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Global Maxwell Tomography using an 8-channel radiofrequency coil: simulation results for a tissue-mimicking phantom at 7T

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Abstract—We simulated a Global Maxwell Tomography experiment for the estimation of electrical properties in a numerical tissue-mimicking phantom using a decoupled 8 channel radiofrequency coil designed for 7 Tesla magnetic resonance scanners. The goal of this work was to investigate whether the orthogonality of the coil’s transmit fields (b1 measurements) is required to ensure accurate results. We demonstrated a normalized root mean squared error smaller than 0.6% with respect to the true electrical properties distribution. Our results showed that electrical properties reconstruction with Global Maxwell Tomography is accurate and robust.

I. INTRODUCTION

Global Maxwell Tomography (GMT) [1] is a quasi-Newton optimization technique, based on higher-order volume integral equations (IE) [2], recently proposed for the estimation of the electrical properties (EP) of human tissue using magnetic resonance (MR) measurements. GMT has been demonstrated in simulation using 8 orthogonal incident fields, obtained from a numerical electromagnetic (EM) basis, as the independent transmit fields of a hypothetical coil array [3]. In particular, eight (maximum number of channels commercially available in 7 Tesla MR scanners) orthogonal vector fields were generated by enclosing the scatterer of choice in sheets of randomly excited volumetric currents [3]. Exciting the scatterer using one incident field at a time, had led to a well-conditioned optimization procedure and to an accurate estimation of the EP. However, such fields are artificial and it could be difficult to design a coil that generates them. For this reason, in this work we instead performed GMT employing realistic incident fields, using the surface IE method for a radiofrequency (RF) coil that was modeled based on an actual 7T coil presented in [4].

II. RF COIL

We simulated an 8 channel transmit-receive array consisting of triangular shaped elements. Its structure, illustrated in Fig. 1, allows capacitive decoupling of 1st order neighbors, through a set of tuning capacitors (1 – 19 pF) distributed on each element, while the 2nd order neighbors are decoupled through a pair of perfectly counter wound inductors, each with inductance equal to 22 nH. Each port was matched to 50 Ohms by a capacitor connected in parallel to the port (5.6 and 4.7 pF for the top and bottom ports, respectively).

The coil was treated as a perfect electric conductor, thus the electric field IE expanded with the RWG basis functions [5] was adopted for its accurate and fast simulation. Moreover, the delta-gap method [6] was employed to model the voltage jumps due to the presence of lumped elements and feeding ports on the coil. Specifically, each port and lumped element were treated as specific edges of the discretization mesh, as shown in Fig. 1 (right) for one representative element of the coil (the same arrangement was used for all elements).

To properly tune the coil, we performed a volume-surface IE coupling procedure [7]. More specifically, we first loaded the coil with our scatterer of choice, which was a four compartment tissue-mimicking cuboid phantom. Second, we calculated the S parameter matrix of the coupled system by considering the tuning capacitors as short-circuits. The multi-port system was reduced to an 8 port system through MATLAB’s RF toolbox, by attaching the tuning capacitors. Different sets of capacitors were tested through an optimization procedure until the 1st and 2nd order neighbors were partially decoupled (< –14 dB) and each port was perfectly
matched (< −25 dB). The $S$ parameter matrix is shown in Fig. 2. In Fig. 3 the scattered EM fields from the tuned coil to free space are presented. These fields were used as a set of incident fields in GMT.

Fig. 2. The $S$ parameters of the coil after tuning the capacitors to decouple the 1st and 2nd order neighbors

The 8 coil incident fields were used to generate synthetic transmit fields maps inside the scatterer ($b_1^+$ maps) for $f = 297.2$ MHz, which is the operating frequency of 7 Tesla MR scanners. These $b_1^+$ maps, shown in Fig. 4, were corrupted by noise yielding peak Signal-to-Noise Ratio (SNR) = 100, which corresponded to a mean SNR within the phantom volume ranging between 23 and 28 for the 8 coils. The maps were then used as input for GMT, which minimizes a cost function operating on the residual between the synthetic transmit fields maps and corresponding maps, iteratively generated for updated guesses of the phantom’s EP.

While the $b_1^+$ maps of the coil elements were not orthogonal, they formed a well-conditioned set with a condition number $\sim 7.7$, which is comparable to that of the ideal case of the EM basis (condition number $\sim 1$ [8]). Starting from a homogeneous guess, GMT was able to accurately estimate the phantom’s EP in 135 iterations. Fig. 5 shows the reconstructed EP for an axial cut at the center of the phantom. The normalized root mean square error for both $\epsilon_r$ and $\sigma$ was $< 0.6\%$. Therefore, we can conclude that GMT does not require strictly orthogonal synthetic MR measurements in order to achieve accurate EP reconstructions.

Fig. 3. (from left to right and top to bottom) The scattered electric and magnetic fields from each channel of the coil, used as incident fields for GMT.

Fig. 4. MR measurements for an axial cut of the tissue-mimicking four-compartment phantom. The field is masked outside the phantom for enhanced visualization

Fig. 5. Reconstructed electrical properties for an axial cut of the tissue-mimicking four-compartment phantom. (left) real part of the relative permittivity and (right) conductivity

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