Compressed Sensing Sodium MRI in Cartilage at 7T: Preliminary Study

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Introduction. Osteoarthritis (OA) is a degenerative disease of articular cartilage associated with a loss of glycosaminoglycans (GAG). Quantitative sodium MRI is highly specific to the GAG content and could be used to assess the biochemical degradation of cartilage in early stages of OA [1]. However, due to the low sodium concentration in vivo and its low NMR sensitivity, imaging of sodium in cartilage still requires long acquisition times (15-20 min for usual sodium 3D images and 25 min for fluid suppressed images) at 7T, with relatively low resolution (>2 mm) [2]. Compressed sensing (CS) is an accelerated imaging method which enables reconstruction of undersampled data by exploiting image sparsity [3]. Moreover, the non-linear reconstruction in CS inherently acts as a denoising procedure [3]. We applied CS to 3D sodium MRI of articular cartilage to test the efficiency of the method to reconstruct undersampled sodium images and test the accuracy of the sodium quantification compared to fully sampled data. It is expected that CS should allow reconstruction of images from undersampled data within clinically feasible acquisition times (within 10 min or less).

Materials and Methods. Acquisition**:** Data acquisition was performed in vivo on 4 asymptomatic volunteers with a 3D radial sequence on a 7T whole-body scanner (Siemens), with a transmit/receive birdcage sodium knee coil single-tuned at 78.6 MHz (Rapid MR International). Acquisition parameters were: 10,000 projections, TE 0.15 ms, TR 100 ms, RF pulse flip angle=90° of duration 0.5 ms, FOV 200 mm isotropic, time of acquisition 17 min. Once the fully sampled data was acquired, undersampling was randomly applied 100 times with the following acceleration rates: R=2 (50% of data), R=3 (33%) and R=4 (25%). Reconstruction: All images were reconstructed off-line in Matlab with a non-uniform Fast Fourier Transform (NUFFT) regridding algorithm as described in [2], as isotropic 100x100x100 voxels images, resulting in a nominal isotropic resolution of 2 mm. Compressed Sensing: CS reconstruction was then applied on the regridded k-spaces of all images (for data consistency) by minimizing the following function: $f(x) = ||Fx-y||_2^2+\lambda_1||\Psi x||_1+ \lambda_2 TV(x)$, where x is the image and y is its corresponding Cartesian k-space, F is the FFT, Ψ the sparsifying transform (Ψ=1 in this case), TV is the total variation, λ_1 and λ_2 are weighting factors. CS was applied with 72 iterations and with different pairs λ_1- λ_2 for optimization of SNR gain without blurring the images. SNR: The standard deviation (std) of all pixels over all the 100 images (with and without CS) obtained from random resampling with R=2, 3, 4 was then calculated. The mean std of the noise was measured from all voxels over 20 coronal slices where no sodium signal could be detected, for data with R=2, 3, 4. The statistical mean std of noise from data with R=1 was extrapolated by linear regression from the mean std of noise from R=2, 3, 4 as a function of $\sqrt{R}$. The mean signal was measured in selected ROIs of 30 voxels in 4 different regions in the cartilage over 4 consecutive slices. The cartilage regions were: patellar (PAT), femoro-tibial medial (MED), femoro-tibial lateral (LAT), and posterior femoral condyle (CON). The signal-to-noise ratio (SNR) was then calculated as the mean signal divided by the mean std of the noise. Sodium quantification [Na^+]: 4 gel phantoms of known sodium concentrations (150, 200, 250, 300 mM) and known relaxation times were place within the FOV and used as calibration phantoms for sodium quantification. Sodium maps were then reconstructed by linear regression [2]. Statistical analysis: For each volunteer and each region in cartilage, a Student's t-test was applied to the resulting sets of pixels (120 voxels) from the ROIs on the sodium maps in order to compare all the data with the original fully sampled data (NUFFT, R=1). Statistical significance was defined as the condition that $p<0.05$. Only data where the t-test showed a non-significant difference in [Na^+] in all of the 4 regions of the cartilage compared to the fully sampled data were considered as valid.

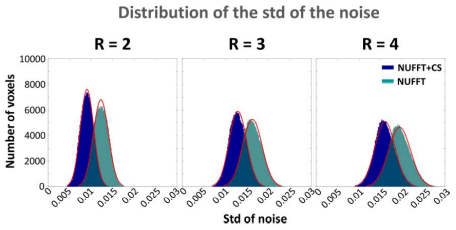

Fig. 1. Histograms of std of noise and fit by normal distribution

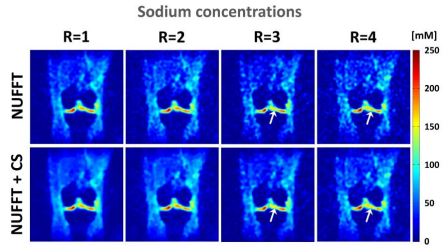

Fig. 2. Sodium maps after NUFFT, with and without denoising with CS.

Table 1. SNR. Percentages = variations of SNR compared to the reference (NUFFT R=1, grey row)

SNR		PAT		MED		LAT		CON	
Recon.	R	SNR	%	SNR	%	SNR	%	SNR	%
NUFFT	1	43.8±7.5	0	43.8±6.2	0	42.5±3.4	0	45.3±6.4	0
	2	26.4±4.5	-40	26.3±3.4	-40	25.6±2.1	-40	27.3±3.9	-40
	3	19.9±3.3	-55	19.8±2.6	-55	19.2±1.6	-55	20.5±2.9	-55
	4	16.8±2.9	-62	16.9±2.6	-61	16.3±1.3	-62	17.5±2.5	-61
NUFFT	1	73.9±13.1	+69	74.4±12.4	+70	71.7±6.4	+69	76.7±13.0	+69
+ CS	2	35.0±6.2	-20	35.2±5.0	-20	34.0±2.9	-20	36.3±5.8	-20
	3	24.5±4.2	-44	24.6±3.5	-44	23.8±2.0	-44	25.4±3.9	-44
	4	20.0±3.5	-54	20.2±2.7	-54	19.4±1.6	-54	20.9±3.2	-54

Results and Discussion. Representative examples of the distribution of the std of the noise (over 200,000 voxels) are shown in Fig. 1 for R=2, 3, 4, for NUFFT and NUFFT+CS reconstruction. They are all very similar to the normal distribution (red fit), which is to be expected for large number of values (N=100) for calculating std (χ^2 distribution of std becomes a normal distribution when N>50 [4]). We can see that applying CS reduces the mean std while keeping the normal distribution shape. Table 1 shows SNR values measured in 4 regions of cartilage and percentage of variations compared to fully sampled images (grey row). We can see that CS applied on R=1 data can increase SNR by 70% and allows a reduction of SNR of only 20% for R=2. Sodium maps are presented in Fig. 2. Arrows indicate regions in cartilage where a loss of signal from undersampling could be misinterpreted as a loss of sodium/GAG for R=3 and 4. From the t-test, only data with R=2 (with and without CS) show no significant difference with R=1 data and no risk of misinterpretation of [Na^+] due to loss of SNR. Data from R=2 and CS shows better SNR and could also allows [Na+] measurements in a broader range of small regions in cartilage but also in muscle.

Conclusion. This preliminary study shows that CS can be applied to decrease the acquisition time of sodium MRI of cartilage at 7T by a factor of 2 without losing accuracy in [Na^+] quantification over different ROIs in cartilage for detecting early signs of OA. Further studies will involve testing the application of the CS technique to data acquired at 3T, with and without fluid suppression at both 3T and 7T, combined with new sequences such as Density Adapted (DA) 3D radial [5], Twisted Projection Imaging (TPI) [6] or 3D cones [7] which allow increases in SNR. Further improvements would be obtained by combining CS with regridding included in the iterative process, instead of simply working with the Cartesian k-space (obtained after one NUFFT reconstruction) for data consistency.

References. [**1**] Borthakur A. et al, NMR Biomed 19(7), 781-821, 2006. [**2**] Madelin G. et al, JMR 207, 42-52, 2010. [**3**] Lustig M et al. MRM 58, 1182-1195, 2007. [**4**] Box GEP et al. Statistics for experimenters, 2dn Ed.,2005. [**5**] Nagel A.M. et al, MRM 62(6), 1565-1573, 2009. [**6**] Boada F.E. et al, MRM 37(5), 706-715, 1997. [**7**] Gurney P.T. et al, MRM 55(3) 575-582, 2006.

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