

# DIRECT RECONSTRUCTION OF PROTON RESONANCE FREQUENCY-SHIFT TEMPERATURE MAPS FROM K-SPACE DATA FOR HIGHLY ACCELERATED THERMOMETRY

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**Target Audience** Scientists and clinicians interested in accelerated PRF-shift MR thermometry.

**Purpose** Real-time volumetric MR thermometry is desirable for several applications of MR-guided focused ultrasound. While high frame rates can be achieved over limited volumes using standard imaging techniques, real-time 3D temperature imaging requires some form of acceleration. Existing accelerated thermometry techniques use temporal regularization [1] and/or parallel imaging and compressed sensing [2] to suppress aliasing artefacts. We propose and validate a constrained temperature reconstruction method that estimates temperature changes directly from k-space data. Because we fit an image model comprising fully-sampled baseline images to the accelerated k-space data, temperature maps containing aliasing artefacts are removed from the solution space, and high acceleration factors can be achieved without temporal regularization that sacrifices temporal resolution.

**Methods** We reconstruct temperature maps by fitting a hybrid image model [3] directly to acquired k-space data. The k-space signal model is  $\tilde{y}_i = \sum_{j=1}^{N_s} e^{i\vec{k}_i \cdot \vec{x}_j} (\sum_{l=1}^{N_b} b_{l,j} w_l) e^{i((Ac)_j + \theta_j)} + \varepsilon_i$ , where  $\vec{k}_i$  is the k-space location of sample  $i$ , the  $b_l$  are baseline images with weights  $w$ ,  $A$  is polynomial matrix,  $c$  is a coefficient vector,  $\theta_j$  are temperature-induced phase shifts, and  $\varepsilon$  is Gaussian noise. We fit  $w$  using a quadratic program and use a Newton algorithm with backtracking line search to fit  $c$ . We combine this descent algorithm with an iteratively reweighted least-squares algorithm [4] to fit a sparse  $\theta$ , reflecting our expectation of a focal temperature rise.

**Simulations.** k-Space data of a simulated phantom with on-off Gaussian-shaped phase shift were generated for a golden angle (GA) trajectory with 101 projections for full sampling and a 64x64 image matrix. Phase change maps were reconstructed at 4x acceleration (25 projections) using Temporally Constrained Reconstruction (TCR) [1] and the proposed k-space-based method.

**Phantom cooling experiment.** GA radial k-space data of a heated gel phantom (Fig. 2a) were acquired at 3T (Philips Achieva, Philips Healthcare, Best, Netherlands) with TR/TE/FOV/matrix/slice thickness = 100ms/10ms/256x256mm<sup>2</sup>/128x128/3mm. True temperature was recorded using a fiber optic probe inserted in the heated tube. Temperature maps were reconstructed using an image-domain hybrid method [3] with no acceleration (200 projections), and at 8x acceleration (25 projections) using both the image-domain hybrid method and the proposed k-space-based method. 4 baseline images and a 1<sup>st</sup> order polynomial were used in the reconstructions.

**In-vivo experiment.** To validate the k-space model in vivo in the absence of heat, sagittal brain images were collected using an 8-channel receive array with the same GA scan parameters as the phantom experiment for 5 minutes. 76 temperature maps were reconstructed with 10 baseline images and 0<sup>th</sup> order polynomial fit using image-domain hybrid and the proposed k-space-based method, from data windows spaced 3.2 s apart, using no acceleration (200 projections) and 25x acceleration (8 projections).

**Results** Figure 1 shows the simulation results. The proposed k-space-based method achieves finer temporal resolution and no visible aliasing artefacts (RMSE 4.3e-3 rad, max error 0.08 rad), compared to TCR (RMSE 8.7e-3 rad, max err 0.29 rad). With TCR aliasing artefacts could be reduced by increasing temporal regularization, but this would further degrade temporal resolution. Figure 2 shows reconstructed phantom temperature maps. At 8x acceleration, the k-space-based method's map contains none of the undersampling artefacts seen in the image-domain map. Figure 3 shows the in-vivo model validation results. With no acceleration, both image-domain and k-space-based temperature estimates produce low mean errors (<1°C) over the whole brain. However, at 25x the image-domain temperature maps contain large aliasing artefacts (RMSE 8.1°C), while the k-space-based maps reflect a globally increased temperature uncertainty due to lower SNR, but no significant aliasing artefacts (RMSE 1.2°C).

**Discussion and Conclusion** We have introduced a constrained k-space-based temperature reconstruction method and demonstrated in 2D simulations and experiments that it estimates temperature changes accurately at high acceleration factors without temporal blurring or aliasing artefacts. The method will readily extend to 3D, where it will enable accurate real-time volumetric thermometry at a high frame rate.

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**References** [1] Todd et al., MRM (62):406-419, 2009. [2] Cao et al., ISMRM 2011, p. 2842. [3] Grissom et al., Med Phys 37(9):5014-26, 2010. [4] Chartrand and Yin, ICASSP, 2008.

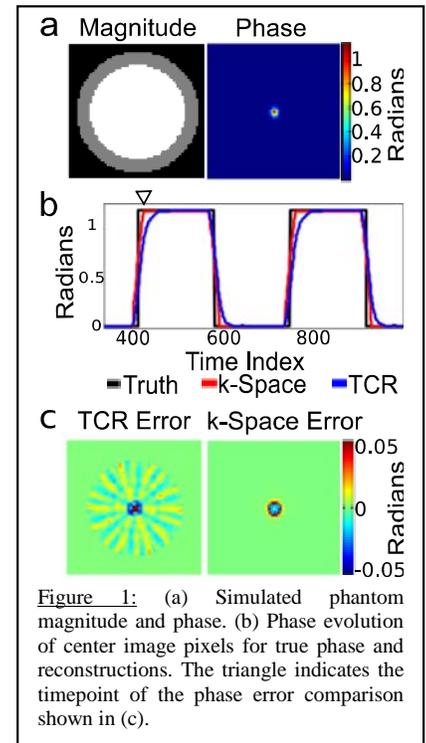


Figure 1: (a) Simulated phantom magnitude and phase. (b) Phase evolution of center image pixels for true phase and reconstructions. The triangle indicates the timepoint of the phase error comparison shown in (c).

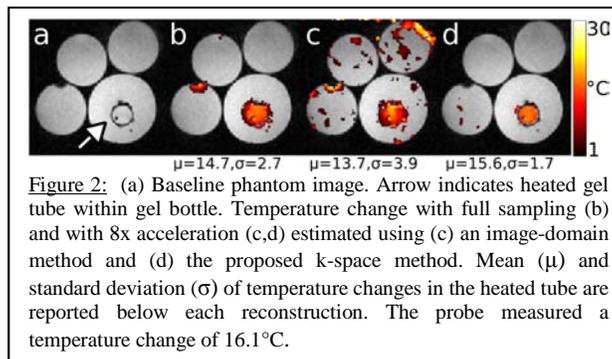


Figure 2: (a) Baseline phantom image. Arrow indicates heated gel tube within gel bottle. Temperature change with full sampling (b) and with 8x acceleration (c,d) estimated using (c) an image-domain method and (d) the proposed k-space method. Mean ( $\mu$ ) and standard deviation ( $\sigma$ ) of temperature changes in the heated tube are reported below each reconstruction. The probe measured a temperature change of 16.1°C.

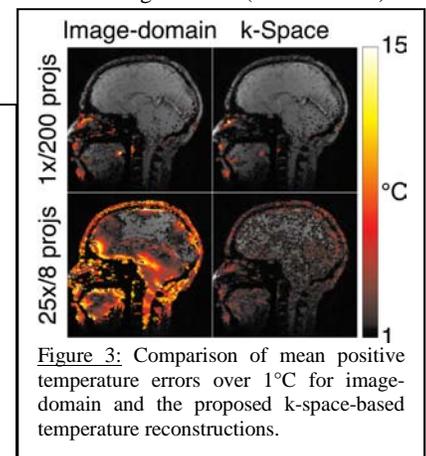


Figure 3: Comparison of mean positive temperature errors over 1°C for image-domain and the proposed k-space-based temperature reconstructions.