

Heat Equation Inversion (HEI) Algorithm Sensitivity Assessment for Computation of SAR from MR Thermometry Acquisitions

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Synopsis

MR thermometry methods are often used to assess safety of RF antennas. Typically thermal mapping is conducted in phantoms, which measures the temperature change as result of exposure to RF waves. From these temperature difference maps, SAR distribution can be reconstructed using the inverse heat equation (HEI) framework . With a goal of testing the robustness of this method, in this work, we assessed the fidelity of the algorithm with respect to different regularization parameter, different SAR distributions, excitation frequencies and heating durations.

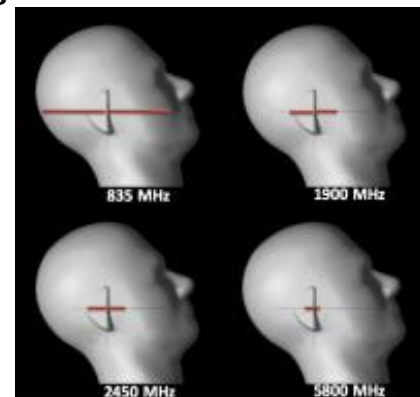
Background

Magnetic resonance thermal imaging has been a tool to measure 3-dimensional temperature change in phantoms being exposed to radiofrequency waves. Conversion from temperature change to specific absorption rate (SAR) is nontrivial especially when the heating duration is long, as heat-diffusion effects become more prominent [1]. The heat equation inversion (HEI) algorithm that was first introduced in reference [2], provides a framework to overcome challenges associated with computation of SAR when heating durations are long. This algorithm accounts for energy exchange that occurs during energy source exposure and utilizes a compressed sensing type optimization to reconstruct the energy source term – SAR. This is applicable to MRI since MRI thermal mapping can be used to assess safety of low power wireless devices, as well as, in RF hyperthermia interventions where the thermal dose and temperature hotspot size need to be determined [3]. In this work, we investigated the fidelity of the HEI algorithm in simulations with respect to changes in regularization parameters, SAR exposure levels and heating durations. Sensitivity analysis was performed on antennas operating between 838MHz and 5.8GHz.

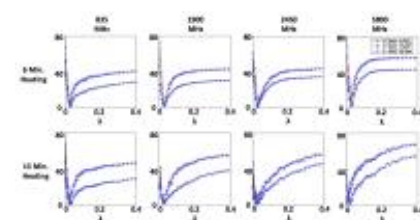
Methods

The mathematical framework for the heat equation inversion can be find in [2]. Four dipole antenna simulations were modeled using a commercially available finite difference time domain (FDTD) solver (XFDTD version 7.3, Remcom, State College, PA, USA). Four different dipole antenna tuned to frequencies 838 MHz, 1900 MHz, 2450 MHz and 5800 MHz were placed adjacent to the specific anthropomorphic mannequin (SAM) head phantom [4,5], with different electrical properties selected to match the standards at the operating frequency of the dipole antennas [6]. A voltage source was placed at the center of the dipole antennas. For the 838 MHz, 1900 MHz, 2450 MHz and 5800 MHz bands dipole lengths were 17.1 cm, 7.5 cm, 5.8 cm and 2.5 cm, respectfully. For the excitation, a voltage source providing unit voltage was placed between the legs of the dipole antenna. The simulation mesh size was 170×126×336 and resolution was of 2×2×2 mm³. A seven-layer perfectly matched layer (PML) absorbing boundary condition was applied at all outer boundaries, and the convergence criterion was set to -50dB. Upon convergence of the simulation, the match of the antennas was <-15dB. Each of the simulations was scaled to such that the output power of the simulation was 100mW and 200mW and the resulting 6- and 15-minute RF heating maps were computed using a thermal simulator [7] with a time step size of 4 seconds. This resulted in 4 simulations for each frequency band (100 mW-6 minutes, 100mW-15 minutes, 200 mW-6 minutes, 200mW-15 minutes). Gaussian noise with 0 mean and standard deviation of 0.035 °C was injected into temperature difference maps. The noise was chosen based on empirical noise figures in MR thermal mapping phantom data [8]. The thermal maps were then into the HEI reconstruction framework and the SAR maps were reconstructed using different lambda values between 0 and 80 in a logarithmic scale. In order to remove the effect of energy deposited on analysis, λ values were normalized using the total temperature change injected into object. Overall, 1280 reconstruction simulations were conducted. The reconstruction of the SAR maps from the 3D temperature maps was performed on a high performance computing (HPC) cluster with 112 nodes, each with 2 Intel Xeon E-2690v2 3.0GHz CPUs and 64 GB of memory. Once the computations were finished, 1g and

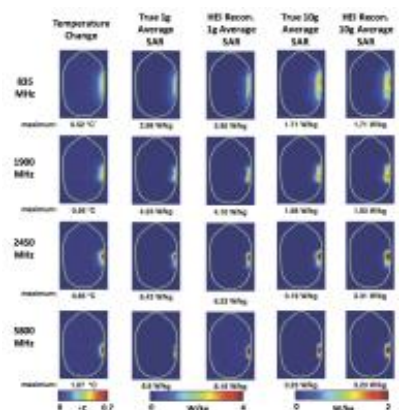
Figures



Dipole antenna of different sizes, tuned to 4 different frequencies were placed next to the SAM head model.



Regularization parameter and its effect on the on HEI reconstruction. Maximum 1g and 10g average SAR reconstruction error for 6 minutes and 15 minutes with 100mW or 200mW of net input power is plotted.



Reconstructed 1g and 10g average SAR maps using the HEI method. Reconstruction was conducted from the temperature difference maps due to 15 minutes of heating.

10g average maps were reconstructed and the maximum 1 or 10g average SAR was recorded, respectively. The maximum 1g and 10g average SAR error (%) versus regularization parameter, λ , were plotted for each simulation and heating duration. Additionally, the reconstructed 1g and 10g average SAR maps at a center slice of the SAM phantom were plotted.

Results

The sensitivity of the HEI process to the parameter λ is illustrated in figure 2, where the percent error in maximum 1g and 10g SAR is plotted versus the regularization parameter λ . For dipole antenna simulations at different frequency bands, an error of <16% was observed with a normalized $\lambda=0.03$. These errors were observed after injection of Gaussian noise into the temperature maps that were used for the HEI reconstruction. Reconstruction results remained consistent across different output power levels (100mW and 200mW) and heating durations (6 and 15 minutes). Reconstruction maps with a normalized $\lambda=0.03$, heating duration=15 minutes, and output power = 100mW are shown in figure 3. For an axial slice in the center of the SAM phantom, the true 1g and 10g average SAR maps are juxtaposed next to the HEI reconstructed average SAR maps. The largest error in the maximum 1g average SAR and 10g average SAR was 7.3% and 3.8%, respectively. Reconstructed SAR maps are closely correlated with true average SAR maps in distribution and magnitude.

Conclusions

In this work, sensitivity assessment of the HEI framework is presented for different operating frequencies, power levels and heating durations. Results demonstrate that the combination of 3-dimensional temperature mapping with realistic noise levels present in MR thermometry, alongside thermal property measurements of the phantom enables conversion of temperature change to average SAR when heating durations were up to 15 minutes long. A stable regularization parameter was identified enabling use of the HEI algorithm for experimental safety assessment of a myriad of RF sources.

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