In vivo Imaging of Electrical Properties of Human Brain Using a Gradient Based Algorithm

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Introduction Being able to image tissue electrical properties—conductivity and permittivity—*in vivo* using MRI, Electrical Properties Tomography (EPT) has drawn considerable interests from the community [1]. Currently, most studies have focused on the homogeneous Helmholtz equation based method [2], whereas the ignored gradient term of electrical properties could potentially carry rich information for a more reliable reconstruction. For example, in the field of Magnetic Resonance Electrical Impedance Tomography (MREIT), the distribution of conductivity σ was reconstructed based on the derived gradient $\nabla\sigma$ [3]. In this study, a new gradient-based algorithm, called G-algorithm, for EPT was developed, and initial feasibility was demonstrated through *in vivo* experiment for imaging human brain at 7T.

Theory In order to derive the gradient of electrical properties, inhomogeneous Helmholtz equations for transmit and receive B_1 fields were utilized. At the Larmor frequency (ω) for protons, assuming that magnetic permeability for biological tissue equals that of free space μ_0, a general algorithm has been proposed for inhomogeneous tissue distributions [4], based on laboratory-frame components (H_x and H_y). Ignoring H_z component and its gradient in z-direction, combining the Cartesian components (H_x and H_y) according to the principle of reciprocity [5] and Gauss's law, the inhomogeneous Helmholtz equations for both right and left circularly polarized magnetic fields $H_1^{\pm}$ have been derived as in (1) [6], in which $\varepsilon_c=\varepsilon-i\sigma/\omega$ is the complex permittivity. Using a multichannel transceiver coil, the magnitude $|H_{1j}^{+}|$, relative phase ϕ_j^{+} between transmit channels, proton density weighted magnitude $|\rho H_{1k}^{-}|$ and relative phase ϕ_k^{-} between receive channels, can be measured for each individual channel in the experiment, respectively. Utilizing these measurements and removing proton density ρ, this set of equations can be solved with estimated $\nabla\ln(\varepsilon_c)$. Using *a priori* information about the distribution of ε_c, such as the value at certain voxels, quantitative map for ε_c can be determined through integration.

$$\nabla^2 H_1^{+} = -\omega^2\mu_0 H_1^{+}\varepsilon_c + (\nabla H_1^{+})^T \begin{bmatrix} 1 & i & 0 \\ -i & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \nabla\ln(\varepsilon_c)$$
$$\nabla^2 H_1^{-} = -\omega^2\mu_0 H_1^{-}\varepsilon_c + (\nabla H_1^{-})^T \begin{bmatrix} 1 & -i & 0 \\ i & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \nabla\ln(\varepsilon_c) \quad (1)$$

Methods The G-algorithm was tested through an *in vivo* human experiment. ***Data acquisition:*** The experiment was conducted in a 7T magnet (Magnex Scientific, UK) driven by a Siemens console. A 16-**c**hannel transceiver stripline coil [7] with coil elements parallel to the main magnetic field was used for transmission and reception. B_1 field data was collected for the 16 channels with a resolution of 1.5x1.5x5 mm^3 over 12 contiguous slices in the head. In order to obtain the magnitude $|H_{1j}^{+}|$ and relative phase ϕ_j^{+} of transmit B_1 fields, a series of small flip angle 2D GRE (gradient-recalled echo) images were acquired with one channel transmitting at a time and all channels receiving together, and merged with a 3D AFI (Actual Flip Angle) map [8–10]. The proton density weighted magnitude $|\rho H_{1k}^{-}|$ and relative phase ϕ_k^{-} of receive B_1 fields were obtained via another series of long TR (TR=8s), large flip angle 2D GRE images with all channels transmitting together and one channel receiving at a time, normalized by the sine of the 3D AFI map [10]. ***Data analysis:*** Proton density was removed based on the symmetric observation about magnitude of transmit and receive B_1 fields [10], [11]. A Gaussian filter was applied on the acquired field data to reduce noise. $\nabla\ln(\varepsilon_c)$ was obtained based on the proposed algorithm. A 2D image of $\ln(\varepsilon_c)$ was estimated through an inverse gradient algorithm, utilizing one voxel (shown as red dot in Fig. 1A) with its pre-determined σ and ε_r values (according to its anatomy and literature-reported *ex vivo* data of electrical properties [12]). The mean and standard deviation of the reconstructed σ and ε_r were analyzed for the tissue of interest, based on segmentation using a simple threshold on the T_1 weighted image (Fig. 1A).

Results The reconstructed electrical property maps are shown in Fig. 1. Strong correlation between the T_1 weighted structural image and different reconstructed contrasts is observed. Using the proposed gradient-based algorithm, boundaries across tissues are clearly delineated. The statistics (mean±SD) for three types of tissue, grey matter (GM), white matter (WM) and cerebrospinal fluid (CSF) are summarized in Table 1 and compared with literature reported values [12].

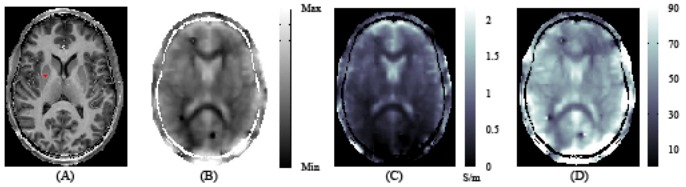

Figure 1. (A) T_1 image of slice 6. (B) Reconstructed $\ln|\varepsilon_c|$. (C) Reconstructed σ. (D) Reconstructed ε_r.

Table 1. Reconstructed electrical properties for three tissues

	σ [S/m]		ε_r	
	Reconstruction	Literature	Reconstruction	Literature
WM	0.46±0.25	0.43	47.4±10.1	43.8
GM	0.71±0.36	0.69	60.6±9.9	60.1
CSF	1.15±0.34	2.22	66.0±10.8	72.8

Discussion and Conclusion In this study, the G-algorithm, utilizing the gradient information in the inhomogeneous Helmholtz equation, for solving the EPT problem has been investigated. The accuracy of the method was experimentally demonstrated with *in vivo* data obtained at 7T. Its framework is based on measurable B_1 field components and does not depend on the knowledge of absolute phase distribution or field strength. In this paper, the symmetry of the sample was exploited to remove proton density from receive B_1 maps, however, a more general approach for removing proton density, under investigation, is expected to provide even more generality to the proposed algorithm. The G-algorithm can substantially reduce boundary errors which represent a very significant challenge in current EPT studies [13]. Not only can this method directly estimate electrical properties, it also provides new insights to further explore EPT problem solving approaches. Future directions for this work include more robust algorithms combining G-algorithm with other EPT frameworks, aiming for zero-order ε_c, for enhanced performance.

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