Feasibility of Full RF Current-Vector Mapping for MR Guided RF Ablations

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Introduction: Radiofrequency ablation is an effective, minimally invasive method for therapies including cardiovascular electrophysiology and cancer tumor ablation. Radiofrequency current density imaging (RFCDI) is a technique that can image current at the Larmor frequency[1]. Because field patterns remain quasi-static near the electrode at the Larmor frequency, as they are at the typical ablation frequency of 500 kHz, the current pathways will be the similar. RFCDI can be used to image ablation current pathways of spatially varying phase if the current is dominantly along the direction of B_0[2]. For clinical ablation, the direction of current is not always possible to ensure. If instead all currents have the similar phase, it is possible to measure two components of the RF magnetic field and calculate the third using volumetric field measurements and limited *a priori* information. We can then find all three components of current density without subject rotations. This will allow MRI to become a treatment predictor and monitoring tool for RF ablations.

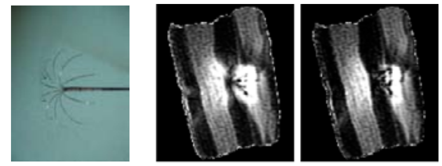

Figure 1: Ablation electrode (left) used to produce RF current images. Complex J_z amplitude is calculated assuming J_z is dominant (center) and with the equi-phase assumption (right). Muscle tissue is conductive and appears bright. The equi-phase assumption reduces the apparent current in insulating fat.

Theory & Methods: Previous RFCDI methods measured the rotating frame magnetic fields produced by an RF current density and reconstructed the current density component along B_0, assuming the other current components were negligible. These methods solve for the magnitude and phase of that current density component. If all the currents are in phase, we can instead use the rotating frame measurements to reconstruct the magnitude of both RF magnetic fields perpendicular to B_0 (B_x and B_y)[3]. Since fatty tissues act as electrical insulators and water-based tissues have similar impedance phase in the frequency range of interest, this equi-phase requirement is met. The rotating frame fields are then simply related to the lab frame fields by a simple global coordinate rotation in the image.

Because magnetic fields have zero divergence, the measured fields contain information about the missing B_z field component. The partial z-derivative of B_z can be calculated from volumetric B_x and B_y data. If a single x-y plane of B_z is known, B_z in the rest of the volume can be found by integration. Once all components are known, the current density can be calculated by taking the curl of the magnetic field.

An x-y plane of B_z can be estimated using some prior knowledge of the current distribution. Sources of prior information include the fact that current will be perpendicular to conducting surfaces like the ablation electrode and will be small at distances far from the electrode. For our simulations, we assumed that the bottom x-y plane of the phantom has current only in the z-direction, along B_0.

To demonstrate the feasibility of reconstructing all RF current components from a single orientation, we simulated a cylindrical conducting phantom with an insulating sphere in the center. The current runs primarily in the y-direction, perpendicular to B_0, so it cannot be imaged well using prior methods. The field from the current distribution was calculated numerically from Maxwell's equations using appropriate boundary conditions. Return wires were included, breaking the cylindrical symmetry of the fields. Gaussian noise was added to make the simulations more realistic.

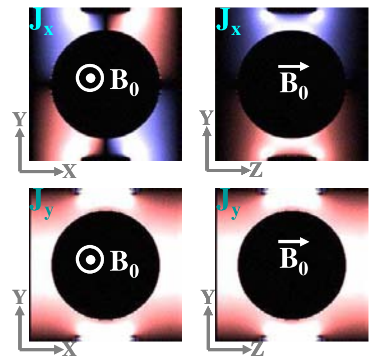

Figure 2: Simulated current densities including measurement noise. X-Y and Y-Z planes of J_x and J_y are shown. The planes are offset from the center of the phantom by 1/8 of the phantom width. The scale for J_y (the dominant current component) is ten times as large as the scale for J_x. Positive currents are tinted red, negative currents blue.

Results: Figure 1 shows the experimental reconstruction of the current density component J_z for an RF ablation electrode using both the dominant J_z assumption and the equi-phase assumption. Because the images are near the ablation electrode, the J_z component is not truly dominant. Thus the reconstruction made with the dominant J_z assumption shows significant current in the insulating fat layer, while the equi-phase reconstruction shows current primarily in the conducting muscle. The equi-phase assumption should allow us to reconstruct all RF fields even in areas where J_z is not dominant.

Figures 2 and 3 show that if all fields are in phase, it is also feasible to reconstruct current density components perpendicular to B_0 from a single subject orientation. In Figure 2 the current densities are calculated from the noisy simulation data. In Figure 3 the data is reconstructed without using B_z. The noise level is increased significantly since B_z is calculated from noisy derivatives of the other field components. There are streaks along the z-dimension due to integration of noise.

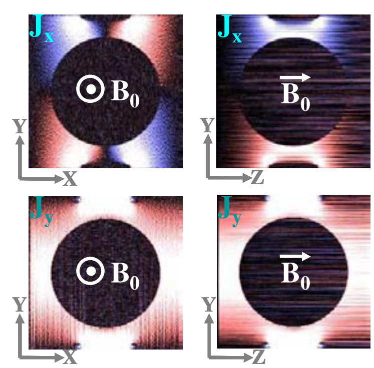

Figure 3: Reconstructed current densities. X-Y and Y-Z planes of J_x and J_y are shown. J_z is not shown since it does not depend on the reconstructed B_z field.

Discussion & Conclusions: All three RF current density components can be measured from one subject orientation with no restrictions on the direction of the current as long as the currents have equal phase. The SNR for the current components perpendicular to B_0 is degraded. The SNR could be improved by using more prior information about B_z. Since the current density is calculated from the derivative of the magnetic field, the SNR can be further improved by weighting the higher frequencies more heavily in data acquisition. The streakiness of reconstructions is due to favoring the z-dimension in integration. This may be reduced by a Green's Theorem formulation of the field relations. Methods that do not bias the integration direction are currently being investigated. With the addition of complete RF current mapping, MRI will have the means to predict and monitor local SAR deposition during RF ablation therapies.

References:

[1] G. Scott et al, Magn. Reson. Med. 33:355, 1995.

[2] G. Scott et al, Proc 13th ISMRM, p151, 2005.

[3] G. Scott et al, IEEE Trans. Med. Imaging 14(3), 515, 1995.