# Rapid MR temperature imaging based on model-predictive filtering of undersampled data

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## INTRODUCTION

To ensure safety and efficacy during MRI-guided tumor ablation procedures, tissue temperatures must be monitored in real time throughout these treatments. The proton resonance frequency (PRF) technique is the most commonly used MRI method for obtaining temperature change maps. While PRF has been shown to be accurate, its temporal resolution is inadequate for monitoring treatments that induce rapid heating to high temperatures. Here we present a method for accelerating the image acquisition of PRF scans known as model predictive filtering (MPF). Our technique combines temperature predictions made from an identified thermal response model with measurements from undersampled k-space data. Undersampling k-space by a factor of R leads to the same factor of acceleration in image acquisition.

## METHODS

*Model Identification*

A site-specific model of thermal response can be described by a system of linear equations:

$$T_{n+1} = AT_n + Bu_n \qquad [1]$$

where $T_n$ is a vector of temperatures at time n, $A$ describes the heat dissipation by conduction and convection, and $Bu_n$ is a vector that models the energy input at time n that causes temperature elevation. The model is identified prior to treatment by applying mild heating, using images acquired during sonication to determine $B$ and $u$, and using images acquired during cooling to identify the system matrix $A$[1]. Fig. 1 shows a typical temperature map created using fully sampled k-space data and compares the focal zone temperature distribution of the full data temperature map to the model predicted temperature map.

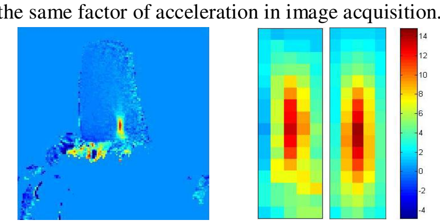


**Fig. 1.** *Left: Temperature map created from fully sampled k-space. Center: Close up of the focus. Right: The same region, as predicted by the thermal model.*

*Heating and MRI Image acquisition*

A heating experiment was performed on an ultrasound compatible agar phantom using a 256-element MRI-compatible phased array ultrasound transducer (IGT, Bordeaux, France). The ultrasound heating is controlled externally and images can be acquired during sonication with no apparent artifacts.

PRF data was obtained on a Siemens TIM Trio 3T scanner by using a gradient echo sequence with the following parameters: 8ms TE, 65ms TR, 2.3x2.3x3.0mm$^3$ resolution, 128x96 imaging matrix (zero-filled to 128x128). Using these parameters, a 5 slice volume was imaged every 6.2 seconds. The full k-space data set was acquired at each time frame, and undersampled k-space data sets were created by retrospectively zeroing out phase encode lines. A variable density undersampling scheme was used in which k-space phase encode lines near the center of k-space were sampled more heavily.

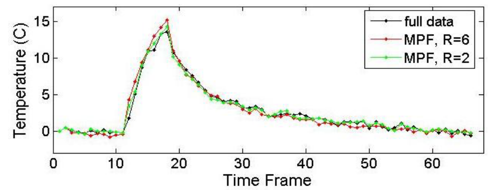


**Fig. 2.** *Temperatures from one voxel within the focal zone. Full data temperatures are compared to MPF temperatures with reduction factors 6 and 2.*

*Creating temperature maps*

Temperature maps using the MPF method are created in a multi-step recursive process. Starting with a temperature distribution at time point ($n$), the identified model is used to predict a new temperature distribution at time ($n$+1). Next, a complex image for time ($n$+1) is created by using the magnitude of the image at time ($n$) and computing the phase, $\phi_{n+1}$, according to[2]:

$$\phi_{n+1} = \phi_n + \gamma B_0 \alpha TE\left(T_{n+1} - T_n\right) \qquad [2]$$

where $\alpha$=-0.01ppm/°C is the chemical shift coefficient[3]. This complex image is then projected into k-space. The undersampled data is incorporated at this time by inserting all phase encode lines that were acquired at time ($n$+1). This data-updated k-space in then projected back into image space and a new temperature distribution for time ($n$+1) is calculated using the phase of the updated image and Eq. [2].

## RESULTS

Data acquired during the phantom heating experiment was used to test the accuracy of the MPF technique at reduction factors of 2 (R=2), 4, and 6. Temperatures calculated from fully sampled k-space were compared to those calculated from the MPF algorithm at R=6 and R=2, and the results for one voxel in the focal zone are shown in Fig. 2. Deviations from the full data temperature where calculated for all voxels in a 5x16x3 ROI about the focal zone (the same region displayed in the right of Fig. 1) and the results for time frames 10 through 30 are shown in Fig. 3. The top plot shows the error of every voxel within the ROI for R=6. The bottom plot shows the percentage of voxels within the ROI for which the MPF temperature (at R=2, R=4 and R=6) deviates more than +/- 1°C from the full data temperature.

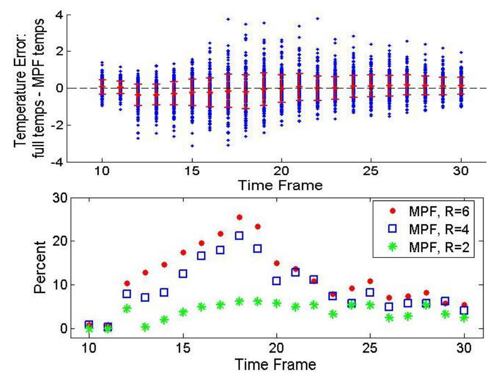


**Fig. 3.** *Top: blue points show the temperature error of every voxel within the heated region at time frames 10 through 30 for R=6 MPF data (mean and STD in red). Bottom: Percentage of voxels within the heated region that differ from the full data temperatures by more than +/- 1°C.*

The performance of the MPF algorithm was compared against data generated using only the thermal response model and against two other undersampled reconstruction schemes, sliding window and low resolution. R=4 was used for all methods and results for one voxel in the focal zone are shown in Fig. 4. A root mean square error was calculated for the various methods and the MPF technique (RMSE = 0.5 +/- 0.30) outperformed the sliding window (RMSE = 0.6 +/- 0.37), low resolution (RMSE = 0.6 +/- 0.47), and model only (RSME = 1.0 +/- 0.96) techniques.

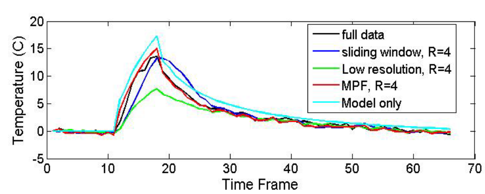


**Fig. 4.** *MPF reconstructed temperatures outperform temperatures created from sliding window data, low resolution data, and model-only data.*

## CONCLUSIONS

The MPF method can improve the temporal resolution of MR temperature mapping by a factor of 6 with minimal loss of accuracy. At R=6 the maximum error was under 4°C and less than 25% of voxels within the heated region showed a deviation of +/- 1°C or more from the full data temperatures. The efficient computation time of this algorithm (0.17 seconds per time frame for 5 slices) makes it suitable for real time applications.

## REFERENCES

1. R. Niu et al. ACC 2006, p.1481 – 1486
2. J.C. Hindman. J. Chem Phys, 1966, 44(12)
3. J. De Poorter et al. MRM 1995 33(1), p.74-81.

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