Accelerated Real-time MR Thermometry Using a New Compressed Sensing Framework of Nonlinear Filter and K-t FOCUSS

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Target audience: Researchers on MR thermometry and phase image reconstruction methods.

Purpose: Phase information is a focal point in MR thermometry using proton resonance frequency shift (PRFS) method [1]. In order to shorten the imaging duration and accomplish real-time temperature mapping, acceleration methods can be applied to the reconstruction of phase information. Thus, a method to improve the accuracy of phase reconstruction in dynamic scans is highly needed to get the precise real-time temperature estimation. K-t space FOCal Underdetermined System Solver (k-t FOCUSS) is an effective tool for sparse reconstruction in both k-space and time domain using initial estimation and residue encoding [2]. In order to make better use of the sparsity of phase differential information, Compressed Sensing with nonlinear filters such as median filter [3] is combined in our method for exploiting gradient sparsity with spatiotemporal correlations. This combination of k-t FOCUSS and CS with nonlinear filter in phase mapping is a promising tool for real-time temperature monitoring using PRFS according to our preliminary results.

Method: A new Compressed Sensing framework combining nonlinear filter (NFCS) [3] and k-t FOCUSS is proposed in our research (see Fig.1). K-t FOCUSS is implemented in our method to detect and exploit sparse information in k-t domain based on the temporal average prediction and residue encoding. Considering the fact that k-t FOCUSS is designed for dynamic processes with periodic motion and temperature change is nonlinear during the whole experiment, NFCS is additionally used to enhance the fidelity of the reconstruction from the under-sampled data. The implementation of this combined method is generally divided into four steps:

(1) Using the latest N frames (N = 15 in this research) for batch k-t FOCUSS to get the preliminary reconstructed frames since the batch k-t FOCUSS does not require fully-sampled reference scans at the end of all frames, which meets the requirement of dynamic temperature mapping. In the algorithm of batch k-t FOCUSS (see Fig.1), $\Delta\rho$ represents the difference between prediction ρ_0 and under-sampled data. $\boldsymbol{F}$ is the Fourier Transform along y and t directions.

(2) Using NFCS for second reconstruction. In NFCS algorithm, ∇U represents the gradient sparsity with spatiotemporal correlations. *NF* is the number of frames and $\left\| F_{S_l} u_l - y_l \right\|$ represents the data fidelity term. Specifically, the latest three frames are reconstructed using a 3D median filter in image domain.

(3) Calculating the phase difference map using the reconstruction result from NFCS;

(4) Calculating the final temperature map based on the PRFS method using the value of echo time.

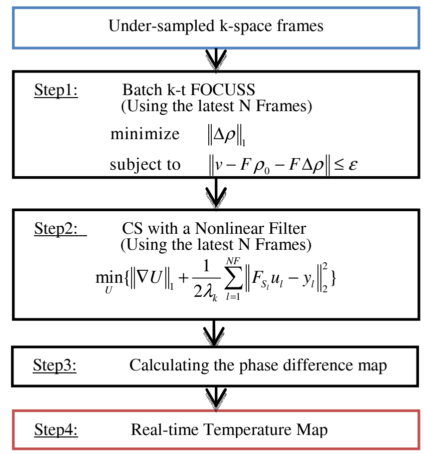

Fig. 1 *The flowchart of our proposed method. The algorithms of each step are listed in the blocks.*

Results: 30 frames of fully-sampled 2D Cartesian data were acquired using a 3T Philips Achieva scanner during a heating experiment. The parameters for dynamic images were: TR/TE =70ms/5ms, resolution=1.6×1.6×4 mm^3, FOV=256×256 and flip angle=40°. The composition of the phantom is: 100% water for the outer ring, 20% fat mixed with 80% water for the central area in order to add boundary information and improve the gradient sparsity. The fully acquired data were artificially down-sampled with a reduction factor of 4 using a variable density acquisition trajectory. Fig.2 displays the temperature change curves for three different phase reconstruction methods (2D FOCUSS, batch k-t FOCUSS and batch k-t FOCUSS with NFCS) at R=4. Fig. 3 shows the 5-time brightened error maps of phase reconstruction for the under-sampled data using batch k-t FOCUSS with NFCS and batch k-t FOCUSS at R=4. Table 1 shows the maximum temperature error after an initialization of 10 frames based on the theory of PRFS [1].

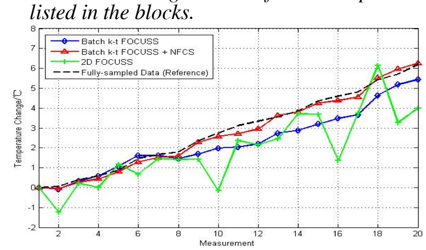

Fig.2 *The temperature change curves of three different phase reconstruction methods (2D FOCUSS (green line), batch k-t FOCUSS (blue line) and batch k-t FOCUSS with NFCS (red line)) for the under-sampled data compared with fully-sampled data (black line) at a reduction factor of 4 after an initialization process of 10 frames.*

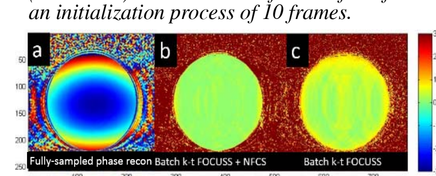

Fig.3 *The 5-time brightened error of phase reconstruction for the under-sampled data using batch k-t FOCUSS with NFCS* **(b)** *and batch k-t FOCUSS* **(c)** *at a reduction factor of 4. The fully-sampled data* **(a)** *is used for comparison.*

Discussion: As shown in Fig.2, the temperature change curve of our proposed method demonstrates the best agreement with the fully-sampled data among all the three methods. Thus, combining k-t FOCUSS and NFCS enables an accurate prediction as well as a robust correction for phase information. The results shown in Fig.3 also indicate that our proposed method can accurately reconstruct phase information at a reduction factor of 4 and is able to exploit the advantages of both k-t FOCUSS and NFCS in dynamic reconstruction especially when prediction might be inaccurate. Table 1 shows that the temperature error of our proposed method is lower than other methods after the initialization process.

Table 1 Maximum Temperature Error after an Initialization Process

Location	Zero-Padding /°C	2D FOCUSS /°C	Batch k-t FOCUSS /°C	Our method /°C
Central 5×5 pixel	4.9531	1.5992	1.1717	0.4845
Left side 5×5 pixel	3.2162	1.7895	1.0947	0.4972
Right side 5×5 pixel	3.7875	1.6067	0.8561	0.4307

Conclusions: Phantom experiments have demonstrated that our new Compressed Sensing framework combining k-t FOCUSS and nonlinear filter is superior to other methods in maintaining accurate phase information at a reduction factor of 4. Further study could be conducted on *in-vivo* experiments to demonstrate the potential of the proposed method in clinical practice.

References: [1] Ishihara Y, MRM 1995; [2] Jung H, MRM 2009; [3] Montefusco L, IEEE Trans. Med. Imag. 2011.