In vivo Quantitative Conductivity Imaging based on B1 Phase Information

T. Voigt[1], U. Katscher[2], and O. Doessel[1]
[1]Institute of Biomedical Engineering, University of Karlsruhe, Karlsruhe, Germany, [2]Philips Research Europe, Hamburg, Germany

Introduction: Electric conductivity could be used as a parameter for diagnosis in oncology [1], stroke [2], or myocardial infarction [3]. To determine tissue conductivity *in vivo*, Electric Properties Tomography (EPT) provides a framework by postprocessing amplitude and phase of a B1 map [4]. This study presents an approximation for conductivity reconstruction based only on the phase information of B1. Since the determination of the B1 amplitude requires typically twice the scan time of the determination B1 phase, this approximation significantly reduces the total scan time necessary for EPT. The approach, aiming for clinical applicability of conductivity imaging, is validated in simulations and *in vivo* experiments.

Theory: Electric conductivity σ and permittivity ε can be obtained from the complex magnetic field vector **H** [4]. In Eq. (1), ∂A is a closed path around an area (pixel) with constant $\kappa = \varepsilon - i\sigma/\omega$. For a determination of electric properties, all three complex components of **H** are needed in Eq. (1). Since A is an arbitrarily orientated surface, this additional degree of freedom can be used to further reduce the required input quantities. Integration for, e.g., the A_{yz} surface along the x-direction yields an expression for a compartment (voxel), shown in Eq. (2). Taking into account explicitly that $\underline{B_1}^+ = e^{i\varphi} B_1^+$ is a complex quantity; the derivation in the numerator can be executed. Rearranging the resulting equation allows the separation of real and complex parts, leading to the expressions

$$\oint_{\partial A} \nabla \times \mathbf{H}(\mathbf{r}) \mathrm{d}\mathbf{l} \Big/ \omega^2 \mu \int_A \mathbf{H}(\mathbf{r}) \mathrm{d}\mathbf{a} = \kappa(\mathbf{r}) \qquad (1)$$

$$-\oint_{\partial V} \nabla \underline{B_1}^+(\mathbf{r}) \mathrm{d}\mathbf{a} \Big/ \omega^2 \mu \int_V \underline{B_1}^+(\mathbf{r}) \mathrm{d}V = \kappa(\mathbf{r}) \qquad (2)$$

$$\sigma(\mathbf{r}) = (\omega \mu A_{xyz})^{-1} \left(\oint_{\partial V} \nabla \varphi(\mathbf{r}) \mathrm{d}\mathbf{a} + 2 \int_V \left[\nabla \ln\left(B_1^+(\mathbf{r})\right) \cdot \nabla \varphi(\mathbf{r}) \right] \mathrm{d}V \right) \qquad (3)$$

$$\sigma \approx \oint_{\partial V} \nabla \varphi(\mathbf{r}) \mathrm{d}\mathbf{a} \Big/ \mu_0 \omega A_{xyz} \qquad (4)$$

In Eq. (4), it has been assumed that the variation of B_1^+ is much smaller than the variation of φ according to typical experimental findings. This approximation was tested in the following experiments.

Subjects and Methods: 1) An FDTD simulation study was performed using the visible human model in Semcad [5]. The head of the visible human was placed at the isocenter of a body coil at 1.5T. The resulting $\underline{B_1}^+$ field was used for reconstruction according to the exact formula Eq. (2) and the phase based approximation Eq. (4). 2) Coronal images of a healthy volunteer were obtained using a 1.5T MR scanner (Philips Healthcare, Best, The Netherlands). 11 slices were acquired in 3D acquisition mode with resolution 1.6 × 1.6 × 2mm³. For B_1^+ magnitude mapping, a MTM sequence [6] with $TR_{11,12}$ = 15/215 ms and $TR_{21,22}$ = 15/315 ms was used, leading to a total scan time of 11min. To estimate the transmit phase φ, the phase of a SE image (TR = 200 ms, nominal flip angle 90°, TE = 8 ms, total scan time 5 min) was cut in half to separate transmit from receive phase [1]. Conductivity values were reconstructed using Eq. (2) and Eq. (4).

Results/Discussion: The reconstructed quantitative conductivity based on simulated data is shown in Fig. 1. *In vivo* results are shown in Fig. 2. The conductivity values were computed based on complex B1 (phase only) inside three regions of interest. In the simulation study, σ_{WM} = 0.34 ± 0.03 S/m (σ_{WM} = 0.39 ± 0.09 S/m), σ_{GM} = 0.59 ± 0.05 S/m (σ_{GM} = 0.59 ± 0.13 S/m), and σ_{CSF} = 2.03 ± 0.11 S/m (σ_{CSF} = 2.44 ± 0.36 S/m) were obtained. *In vivo* quantitative conductivity results are σ_{WM} = 0.53 ± 0.27 S/m (σ_{WM} = 0.55 ± 0.27 S/m), σ_{GM} = 0.98 ± 0.31 S/m (σ_{GM} = 1.03 ± 0.32 S/m), and σ_{CSF} = 1.75 ± 0.34 S/m (σ_{CSF} = 1.82 ± 0.37 S/m).

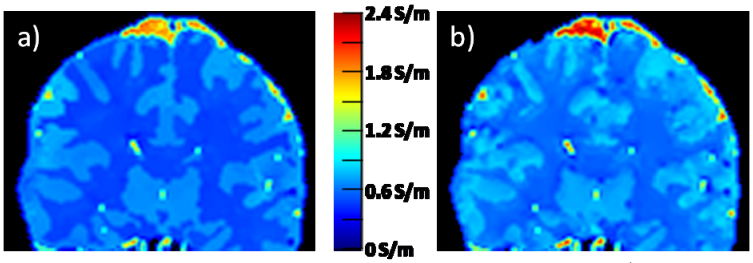

Fig. 1: (a) Conductivity reconstruction based on complex $\underline{B_1}^+$ field from visible human FDTD simulation. (b) Reconstruction of FDTD data based on phase only.

Conclusion: Tissue conductivity predominantly influences the phase of B1. This allows the reconstruction of the conductivity based on B1 phase measurements, skipping lengthy B1 amplitude measurements. Simulation and *in vivo* results indicate that sufficient accuracy is achieved compared with a reconstruction based on complex B1. Thus, a new and quantitative contrast for MRI can be obtained in 3D within 5 min by means of phase-based reconstruction. In future work, this technique needs to be evaluated clinically.

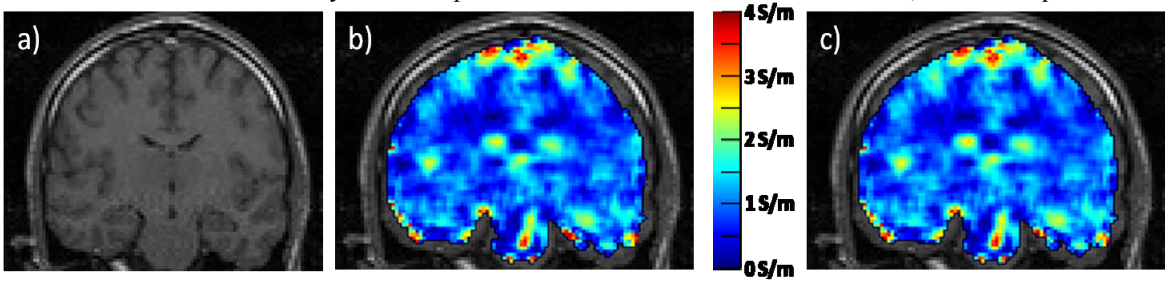

Fig. 2: (a) anatomy. (b) *In vivo* conductivity reconstruction based on complex $\underline{B_1}^+$ field. (c) *In vivo* conductivity reconstruction based on phase only.

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