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MPI-based estimation of absolute temperature using 1D system matrices

Serhat Ilbey [a,*] · Oliver Buchholz [a] · Jochen Franke [a]

[a] Bruker BioSpin GmbH & Co. KG, Ettlingen, Germany
[*] Corresponding author, email: Serhat.Ilbey@Bruker.com

Abstract

Magnetic Particle Imaging (MPI) thermometry enables temperature mapping by exploiting temperature-dependent response of magnetic nanoparticles. These changes, influenced by particle physics (thermal agitation, relaxation dynamics), allow MPI to provide time-resolved temperature monitoring, making it a promising feed-back parameter for applications such as hyperthermia. However, current system matrix-based or 'multi-color' methods require time-consuming, three-dimensional calibration measurements that limit practical application and primarily yield relative temperature values only. Here, we present a novel system matrix thermometry method to enhance the efficiency of local MPI-based temperature estimation comprising MPI signals acquired at various temperatures and spatial positions along a defined line. Using MPI signals with 1D excitation and 100 averages, we demonstrate accurate estimation of absolute temperature (std <2 K) based on calibration with 11 individual matrices (∼1 min each) in 2 K increments (T_{min}=25°C, T_{max}=45°C). This approach enables estimation of absolute temperatures within ∼1 s and significantly reduces calibration time to ∼20 minutes.

I. Introduction

Integration of magnetic particle imaging (MPI) and magnetic fluid hyperthermia (MFH) has been shown to offer precise and non-invasive hyperthermia application by localizing MFH application to the user defined position of the field free region [1, 2]. MPI-based thermometry has the potential to further improve hyperthermia applications by providing immediate feedback on local temperatures, allowing for in situ treatment adjustments. It leverages temperature-dependent variations in signal properties, enabling differentiation of signals based on environmental temperature changes, effectively acting as nanoscale sensors. Conventional multi-color thermometry requires acquisition of at least two 3D calibration system matrices (SMs) that represent the experimental temperature range [3]. It was initially presented as a method to obtain relative temperature progressions. The absolute temperature is calculated indirectly by obtaining the temperature offset relative to the reference temperature based on reconstructed particle concentrations, assuming that the MPI signal is linearly related to temperature. The accuracy of this normalization procedure is highly dependent on regularization parameters, limiting its broader applicability. In this study, we propose an alternative approach of multi-color MPI for absolute temperature estimation by measuring multiple SMs of different particle temperatures (tSM) at 1D spatial positions along the excitation direction. The absolute temperature along the excitation line is estimated using the concatenated tSM and MPI signal acquired with 1D excitation.

II. Methods and materials

All measurements were performed using a preclinical MPI system (MPI 25/20 FF, Bruker BioSpin). The MPI calibration sample consisted of a cubic temperature-stable PVC tube (Bruker BioSpin) filled with 27 μL synomag-D (70 nm, plain, 10 mg(Fe)/mL, micromod). The sample was placed in a 3D printed sample holder connected to a heating-water bath enabling stable control of sample temperature during measurements. The sample was positioned at the center of the MPI bore using a robot-controlled sample rod that was securely positioned within a 3D printed circular holder to stabilize the entire assembly. The sample temperature was calibrated by setting the water bath temperature and allowing the sample to reach steady-state conditions.

II.I. Spatio-thermal validation

The 1D field-based SMs along the z-direction were measured using field offsets with focus fields for the following parameters: FOV$_z$=13 mm, 0.5 mm pixel size, f_z=25.25 kHz, A_z=14 mT, G_z=3 T/m (field-free point), 3 orthogonal Tx/Rx coils, and 100 averages. These calibration measurements were repeated for 11 sample temperatures from 25°C to 45°C in 2 K increments. The spatio-thermal tSM $\mathbf{A}$ was obtained by concatenating 1D SMs with varying temperatures:

$$\mathbf{A} = \left[\mathbf{A}^{25^\circ\mathrm{C}} \quad \mathbf{A}^{27^\circ\mathrm{C}} \quad \cdots \quad \mathbf{A}^{45^\circ\mathrm{C}}\right] \tag{1}$$

The proposed 1D thermometry method was evaluated by estimating the sample temperature for independent measurements at 38°C and 43°C at positions z=0 and z=2.5 mm. 14 fundamental harmonics from 3$^{\mathrm{rd}}$ to 16$^{\mathrm{th}}$, which were above the noise floor, were selected. For spatio-thermal reconstruction, the fast iterative shrinkage-thresholding algorithm was used ($\lambda = 10^{-6}$) with 5000 iterations using the forward model:

$$\underset{\rho}{\operatorname{argmin}} \|\mathbf{A}\rho - b\|_2^2 + \lambda \|\rho\|_1, \tag{2}$$

where b is the measurement vector acquired with 1D excitation, and ρ is the spatio-thermal image, representing the estimated temperature distribution for each z-position. The standard deviation (std) of the estimated temperatures was calculated assuming a normal distribution using the formula: FWHM/2.355.

III. Results and discussion

The reconstructed normalized spatio-thermal images are shown in Fig. 1. Sample temperatures were estimated with an accuracy of <2 K (Table 1). The temperature std for the sample at 43°C was significantly lower than 38°C, as the acquired tSM included a measurement with sample at 43°C , but not at 38°C.

The accuracy of temperature estimation requires further validation (Condition no. of $\mathbf{A}$ was ~1100). Additionally, the optimal temperature discretization required in

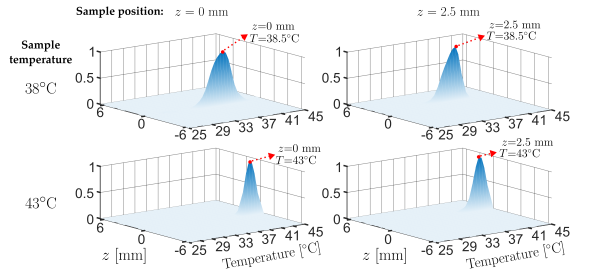

Figure 1: Normalized spatio-thermal images for sample at z=0 and 2.5 mm and temperatures 38°C and 43°C. Red points show the peak positions.

Table 1: Estimated temperatures

Sample	[°C] [mm]	38 0	38 2.5	43 0	43 2.5
Estimated temperature	[°C] [K]	38.5 ±2	38.5 ±1.8	43 ±1.3	43 ±1.3

tSM for accurate reconstruction, as well as the effects of tracers that are not aligned with the 1D line should be further investigated. 1D particle concentration can also be estimated by calculating the sum-of-squares of the spatio-thermal image ρ along the temperature dimension.

IV. Conclusion

MPI thermometry based on 1D SMs presents a viable addition to current SM-based approaches. We have demonstrated precise estimation of two exemplary absolute sample temperatures using a brief measurement duration (~1 s) and ultra-fast reconstruction (~0.3 s), as opposed to the time-consuming MPI measurements typically required for 3D multi-color reconstruction.

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Author's statement

Conflict of interest: Authors currently work for Bruker BioSpin GmbH & Co. KG.

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