Reduction of boundary artifact in electrical property mapping using MREPT

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Introduction: Magnetic Resonance Electrical Property Tomography (MREPT) is an imaging modality to map the distribution of electric conductivity and permittivity of the subject at Larmor frequency using measured B1 maps from MRI[1-5]. Current MREPT approaches using the Helmholtz equation rely on an assumption that conductivity and permittivity of the subject are homogeneous locally[1-2]. However, at the tissue boundaries, the assumption of locally homogeneous electric properties is violated, and thus the conductivity estimates deviate from the actual values, so called "Boundary Artifact"[6]. In this work, instead of using Helmholtz Equation, three key identities are derived from the time-harmonic Maxwell's Equation. Using this, we developed a novel reconstruction approach to estimate the electric properties and reduce the boundary artifact using the B_1^+ map acquired at a single transmit channel MR system.

Methods: Key Identities for admittivity reconstruction: The time-harmonic Maxwell equation at the angular frequency, ω, can be represented as $\nabla \times H = \tau E, \nabla \times E = -i\omega\mu_0 H, \nabla \cdot (\mu_0 H) = 0$, where σ is the electric conductivity, ε is the electric permittivity, and τ is the electric admittivity at the angular frequency ω, $\tau = \sigma + i\omega\varepsilon$. The proposed method is based on the following three key identities which do not contain anti-circularly polarized component of the magnetic field (i.e. H^-):

$$\tau E_z = -2i\frac{\partial H^+}{\partial x} - 2\frac{\partial H^+}{\partial y} - i\frac{\partial H_z}{\partial z} \text{ (Eq. 1)}, \tau(E_x + iE_y) = 2i\frac{\partial H^+}{\partial z} - \frac{\partial H_z}{\partial y} - i\frac{\partial H_z}{\partial x} \text{ (Eq. 2)}, \left(\frac{\partial}{\partial y} - i\frac{\partial}{\partial x}\right)E_z = -2i\omega\mu_0 H^+ - i\frac{\partial}{\partial z}(E_x + iE_y) \text{ (Eq. 3)}.$$

Iterative Reconstruction Algorithm: The proposed reconstruction algorithm is an iterative process that determines the admittivity using the measured B_1^+, i.e, $\mu_0 H^+$. The H_z and its derivatives are assumed to be zero. In the initialization process, the admittivity, τ^0, is estimated using Helmholtz equation from a chosen homogeneous region, which was used as an initial artifact-free mask, Ω^0, detected from the estimates of the admittivity. In each iterative step, we then estimate the electric fields, E_x+iE_y, E_z, and expand the artifact-free mask, Ω, where the contribution of the boundary artifacts is small. In the steps that follow, the estimated electric fields and admittivity in Ω are not changed. The iterative processes are (i) update E_z and E_x+iE_y from the estimates of τ (Eq. 1, 2), (ii) solve E_z precluding the artifact free mask, Ω, using the estimates of E_z in the Ω as boundary conditions (Eq. 3), (iii) update the admittivity, τ (Eq. 1,2), (iv) update the artifact free mask, Ω, including the voxels with the small changes in the conductivity estimate.

Numerical Simulation and Validation: A cylindrical phantom model shown with the conductivity values shown in Fig 1(a) were constructed and used to validate the proposed reconstruction methods. The cylindrical phantom model contains three tissue types with the conductivity of 1, 2, and 3, and relative permittivity of 80. In this model, the largest tissue surrounds the two other smaller tissues whose width is 2~3mm. The radius and the height of the phantom are 40mm and 160mm. The electric fields, magnetic fields, and current density driven by a birdcage RF coil at 3T were simulated by a XFDTD software(REMCOM, State College, PA) with voxel size of $1\text{mm} \times 1\text{mm} \times 1\text{mm}$. The proposed reconstruction process were performed for all 3D tissue regions.

Results: Ideal and reconstructed conductivity values with noiseless H^+ are shown in Fig. 1 for three axial slices located at -60mm, -30mm, 0mm away from the iso-center of the RF coil, (a) ideal, (b) Helmholtz, (c) proposed. In Fig. 2, reconstructed conductivity values and initial artifact-free mask are shown for noisy H^+ with three different level of noise, SNR = 10^5, SNR = 10^4, and SNR = 10^3 at an axial slice at -60mm. Compared to the conventional reconstruction using the Helmholtz Equations, the boundary artifact in the conductivity estimates are strongly reduced using the proposed reconstruction method. In Fig. 3, ideal and reconstructed electric fields are shown with noiseless H^+ for the five axial slices. For a longitudinal electric field, E_z, the reconstructed maps are close to the simulated fields. For E_x+iE_y, the accuracy is reduced as moving away from the iso-center since the approximation becomes less accurate, i.e., the derivatives of H_z become more dominant in Eq. 2.

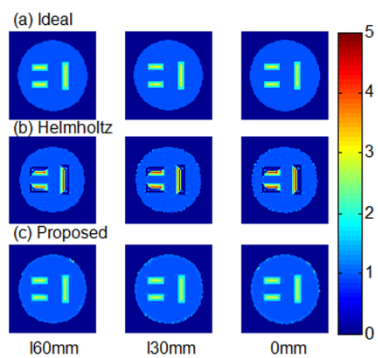

Fig. 1: Reconstructed conductivity maps for noiseless data: (a) Ideal, (b) Estimates using Helmholtz Eq., (c) Estimates using proposed method

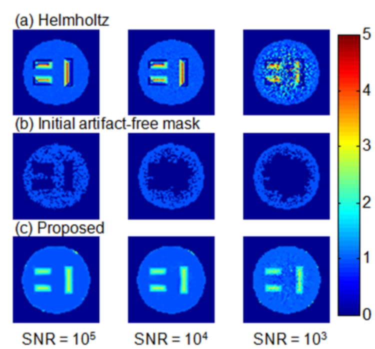

Fig. 2: Reconstructed conductivity maps for noisy data: (a) Estimates using Helmholtz Eq., (b) Initial artifact-free mask, (c) Estimates using proposed method

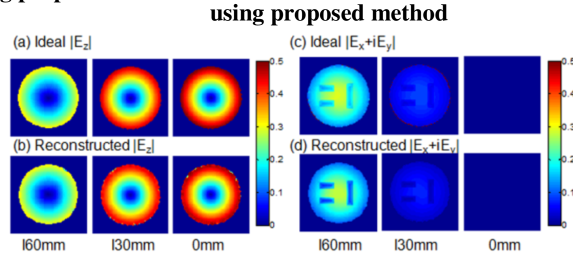

Fig. 1: Reconstructed electric fields: (a) Ideal magnitude of E_z, (b) Reconstructed magnitude of E_z, (c) Ideal magnitude of E_x+iE_y, (d) Reconstructed magnitude of E_x+iE_y.

Conclusions & Discussions: We developed a novel reconstruction approach for electric properties to reduce the boundary artifacts in MREPT. The proposed approach reconstructs the conductivity and permittivity as well as two components of the electric fields, E_z and E_x+iE_y using measured B_1^+ maps. Instead of using Helmholtz Equation, the proposed approach is based on three key identities of electric fields, B_1^+, and electric properties derived from the time-harmonic Maxwell's Equation. The details of the derivation is omitted here. The performance was evaluated using EM simulated fields of numerical phantom using a single transmit channel MR system. Compared to the conventional MREPT approaches, the boundary artifacts are greatly reduced.

References: [1] Katscher et al, IEEE TMI, 28:1365-1374 2009, [2] Voigt et al, MRM, 66:456-466, 2011, [3] Zhang et al, IEEE TMI, 29:474-481, 2010, [4] van Lier et al, MRM, 67:552-561, 2012, [5] Voigt et al, MRM, 68:1117-1126, 2012, [6] Seo et al, IEEE TMI, 31:430-437, 2011.

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