Comprehensive Comparison of Six Referenceless PRF Shift MR Thermometry Methods

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Introduction Proton resonance frequency shift (PRFS) MR thermometry (MRT) provides an important tool for real time monitoring of temperature changes during MR thermotherapy. Conventional PRFS method is highly sensitive to inter-scan motion and the temporal field change. Recently, referenceless MR thermometry has been proposed to address these problems [1]. The method obtains the baseline phase of heated region from a region of reference (ROR) inside the image and doesn't require the acquisition of baseline images. Several referenceless methods have been proposed: the original referenceless (ORG) method[1], complex field estimation (CFE) method[2], reweighted L1 (RL1) method[3], phase gradient (PG) method[4], near harmonic (NH) method[5] and phase finite difference (PFD) method[6]. Yet, the accuracies of these methods and their relevance to real time temperature monitoring have not been compared. This work compared the performance of the six referenceless methods mentioned above in terms of temperature accuracy and computational requirements. The results would help the selection of appropriate methods for specific MR thermometry applications.

Table I. Computation configuration of six algorithms. Numbers show the radii of the ROI.

Method		ORG	CFE	PG	PFD	RL1	NH
Phase unwrapping		√	—	—	—	—	√
ROI (Pixels)	Simulation	10	10	4	10	18	6
	In-vivo	10	10	4	10	18	6
	Ex-vivo	8	8	4	8	14	6
ROR/ROI Area ratio		3	3	3	3	—	—

Table II. Comparison of computation times for six algorithms.

Method	ORG	CFE	PG	PFD	RL1	NH
Times(ms)	21	29	84	32	12362	170

Materials and Methods All experiments were conducted on a 3T MR system (Siemens TIM Trio, Erlangen, Germany). Temperature imaging was performed with a 2D gradient echo (GRE) sequence. Basic imaging parameters were: TR/TE = 25/10ms, spatial resolution = 1.5×1.5×3.0 mm^3, flip angle = 10^o, bandwidth = 160 Hz/pixel, matrix size=192×192. A water excitation pulse was used for fat suppression. In the simulation study a temperature induced phase change with a Gaussian spatial profile was superimposed on an agar phantom image with peak = 0.5 radians and standard deviation = 4 pixels. Then an *in-vivo* room temperature experiment was performed in the human brain on six volunteers under IRB approval. Lastly, *ex-vivo* heating experiments were conducted in the porcine muscle and bovine liver using an MR compatible HIFU prototype system.

Data analysis All calculation algorithms mentioned above were written in MATLAB (Mathworks, NATICK, USA) and run on a desktop computer with dual core 2.5GHz CPUs and 4GB RAM. Goldstein's quality guided path finding algorithm was used for phase unwrapping whenever needed [1,5]. The RORs/ROIs used were concentric circles. The radii of ROR and ROI were optimized to produce best results for each method (see Table I). Except for NH method, optimal polynomial orders based on [1] were used for all other methods. Temperature error of a specific method is defined as the difference between that method and the reference subtraction (RS) method since there was no motion during the experiments. Temperature accuracy was assessed in three ways: (1) standard deviation (SD), (2) root mean square of error (RMSE) and (3) 98% percentile of absolute error (PRCT98) all over the ROI.

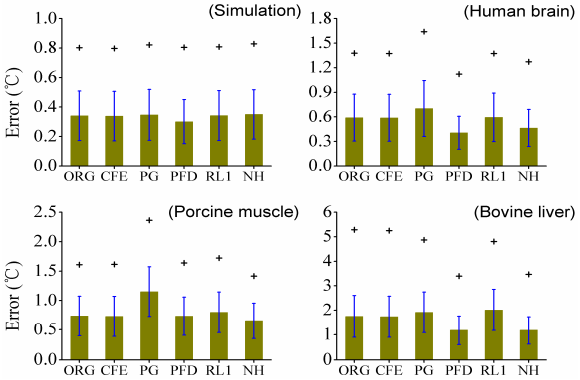

Figure 1. Temperature error from all the six algorithms from simulation and three experiments.

Results For a 192×192 image, the phase unwrapping process took about 23 sec in our computer. The averaged computation time per slice for each method, excluding phase unwrapping, is summarized in Table II. The temperature errors of all algorithms on all experiments are shown in Figure 1 where color bar = RMS error, error bar = SD of error, and "+" = PRCT98 of absolute error. Both simulation and experiments showed that the PFD and NH methods have the best overall accuracy over other methods. Comparison of the temperature maps in *ex-vivo* heating bovine liver is shown in Figure 2 by RS, ORG, CFE, PG, PFD, RL1, NH.

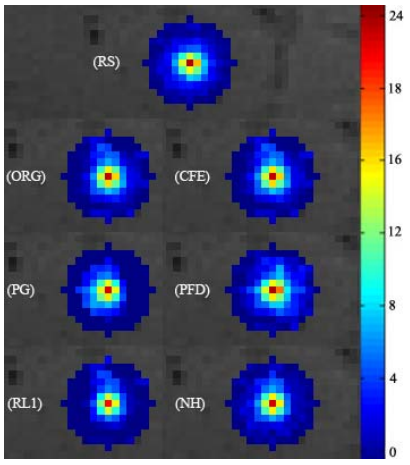

Figure 2. Temperature maps of ex-vivo bovine liver.

Discussion In the simulation study, all six methods show comparable accuracy. In the porcine muscle experiment, phase gradient method showed larger error than other methods. In both the *in-vivo* brain study and the *ex-vivo* bovine liver study, the phase finite difference method and near harmonic method outperform others in terms of temperature accuracy. The reason may be that the two methods use more local boundary information, and have better baseline estimation than other methods. From the computational efficiency point of view, phase unwrapping is always a time-consuming procedure and sometimes even fail in the presence of low SNR and susceptibility artifact. Methods that do not require phase unwrapping, such as complex field estimation, phase gradient, phase finite difference, are more favorable in the real-time temperature monitoring. The reweighted L1 method does not need phase unwrapping, nor the need to set the ROR/ROI but it is most computational demanding.

Conclusion Six referenceless MRT methods were compared in terms of computation requirements and accuracy for their applicability in MRT application. The NH method and PFD methods are more accurate than the others though the NH method requires phase unwrapping. Our results can help to select the appropriate referenceless methods in different MR thermometry applications.

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