Highly-Accelerated 3D T1rho Mapping of the Knee Using k-t SPARSE-SENSE

Ding Xia[1,2], Li Feng[1,2], Tiejun Zhao[3], and Ravinder R. Regatte[1,2]

[1]*Center for Advanced Imaging Innovation and Research (CAI2R), Department of Radiology, New York University School of Medicine, New York, NY, United States,*
[2]*Bernard and Irene Schwartz Center for Biomedical Imaging, Department of Radiology, New York University School of Medicine, New York, NY, United States,*
[3]*Siemens Medical Solution USA. Inc, New York, NY, United States*

Target Audience: Researchers and clinicians interested in quantitative measure of early biomarkers for musculoskeletal diseases such as osteoarthritis

Introduction: T1rho mapping has been widely used for musculoskeletal MRI exams to detect early biochemical changes in osteoarthritis (OA) [1] due to its high sensitivity to the low frequency motional process. However, most of the current T1rho mapping techniques suffer from long scan times due to the requirement to acquire data at multiple spin-lock lengths (TSL), which also lead to increased sensitivity to motion as well as specific absorption rate (SAR) [2]. Compressed sensing has become a powerful approach for rapid parametric mapping [3] and can be also combined with parallel imaging [4] to exploit joint sparsity among multicoil with improved reconstruction performance [4-5]. 3D T1rho mapping is an ideal candidate for compressed sensing, because the extensive spatiotemporal correlation allows accelerated data acquisition through undersampling of the k-space far below the Nyquist requirements. The purpose of this work is to investigate the feasibility of highly-accelerated 3D T1rho mapping in human knee cartilage using *k-t* SPARSE-SENSE, which is a reconstruction framework combining compressed sensing and parallel imaging [3]; and also evaluate the accuracy of T1rho maps estimated at different acceleration rates (R).

Methods: (a) ***Data Acquisition:*** IRB-approved knee imaging was performed on five healthy volunteers (age=33±6.3) on a 3-T whole-body MRI scanner (TimTrio, Siemens, Germany) using a Tx/Rx knee coil with 15 coil-elements (QED, Cleveland OH). A 3D T1-weighted single-shot Turbo-FLASH sequence with a T1rho magnetization preparation [6] was employed for data acquisition with the following imaging parameters: FOV=130x130mx128m^3, matrix size=256x128x64, spatial resolution=0.5x1x2mm^3, TR/TE= 1.5s/4.0ms, flip angle=8^o, echo space =7.8ms and spin-lock frequency=500Hz. A binomial water excitation pulse was used for signal excitation and 6 echoes were acquired with different TSL including 5/15/25/35/45/55ms. The total acquisition time was 19 min 14 sec for each subject without any acceleration.

(b) ***Undersampling Simulation and Image Reconstruction:*** The fully sampled k-space data (R=1) in each subject were retrospectively undersampled by multiplying with k_y-t variable density undersampling patterns at different acceleration rates from 2 to 6. Different undersampling patterns were generated for each frame along the TSL dimension to increase the incoherence for compressed sensing reconstruction [4]. Undersampling was only performed along the phase-encoding dimension (k_y) because all the partition k-space lines at a given phase-encoding step were acquired after one T1rho magnetization preparation within each TR. *k-t* SPARSE-SENSE reconstruction [3] was performed for image reconstruction by solving the following optimization:

$$\boldsymbol{x} = \arg\min_{x} \left\| \boldsymbol{F}\cdot\boldsymbol{S}\cdot\boldsymbol{x}-\boldsymbol{y}\right\|_2^2 + \boldsymbol{\lambda}_1\left\|\boldsymbol{P}\cdot\boldsymbol{x}\right\|_1 + \boldsymbol{\lambda}_2\left\|\boldsymbol{W}\cdot\boldsymbol{x}\right\|_1$$

Where $\boldsymbol{F}$ is the fast Fourier transform operator, $\boldsymbol{S}$ is the coil sensitivity maps that estimated by averaging all the TSL frames together, $\boldsymbol{x}$ is the 4D image set (3 spatial dimensions+1 TSL dimension) to be reconstructed and $\boldsymbol{y}$ is the corresponding multicoil k-space data. P is the principle component analysis operator performed along the TSL dimension as one sparsifying transform [4] and $\boldsymbol{W}$ is the 3D Daubechies 4 wavelet transform applied in the spatial dimensions as a second sparsifying transform, with regularization parameters $\boldsymbol{\lambda}_1$ and $\boldsymbol{\lambda}_2$, respectively. The reconstruction was implemented in MATLAB and the regularization parameters were empirically selected by comparing different values in one representative dataset and then applied to all the following reconstructions.

(c) ***Image Analysis:*** Regions of interest (ROIs) for the cartilage were manually selected in 10 slices that included both lateral and medial segments in each subject using an in-house program. Pixel-wise T1rho values were estimated by performing an exponential fitting of reconstructed T1rho weighted images along the TSLs dimension with a model: $M_{TSL}=M_0*\exp(-TSL/T1rho)$, where M_0 is the equilibrium signal intensity before applying the spin-lock pulse. The accuracy of the 3D-T1rho maps estimated from the accelerated datasets was evaluated by quantitatively comparing with the references (R=1) using Wilcoxon Rank-Sum Test and Bland-Altman analysis.

Results: Fig.1 shows one representative lateral slice and one representative medial slice with TSL of 5ms at different accelerations (from R1 to R6). The T1rho maps of the cartilages (overlaid on the T1rho weighted images) did not produce significant visible errors. The mean values of T1rho estimated from the accelerated datasets at different accelerations were averaged over 5 subjects (Fig 2) and achieved good agreement with that obtained from the fully sampled references in all compartments. No statistically significant differences were observed in Wilcoxon Rank-Sum Test for the mean T1rho values between the accelerated datasets and the fully sampled references ($\boldsymbol{P}$ = 0.57, 0.19, 0.38 and 0.06 for R=2, 3, 4 and 5), except R=6 ($\boldsymbol{P}$ = 0.03). The Bland-Altman analysis (Fig 3) further demonstrated that the T1rho maps obtained with different acceleration rates were in agreement to the fully sampled references (mean difference = 1.36 ms; upper and lower 95% limits of agreement were 3.38 and –0.66 ms, respectively), suggesting that the T1rho maps estimated from the accelerated datasets are quantitatively equivalent with the reference.

Discussion and Conclusion: This work presents preliminary studies of retrospectively accelerated 3D-T1rho mapping using the combination of compressed sensing and parallel imaging. The results suggest that 4~5-fold accelerations are achievable using the proposed approach and accurate T1rho maps can be estimated reliably from the undersampled datasets without losing SNR or introducing significance difference compared to fully sampled reference scans. The 3D-T1rho mapping with compressed sensing could be promising in assessing musculoskeletal diseases such as OA with reduced scan time, and thus reduced SAR as well as sensitivity to motion.

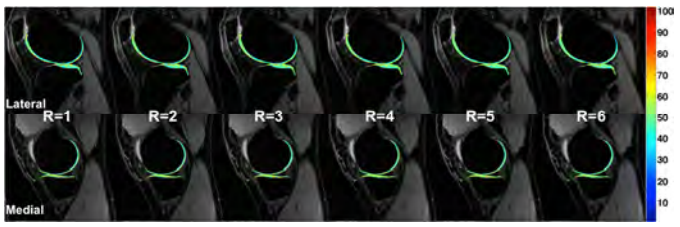

Fig. 1: T1rho weighted images (TSL=5ms) as well as the T1rho maps estimated on cartilages at acceleration rates from 1-6.

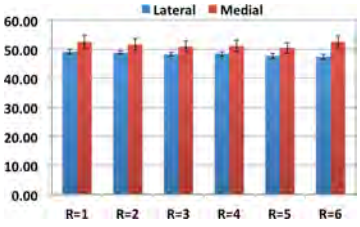

Fig. 2: Mean values of T1rho (ms) of the lateral and medial cartilage averaged over 5 volunteers at different accelerations. The error bars indicate standard deviation T1rho across the subjects.

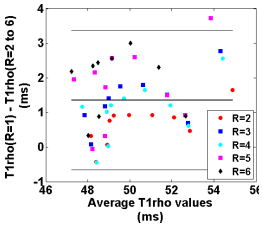

Fig. 2: Bland-Altman plot of the T1rho values comparing different acceleration rates (from R= 2 to 6) with the fully sampled reference (R=1).

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References: [1] Regatte R et al. Acad Radiol 2004; 11:741–749. [2] Wheaton AJ et al MRM 2004 Jun;51(6):1096-102 [3] Doneva M et al. MRM 2010; 64(4):1114-20. [4] Otazo R et al. MRM 2010; 64 (3), 767-776. [5] Feng L et al. MRM 2011; 65 (6), 1661-1669. [6] Liu KC et al. Patent #US 2014/0021951A1