Multi-Channel Image Ratio Constrained Reconstruction And Its Application for Highly Accelerated Temperature Mapping

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Introduction

Image ratio constrained reconstruction (IRCR) [1] is a generalized version of HYPR (HighlY constrained PRojection) [2] for highly accelerated dynamic imaging. As opposed to HYPR, IRCR is not limited to radial acquisition, and is applicable for arbitrary acquisition trajectories. The set of IRCR techniques is suitable for applications when there is no geometry information change between calibration image and the to-be reconstructed image. The difference between these two images is only image contrast. In an ideal scenario, this assumption is true for such applications as contrast enhanced MR angiography, T1 mapping, as well as real time temperature mapping for MR guided HIFU (High Intensity Focused Ultrasound). In this work, IRCR is extended to be combined with parallel imaging, and is applied to highly accelerated temperature mapping for improved spatiotemporal resolution. This higher spatiotemporal resolution of the MR thermometry may be used as such or for improving the spatial coverage, both of which enable a better control of the HIFU therapy. Here, the proton resonance frequency (PRF) method that utilizes phase data is used for calculating the temperature images. Thus, the intended reconstruction needs to preserve the phase information with a high accuracy. Preliminary results show that a net reduction factor of 4.8 (R = 4.8) can be achieved with a 3-channel coil.

Theory

If the difference of two images I_C (calibration image) and I_R (to-be reconstructed) is only contrast, which is mainly low-frequency information, then the difference can be described by the ratio of low-resolution versions of these two images LI_C and LI_R. Hence, the reconstruction can be done using the equation $I_R = LI_R \div LI_C \times I_C$, where $\times$ and $\div$ denote pixel-wise multiplication and division respectively [1]. To avoid singularity, the multiplication/division in image space can be implemented as convolution in *k*-space. When there are multiple channels, the implementation of IRCR with GRAPPA [3] in *k*-space can be described by Eq. 1.

$$S_j = \sum_{l=1}^{N_c}\left(\Theta(j,l)\otimes S_l + \hat{\Theta}(j,l)\otimes \hat{S}_l\right),\ j=1,2,\ldots,N_c \quad (1)$$

$$\sqrt{\sum_{\Omega}|err|^2 \Big/ \Omega} \quad (2)$$

S_l and $\hat{S}_l$ denotes the to-be reconstructed (partially acquired) and the calibration (full) *k*-space data from channel l, Θ is same as the convolution kernel in conventional GRAPPA, $\hat{\Theta}$ is the convolution kernel for IRCR, and $\otimes$ is the convolution operator. Since $\hat{S}_l$ has the full *k*-space data, $\hat{\Theta}$ can be more compact than Θ. In conventional PRF-based MR thermometry [4], one reference image is always fully acquired before heating at t_0. This image can be used as the calibration image for the first set of partially acquired data (t_1). After the reconstruction of t_1, the reconstructed full *k*-space for t_1 can be used as the calibration image for t_2, as so on. If t_0 is used as the calibration image for all time frames, then the algorithm will be too sensitive to any potential motion during the acquisition.

Methods

Acquisition Trajectory: A variable density acquisition trajectory is used. The center *k*-space uses low reduction factor, such as 2, to ensure the accuracy of the low frequency information. The outer *k*-space uses higher acceleration factor, such as 7.

Reconstruction Scheme: There are two steps for the center and outer *k*-space respectively. GRAPPA [3] is used for reconstruction of the center *k*-space. The calibration signal for GRAPPA is from the reference image (t_0) acquired before heating. Eq. (1) is used for reconstruction of the outer *k*-space. The reconstructed center *k*-space (40 lines in current implementation) signal is used to calibrate convolution kernels, $\hat{\Theta}$ and Θ, in Eq. (1). Θ and $\hat{\Theta}$ had sizes 4×5 and 3×3, respectively.

Experimental setup: Using a 3T Philips Achieva scanner, MR thermometry data was collected from 4 HIFU sonications in a standard HIFU phantom using the Sonalleve V1 MR-HIFU platform and its 3-ch coil. Gradient echo EPI images were acquired with parameters used in PRF-based thermometry of clinical MR-HIFU therapy (5 coronal slices, TR = 29ms, TE = 19ms, resolution = 1.5×1.5×5 mm^3 (data sets 1 and 2) /2.5×2.5×5 mm^3 (data sets 3 and 4), FOV 400×240, flip angle 20°, EPI factor = 9, temp. res.= 2.5s (data sets 1 and 2) /2.1s (data sets 3 and 4)). The sonication parameters are summarized in Tab. 1 in the "Para" column. The three parameters are for cell size (mm), power (W), and duration respectively. The fully acquired data were artificially downsampled with variable density. R =2 and R = 7 were used for the center 40 lines and outer k-space lines respectively. This kind of downsampling resulted in a net reduction factor of 4.8 for data sets 1 and 2, and 4 for data sets 3 and 4. The calculated temperature using partially acquired data was compared with that using fully acquired data. T_{peak} is the highest temperature increase in the heated region. Root mean square error (RMSE) was defined as Eq. (2), where *err* is the error of the calculated temperature, and Ω is a 7 × 7 region around the heated point.

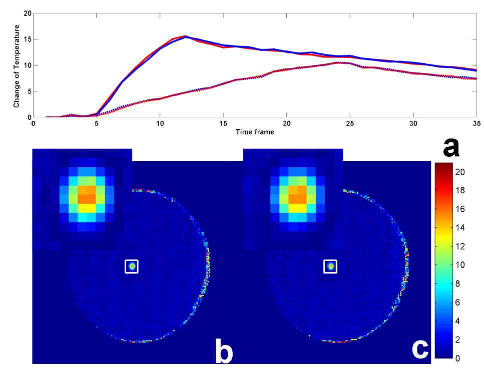

Figure 1. Result of data set 2. a) temperature as a function of time. Red and blue lines are the results of R =1 and 4.8 respectively. The upper and the bottom lines are for slice 1 and 2. b) and c) are the calculated temperature map of R =1 and 4.8 respectively at time frame 12. The left upper corners show the zoomed in regions in the white boxes.

Table 1. Results in Celsius of 4 data sets

Data set	Para	Slice #	T_{peak}	Max *err* of T_{peak}	Std of T_{peak} *err*	RMSE
1	4/50 /20	1	18.3	1.0	0.41	0.21
		2	7.2	0.2	0.1	0.18
2	12/50 /48	1	15.6	0.4	0.26	0.26
		2	10.4	0.3	0.14	0.19
3	4/50 /20	1	19.4	1.0	0.38	0.2
		2	8.5	0.3	0.12	0.2
4	4/20 /20	1	15.2	0.4	0.2	0.1
		2	7.8	0.3	0.1	0.1

Results and Discussion

Results of two coronal slices perpendicular to the HIFU beam path (slice #1 centered on heating and slice #2 10 mm towards the near field) are shown in Table 1 and Figure 1. The errors of T_{peak} were consistently lower than 1°C at net reduction factor 4.8. The maximum RMSE was 0.26°C. The results demonstrate that the multi-channel IRCR can generate accurate results with high reduction factors for dynamic imaging when the differences among these images are only relative contrast, and can thus have a major impact on real-time applications which need high spatiotemporal resolution. The reconstruction time is related to the size of the convolution kernels. In these experiments, the reconstruction time was about twice that of conventional GRAPPA reconstruction. Only phantom data sets were used in these experiments. Hence, there was no motion problem, and the assumption for the applicability of HYPR like methods was met. The sensitivity of the proposed method to motion will be tested with in vivo data sets.

References : [1] Huang, F., ISMRM Recon Workshop, Sedona, 2007, 51 [2] Mistretta, C. A. TMC news, Aug 01, 2007, http://www.tmcnet.com/usubmit/2007/08/01/2830212.htm . [3] Griswold M et al., MRM 2002, 47:p1202-1210 [4] De Poorter J. MRM 1995;34(3):359-36