Phase Constrained Compressed Sensing with Applications for PRF Temperature Mapping

Z. Cao[1], C. T. Sica[2], P. Ehses[3], S. Oh[2], Y. C. Ryu[2], C. M. Collins[1,2], and M. A. Griswold[4]

[1]Bioengineering, The Pennsylvania State University, Hershey, PA, United States, [2]Radiology, The Pennsylvania State University, Hershey, PA, United States, [3]Research Center for Magnetic Resonance Bavaria (MRB), Würzburg, Germany, [4]Radiology, Case Western Reserve University, Cleveland, OH, United States

Introduction: Proton Resonant Frequency (PRF) shift thermometry is important across many fields in MRI, and has been firmly established in interventional applications. More recently, the emphasis on multi-channel transmit arrays for homogeneous transmit field excitations has given new motivation for real-time monitoring of heating using PRF thermometry. In its most common implementation, however, its relatively long acquisition times limit the time resolution of dynamic processes; two full k-space data are required and the phase contrast image is obtained by phase subtraction between the two images. Compressed sensing (CS) methods are being investigated for accelerating every aspect of MRI, and although CS methods have shown great promises for accelerating MR signal acquisition [1], to date there have been few if any CS proposals that explicitly constrain the phase without regard for the magnitude sparsity. In PRF applications this is critical, since the relevant information is largely independent of the magnitude of the signal. Here we propose a phase-constrained reconstruction method for fast and accurate phase contrast imaging and validate it through temperature mapping based on PRF shift. The method can also utilize coils with multiple receive channels for higher acceleration rates.

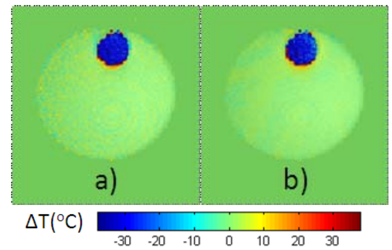

Figure 1. Maps of temperature change for a syringe of hot water placed in a flask of room temperature water created by (a) full k-space reconstruction, and by (b) proposed method with reduction factor R=6. The temperature images are overlaid with the baseline magnitude images.

Theory: Let u_0 and u denote the fully sampled baseline image and under-sampled contrast image in the spatial domain respectively, b_0 and b their corresponding k-space data, and E the hybrid encoding matrix which may include multiple coil sensitivities. We implemented the Iterative Reweighted Least Squares (IRLS) method [2] to solve for the CS problem, assuming the phase contrast (angle(u_i/u_{i0})) is smooth and/or sparse: $\min_u \sum_{i=1}^{N} w_i(u_i - u_{i0})^2\,,\ s.t.\ E(u-u_0) = b - b_0$, with the reweighting coefficient $w_i = \frac{\left|angle\left(\frac{u_i}{u_{i0}}\right)\right| + \alpha * TV\left(angle\left(\frac{u_i}{u_{i0}}\right)\right)}{|u_i - u_{i0}|}$, where TV denotes total variation, α the regularization coefficient, i the voxel index, N the total number of voxel of each image. (Note: the objective function will converge toward zero, not infinity.) For each IRLS iteration, the conjugate gradient method is used for solving the inverse problem based on the encoding relationship.

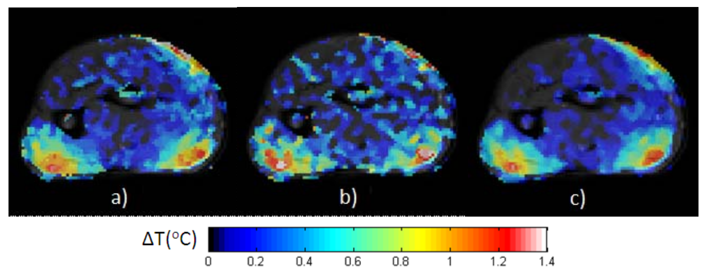

Figure 2. Maps of temperature change during *in vivo* heating of a human forearm with a surface coil created with (a) full k-space data, (b) undersampled and zero-filled data with R=8, and (c) by the proposed method with R=8. The temperature images are overlaid with the baseline magnitude images.

Methods: Three experiments were performed to validate the method. In the first experiment, a syringe of boiling water was put into a flask of water at room temperature. Images are acquired during the cooling process (TE/TR = 10/100ms, matrix size = 256x256, FOV = 200x200 mm^2, slice thickness = 5mm). In the second *in vivo* heating experiment, a circular surface coil (8cm diameter, tuned to 164MHz, matched to 50Ω) was positioned against the ventral side of the forearm of a volunteer inside a single-channel extremity coil. A frequency synthesizer (PTS 200, PTS, MA, USA) and an RF power amplifier (LA200UELP, Kalmus, WA, USA) were used for 20W input power. Images are acquired before and after the heating process. In the third experiment, we explicitly tested whether we could detect thermal changes resulting from RF heating from a body coil. To this end, a gel phantom was made by dissolving agar (7 g/L), NaCl (10 g/L) and $CuSO_4$ (1 g/L), and letting the solution to cool in a plastic former. It was then positioned inside an 8-channel-receive head array. Images were acquired by the head coil before and after the heating by the system body coil. The accuracy of temperature mapping was verified by 4 thermo-optic probes (AccuSens; OpSens, Quebec, Canada) placed inside the phantom. The second and third experiments were both performed with same scanning protocol (TE/TR = 10/100ms, matrix size = 128x128, FOV = 160x160 mm^2 and slice thickness = 5mm) on a Siemens Trio 3T MRI system. All experiments were done with radial gradient echo sequences with a golden angle view ordering. Results were analyzed by routines programmed in Matlab (The MathWorks, MA, USA).

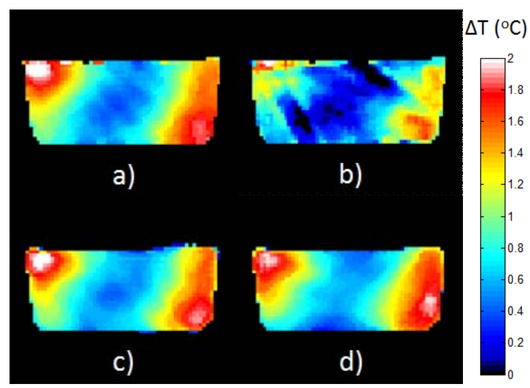

Figure 3. Maps of temperature change during heating of a homogeneous gel phantom with a volume coil created with (a) full k-space data, (b) undersampled and zero-filled data with R=16, and by the proposed method with (c) R=16, and (d) R=40. Here the data from an 8-channel receive array facilitate greater accelerations.

Results and Discussion: The experimental results show the effectiveness of the proposed method for PRF temperature mapping both on phantom and *in vivo*. Single channel experiments demonstrate a reduction factor of 8 can be achieved with 10% error when the temperature changes are either focal and dramatic (Fig.1), or smooth and mild (Fig.2). Combined with 8 receive channels, this method can achieve a reduction factor of 16 with similar error (Fig.3). With such a high under-sampling rate and reconstruction accuracy, this method can be potentially implemented for accurate real time monitoring for *in vivo* temperature changes in a variety of circumstances. Work is in progress to improve the robustness of the method, determine optimal acquisition trajectories and combine it with sliding window reconstruction methods. This method should also be valuable for fast imaging of velocity-encoded flow imaging, ΔB_0/susceptibility mapping and many other applications that are based on phase contrast imaging.

Reference: [1] Lustig *et al.*, MRM 2007, 58(6):1182-1195 [2] Chartrand and Yin, ICASSP 2008

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