

TEMPERATURE MAP RECONSTRUCTION DIRECTLY FROM K-SPACE WITH COMPENSATION FOR HEATING-INDUCED GEOMETRIC DISTORTIONS

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Target Audience Scientists and clinicians interested in proton resonance frequency (PRF)-shift MR thermometry.

Purpose Tissue heating results in a change in PRF which can be measured directly from a change in image phase. However, the PRF change also distorts the image and causes geometric distortions in temperature estimates, in the same manner as other chemical shift distortions if left uncompensated. We propose an algorithm that produces PRF temperature maps free of these distortions by fitting a signal model directly to acquired k -space data, that accounts for PRF-induced phase both up to and during the readout. We hypothesize that compensating for chemical shift distortions will improve the accuracy of temperature change and thermal dose measurements.

Methods Algorithm. We reconstruct temperature maps by fitting a hybrid referenceless and multibaseline image model¹ directly to acquired k -space data², and including a term to account for PRF/chemical shift-induced phase accrual. The k -space signal model is $\tilde{y}_i = \sum_{j=1}^{N_s} e^{i\vec{k}_i \cdot \vec{x}_j} (\sum_{l=1}^{N_b} b_{l,j} w_l) e^{i\{A\}c_j} e^{i\theta_j(1+t_i/T_E)} + \varepsilon_i$, where \vec{k}_i is the k -space location of sample i acquired at time t_i , N_s is the number of spatial locations \vec{x}_j , N_b is the number of baseline images \mathbf{b} with weights \mathbf{w} , \mathbf{A} is a polynomial matrix with coefficient vector \mathbf{c} , θ_j are temperature-induced phase shifts at the echo time T_E , and ε is Gaussian noise. The model is fit using a nonlinear conjugate gradient algorithm and time segmentation to reconstruct the temperature maps.

Simulations. k -Space data of a simulated phantom with a Gaussian-shaped phase shift corresponding to a 33°C temperature rise were generated for a spiral trajectory with 16 interleaves, 16 ms readout time per interleaf, 200 x 200 image matrix, 20 cm field of view (FOV), and 8 receive coils with sensitivities modeled using a finite difference time domain method³. Frequency shifts resulting from the temperature rise were used as an off-resonance field map in the synthesis of the k -space data.

Phantom heating experiment. EPI and spiral data of a heated gel phantom were acquired at 3T (Philips Achieva, Philips Healthcare, Best, Netherlands) with 5 receive coils and EPI/spiral TR 24 ms/32 ms, TE 16 ms, FOV 200 x 200 mm², EPI/spiral matrix size 200 x 196/200 x 200, slice thickness 7 mm, EPI factor 7, and 16 spiral interleaves with 16 ms acquisition readout. The phantom was heated for 41 s using a Philips Sonalleve HIFU system with a 4 mm treatment cell size, 110 W power, and 1.2 MHz frequency. Images from the EPI scan were used to compute temperature maps through conventional complex phase difference. Temperature maps from spiral data were reconstructed directly from k -space with and without compensating for chemical shift in the proposed signal model. Temperature maps used for thermal dose calculations were reconstructed at a 96 x 96 matrix size for both EPI and spiral data. Thermal dose maps were computed from the mean temperature change in each pixel.

Results Figure 1 shows simulation and phantom heating results for the spiral data. Without chemical shift compensation, the 33°C true peak of the simulated hotspot is estimated as 36°C. This overestimation is corrected using the proposed algorithm, which accurately estimates the peak as 33°C. The peak temperatures reconstructed from the phantom heating experiment with the same acquisition trajectory without and with chemical shift compensation were 37°C and 33°C, respectively. Figure 2 shows thermal dose maps calculated from the spiral temperature reconstructions and EPI phase-difference temperature maps. Maximum dose estimated from the spiral temperature maps without chemical shift compensation is 2.5 times higher than the spiral estimate with compensation and 2 times higher than the EPI estimate. The maximum dose estimated from the (higher pixel bandwidth) EPI images is a factor

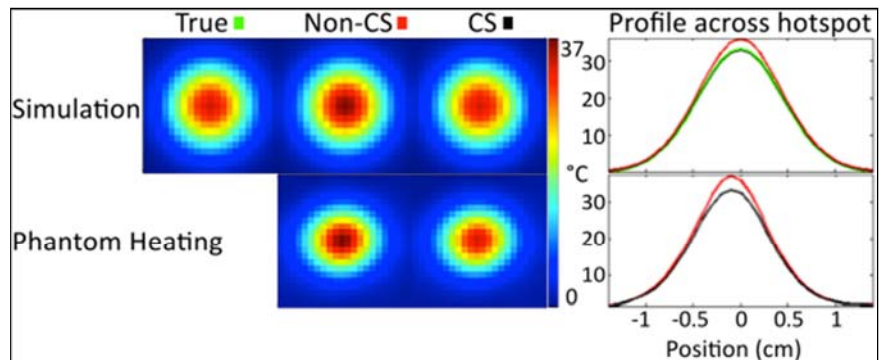


Figure 1: Temperature maps and profiles across hotspot for simulation (top) and phantom heating data (bottom). True temperature (simulation only) and temperature reconstructed without and with chemical shift (CS) compensation are shown.

of 1.25 times higher than the chemical-shift compensated spiral estimate. However, the EPI data have not been compensated for heating-induced distortions, which cause spatial shifting and amplification of temperature estimates⁴.

Discussion and Conclusion Phase accrual resulting from heating-induced off-resonance causes temperature estimation errors. We have presented a reconstruction algorithm that compensates for these distortions that result directly from heating. By accounting for this off-resonance effect, error in simulated and phantom heating estimates are reduced. A difference of a few degrees in the temperature reconstruction propagates into a more than doubled thermal dose estimate. Therefore, compensating for these errors can have a significant positive impact on clinical and research applications of PRF-shift thermometry.

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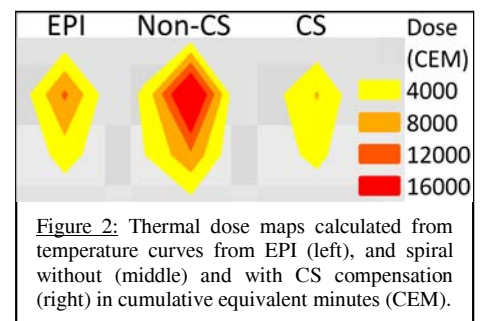


Figure 2: Thermal dose maps calculated from temperature curves from EPI (left), and spiral without (middle) and with CS compensation (right) in cumulative equivalent minutes (CEM).