R21 EB014353, T32 EB008389, P41 EB015894, S10 RR26783 and WM KECK Foundation.