RF shimming improves Phase-Based Conductivity Imaging

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Introduction: In the framework of "Electric Properties Tomography" (EPT) [1-4], approximate conductivity imaging is possible by analyzing the B1 phase, assuming constant B1 amplitude. The more this assumption is violated, the less accurate the reconstructed conductivity. This study analyzes the influence of modifying the B1 amplitude by parallel RF transmission on the precision of phase-based EPT.

Theory: The electric tissue conductivity σ can be reconstructed from the complex 3D RF transmit (TX) field $\underline{B}_1 = \mu_0\, \underline{H}^+ = H^+ \exp(i\varphi^+)$ via Eq. (1) with μ_0 the permeability (assumed to be constant), ω the Larmor frequency, and V the integration volume [3]. For phase-based conductivity imaging, $H^+ = const$ is assumed, and Eq. (1) reduces to Eq. (2), introducing the error δ_{phaBa} given by Eq. (3). In a multi-TX system, $\underline{H}^+$ is given by the overlay of $\underline{H}_n^+$ of the N different TX channels, weighted by the channel weights $\underline{A}_n = A_n \exp(i\phi_n)$, see Eq. (4). The central idea of this study is to optimize $\underline{A}_n$ with respect to minimal δ_{phaBa}, Eq. (3). In general, this can be done via three different methods: (a) minimization of $\nabla(\ln H^+)$, (b) minimization of $\nabla(\varphi^+)$, and (c) minimization of the scalar product of Eq. (3), i.e., making $\nabla(\ln H^+)$ and $\nabla(\varphi^+)$ orthogonal. Method (b) and (c) requires the knowledge and shaping of φ^+, which appears to be an unusual task. Instead, this study is related to method (a) by minimizing the Normalized Root-Mean-Square Error (NRMSE) of H^+ as done for RF shimming [5]. - The linearity of Eq. (2) allows replacing φ^+ by the transceive phase of a suitable MR imaging, superseding the extraction of φ^+ from the transceive phase [3,4].

$$\sigma(\vec{r}) = (\mu_0 \omega V)^{-1}\left(\oint_{\partial V} \nabla\varphi^+(\vec{r})\,\mathrm{d}\vec{a} + 2\int_V \left[\nabla\left(\ln H^+(\vec{r})\right)\cdot\nabla\varphi^+(\vec{r})\right]\mathrm{d}v\right) \quad (1)$$

$$\sigma_{\text{phaBa}}(\vec{r}) = (\mu_0 \omega V)^{-1}\oint_{\partial V} \nabla\varphi^+(\vec{r})\,\mathrm{d}\vec{a} \quad (2)$$

$$\delta_{\text{phaBa}} \sim \nabla\left(\ln H^+(\vec{r})\right)\cdot\nabla\varphi^+(\vec{r}) \quad (3)$$

$$\underline{H}^+(\vec{r}) = \sum_{n\le N} \underline{A}_n\, \underline{H}_n^+(\vec{r}) \quad (4)$$

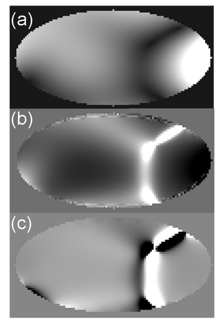

Fig. 1: Abdominal phantom simulation for N = 8 TX channels. (a) H^+ for an arbitrary example shim set (not optimized for B1 homogeneity). (b) Inhomogeneity of H^+ shown in (a), visualized by its Laplacian. (c) Conductivity reconstructed from φ^+ of chosen arbitrary example shim set.

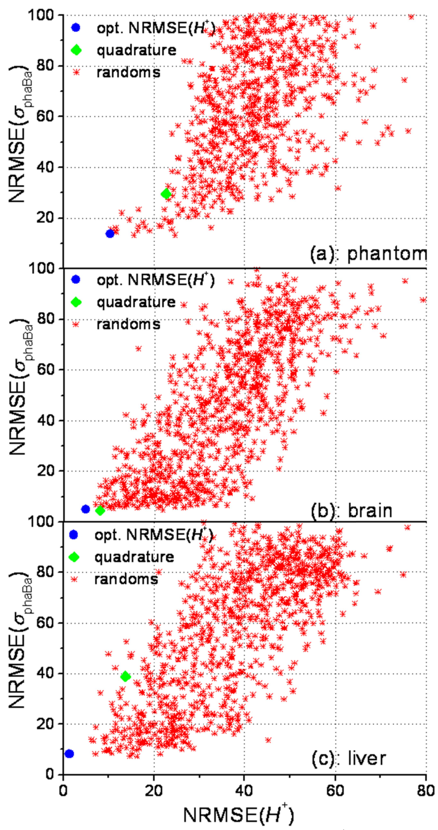

Fig. 2: Minimizing NRMSE(H^+) via RF shimming in an 8-channel TX-system leads to nearly minimal NRMSE(σ_{phaBa}) (i.e., optimal conductivity reconstruction) for all three simulation scenarios investigated.

Methods & Results: For an 8-channel whole body coil at 3T [6], TX sensitivities have been FDTD-simulated ("XFDTD MicroCluster", Remcom Inc., USA, voxel size 5×5×5 mm³) for (a) a homogeneous abdominal phantom (diameters = 20/40 cm, σ = 0.5 S/m, ε_r = 60), (b) the brain of a realistically shaped patient, (c) the liver of a realistically shaped patient. First, an arbitrary example of TX channel weights $\underline{A}_n$, not optimized for B1 homogeneity, has been investigated for the abdominal phantom (Fig. 1). The resulting inhomogeneity of H^+ (Fig. 1a), highlighted by the Laplacian of H^+ (Fig. 1b), corresponds with the error in the phase-based conductivity map (Fig. 1c). Then, σ_{phaBa} has been reconstructed for 1000 different random sets of $\underline{A}_n$. Each resulting NRMSE(σ_{phaBa}) (reflecting δ_{phaBa}) is plotted against the corresponding NRMSE(H^+) (Fig. 2a), together with data from quadrature excitation and RF shimming. The same procedure has been applied for the simulated brain and liver sensitivities (Figs. 2b/c). For all three cases, RF shimming yields NRMSE(σ_{phaBa}) very close to the minimal NRMSE(σ_{phaBa}) found (difference less than 1%). - As expected from theory, reconstruction results using the full EPT equation (1) are not influenced by the choice of $\underline{A}_n$ (not shown).

Discussion & Conclusion: RF shimming improves the reconstruction of tissue conductivity from the TX phase, facilitating phase-based conductivity imaging at high field strengths. Future studies will investigate if dedicated shapes of RF excitation (optimized not only via H^+ but also φ^+) are able to further reduce the error of phase-based conductivity imaging.

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