

TECHNICAL NOTE

Compressed Sensing MR Imaging (CS-MRI) of the Knee: Assessment of Quality, Inter-reader Agreement, and Acquisition Time

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We compared 3 Tesla (3T) compressed sensing (CS)-MRI of different pulse sequences with various acceleration factors to standard fast spin-echo (FSE) sequences in terms of time, quality, and inter-reader agreement. Each sequence was qualitatively ranked and then qualitatively scored for blurring, artifact, low contrast detection, noise pattern, signal-to-noise ratio, and overall quality. The CS-MRI sequences demonstrated very good overall quality compared with routine FSE sequences with overall good inter-reader agreement.

Keywords: *compressed sensing, inter-reader agreement, knee, magnetic resonance imaging, quality scores*

Introduction

MRI of the knee is the imaging gold standard for evaluation of the menisci, ligaments, articular cartilage, bone marrow, and synovium. Most routine knee MRI protocols include fast spin-echo (FSE) sequences with T_1 , T_2 , or proton density (PD) weighted sequences with or without fat saturation (FS). Advances in MRI imaging now enable high resolution isotropic 3D imaging of the knee and quantitative compositional analysis of cartilage ultrastructure using specialized cartilage mapping sequences. However, even at high-field strength (3T) these sequences can be time consuming to obtain, predisposing to motion artifact and limiting the ability to incorporate such pulse sequences into clinical imaging time slots. Thus, only the 2D FSE sequences are included in the routine knee MRI protocols in most practices.

Accelerated MRI data acquisition techniques have therefore been the subject of much research and interest. Parallel imaging is one approach to speed MRI acquisition time, but acceleration factors greater than two cannot be reliably achieved without compromising imaging quality.¹ Compressed sensing (CS) is a newer technique that takes advantage of the inherent redundancy and compressibility of MR images to undersample k -space, allowing fast acquisition at higher acceleration factors.^{2,3}

Compressed sensing has three requirements, which are applicable to MRI: (1) sparsity or transform sparsity, (2) incoherence of undersampling artifacts, and (3) nonlinear reconstruction.⁴ Sparsity refers to the data redundancy (compressibility) of images with little or no perceptible loss of information. MR images are generally sparse in some transform domains, such as the wavelet or the discrete cosine transform. Randomly undersampled k -space (Fourier) data results in incoherent (noise-like) artifacts in linear reconstruction, but using a non-linear iterative reconstruction enforces data consistency and promotes sparsity via denoising (thresholding).^{4,5} Compressed sensing has successfully been applied for a variety of clinical applications, including MRI of the brain, liver, spine, heart, prostate, and breast, with acceleration factors from 2 to 12.5.⁶ A few studies have applied CS to MRI of the knee, including for 3D FSE and cartilage imaging sequences, but these CS images are sequence and vendor specific.^{7–12}

The purpose of this study was to evaluate a new vendor specific compressed sensing technique applied to axial PD FS, coronal T_1 , and sagittal T_2 FS sequences with acceleration rates of two to three times compared with the routine FSE sequences. We hypothesized that the CS-MRI sequences would have similar image quality compared to the routine FSE images and that there would be good to very good inter-reader agreement.

Materials and Methods

Following Institutional Review Board approval, 10 clinical patients scheduled for knee 3T MRI examinations (on a MRI scanner [Vantage titan, Canon, Tochigi, Japan]) for knee pain were prospectively enrolled into the study after informed consent was obtained. Exclusion criteria included prior knee surgery.

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Imaging protocol

In addition to the routine standard clinical FSE MRI sequences, additional 2D FSE compressed sensing axial PD FS, coronal T₁, and sagittal T₂ FS sequences were obtained with acceleration factors of 2.0, 2.4, 2.7, and 3.0 for each sequence. The parameters for each sequence are listed in Table 1.

Table 1 Standard and CS-MRI sequence parameters

	Axial PD FS	Coronal T ₁	Sagittal T ₂ FS
ETL	7	2	9
TE (ms)	44	11	55
TR (ms)	3108	525	3516
Flip angle (°)	90	90	90
Number of excitations	2	1	1
Matrix size	224 × 384	192 × 448	384 × 192
FOV (cm)	16 × 17.4	16 × 17.4	16 × 17.4
Slice thickness (mm)	3	3	3
Interslice gap (mm)	1	1	1
Number of slices	30	24	24
Scan time			
Standard FSE	04:52	04:30	02:52
CS 2.0	02:48	02:16	02:16
CS 2.4	02:20	01:56	01:52
CS 2.7	02:08	01:42	01:40
CS 3.0	01:55	01:32	01:34

CS, compressed sensing; ETL, Echo train length; FS, fat saturation; FSE, fast spin echo; PD, proton density.

Rankings and qualitative scoring

These images were then anonymized, randomized and reviewed by two musculoskeletal radiologists with 9 (G.M.) and 3 (J.G.) years of experience, respectively. Each radiologist ranked the FSE and each CS sequence 1–5 (based on the radiologist's opinion of overall image quality, with 5 being the best) for each set of axial PD FS, coronal T₁ and sagittal T₂ FS sequences. Each radiologist also qualitatively scored each set of images for blurring, artifact, low contrast detection, noise pattern, signal-to-noise ratio, and overall quality using the following image quality rankings: 0 = non-diagnostic; 1 = poor; 2 = fair; 3 = good; and 4 = very good.

Statistical analysis

Inter-reader agreement was assessed by calculating prevalence and bias adjusted kappa (PABAK) with 95% confidence intervals (CI) for each sequence and ranking/quality score, as well as overall. We used κ cut-off values of <0.20 = poor, 0.20–0.39 = fair, 0.40–0.59 = moderate, 0.60–0.80 = good, and >0.80 = very good agreement.

The mean values for the qualitative ranking and each quality score were calculated for each sequence (axial PD FS, coronal T₁ and sagittal T₂ FS) and overall. Differences between the values for the routine FSE sequence were compared with the corresponding compressed sequences for each acceleration factor (2.0, 2.4, 2.7 and 3.0) using the contrast test and corresponding *P*-values were calculated.

Results

A sample image of each routine FSE and each CS-MRI acceleration factor is presented for each sequence (axial PD FS, coronal T₁ and sagittal T₂ FS) in Fig. 1.

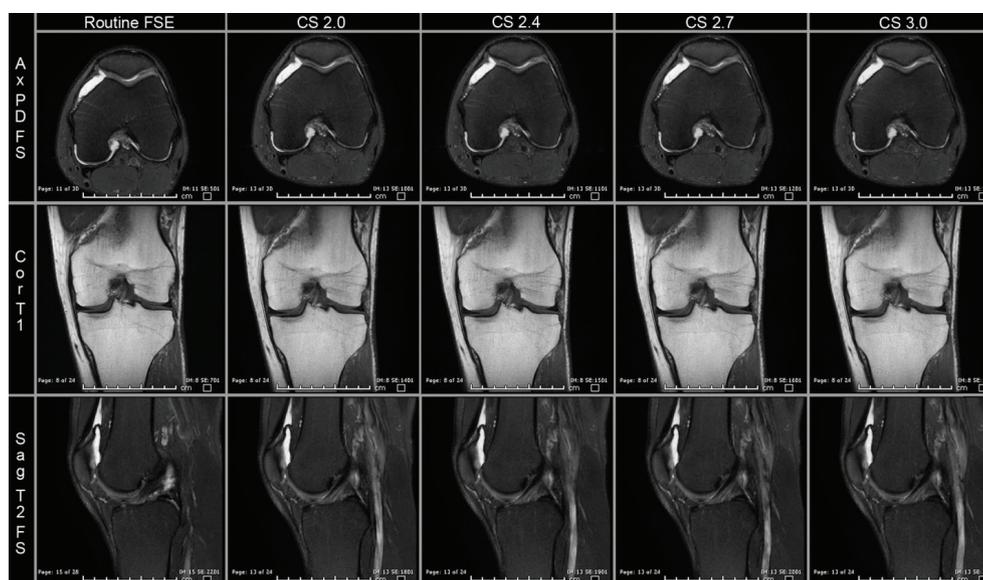


Fig. 1 Sample image of routine (FSE) and each (CS)-MRI sequence and acceleration factor (2.0, 2.4, 2.7, and 3.0) is presented for each sequence: axial proton density (PD) fat saturation (FS), coronal T₁ and sagittal T₂ FS; CS, compressed sensing; FSE, fast spin echo.

Inter-reader agreement

Inter-reader agreement was assessed and PABAK values and 95% CI for each sequence and ranking/quality score are presented in Table 2, with overall agreement for each category presented in the final row. For the qualitative ranking, there was moderate inter-reader agreement for the routine sequence ranking for the axial PD FS and coronal T₁ sequences (0.75), but poor to fair agreement (−0.25 to 0.38) for all other qualitative rankings. For blurring, inter-reader agreement for the quality scores ranged wildly from poor to very good (−0.12 to 1) with overall fair agreement (0.38). For artifacts, there was also prominent variation in inter-reader agreement from poor to very good (0.13–0.88), but overall moderate agreement (0.58). For low contrast

detection, noise pattern, signal-to-noise ratio, and overall quality, there was less variation of the inter-reader agreement ranging from fair to very good (0.25–1), with overall good agreement for each (0.74–0.78).

Rankings and qualitative scoring

The mean qualitative rankings and quality scores for each reader from all three of these sequences are presented in Tables 3 and 4, respectively. For the qualitative rankings, the routine FSE sequence was judged overall as the best, with a mean qualitative ranking of 4.33 overall, which was statistically higher than any of the CS sequences ($P < 0.01$).

The rating for every quality score was either good (3) or very good (4) for each of the evaluated parameters for both

Table 2 Inter-reader agreement* for routine fast spin echo (FSE) vs compressed sensing (CS)-MRI sequence rankings and quality scores

	Qualitative ranking	Blurring	Artifacts	Low contrast detection	Noise pattern	Signal-to-noise ratio	Overall quality
Ax PD FS							
Routine	0.75 (0.44, 1)	0.75 (0.44, 1)	0.88 (0.64, 1)	1 (1, 1)	1 (1, 1)	1 (1, 1)	1 (1, 1)
CS 2.0	0.38 (−0.01, 0.76)	0.5 (0.12, 0.88)	0.75 (0.44, 1)	0.75 (0.44, 1)	0.75 (0.44, 1)	0.63 (0.27, 0.98)	0.75 (0.44, 1)
CS 2.4	0.25 (−0.13, 0.63)	0.25 (−0.13, 0.63)	0.25 (−0.13, 0.63)	0.63 (0.27, 0.98)	0.38 (−0.01, 0.76)	0.75 (0.44, 1)	0.63 (0.27, 0.98)
CS 2.7	0 (−0.31, 0.31)	0 (−0.31, 0.31)	0.38 (−0.01, 0.76)	0.88 (0.64, 1)	0.63 (0.27, 0.98)	0.63 (0.27, 0.98)	0.75 (0.44, 1)
CS 3.0	0.25 (−0.13, 0.63)	−0.12 (−0.36, 0.11)	0.13 (−0.23, 0.48)	0.5 (0.12, 0.88)	0.38 (−0.01, 0.76)	0.25 (−0.13, 0.63)	0.25 (−0.13, 0.63)
Coronal T ₁							
Routine	0.75 (0.44, 1)	1 (1, 1)	0.75 (0.44, 1)	1 (1, 1)	0.75 (0.44, 1)	0.75 (0.44, 1)	0.75 (0.44, 1)
CS 2.0	0.25 (−0.13, 0.63)	0.88 (0.64, 1)	0.88 (0.64, 1)	0.88 (0.64, 1)	1 (1, 1)	1 (1, 1)	1 (1, 1)
CS 2.4	0 (−0.31, 0.31)	0.38 (−0.01, 0.76)	0.5 (0.12, 0.88)	0.75 (0.44, 1)	0.75 (0.44, 1)	0.75 (0.44, 1)	0.75 (0.44, 1)
CS 2.7	−0.25 (−0.25, −0.25)	0.25 (−0.13, 0.63)	0.5 (0.12, 0.88)	0.63 (0.27, 0.98)	0.88 (0.64, 1)	0.75 (0.44, 1)	0.75 (0.44, 1)
CS 3.0	0.13 (−0.23, 0.48)	0.25 (−0.13, 0.63)	0.75 (0.44, 1)	0.75 (0.44, 1)	1 (1, 1)	1 (1, 1)	1 (1, 1)
Sagittal T ₂ FS							
Routine	0.38 (−0.01, 0.76)	0.63 (0.27, 0.98)	0.63 (0.27, 0.98)	0.75 (0.44, 1)	0.88 (0.64, 1)	0.88 (0.64, 1)	0.88 (0.64, 1)
CS 2.0	0.25 (−0.13, 0.63)	0.5 (0.12, 0.88)	0.75 (0.44, 1)	0.88 (0.64, 1)	0.88 (0.64, 1)	0.88 (0.64, 1)	0.88 (0.64, 1)
CS 2.4	0.13 (−0.23, 0.48)	0 (−0.31, 0.31)	0.63 (0.27, 0.98)	0.63 (0.27, 0.98)	0.63 (0.27, 0.98)	0.88 (0.64, 1)	0.5 (0.12, 0.88)
CS 2.7	0.25 (−0.13, 0.63)	0.13 (−0.23, 0.48)	0.38 (−0.01, 0.76)	0.63 (0.27, 0.98)	0.5 (0.12, 0.88)	0.63 (0.27, 0.98)	0.38 (−0.01, 0.76)
CS 3.0	−0.12 (−0.36, 0.11)	0.25 (−0.13, 0.63)	0.63 (0.27, 0.98)	0.75 (0.44, 1)	0.88 (0.64, 1)	1 (1, 1)	0.88 (0.64, 1)
Overall	0.23 (0.13, 0.32)	0.38 (0.27, 0.48)	0.58 (0.49, 0.68)	0.76 (0.68, 0.84)	0.75 (0.67, 0.83)	0.78 (0.71, 0.86)	0.74 (0.66, 0.82)

*Prevalence and bias adjusted kappa (95% confidence interval in parentheses). FS, fat saturation; PD, proton density.

Table 3 Overall mean qualitative rankings for routine fast spin echo (FSE) vs compressed sensing (CS)-MRI sequences and contrast test *P*-values

	Qualitative ranking	
	Mean	<i>P</i>
Reader 1		
Routine	4.73	
CS 2.0	3.17	<0.01
CS 2.4	2.60	<0.01
CS 2.7	2.50	<0.01
CS 3.0	2.00	<0.01
Reader 2		
Routine	3.93	
CS 2.0	3.70	0.47
CS 2.4	2.33	<0.01
CS 2.7	2.47	<0.01
CS 3.0	2.50	<0.01
Average		
Routine	4.33	
CS 2.0	3.43	<0.01
CS 2.4	2.47	<0.01
CS 2.7	2.48	<0.01
CS 3.0	2.25	<0.01

readers. For the quality scores, there was an overall statistically significant difference between the routine FSE sequence and the CS-MRI sequences with acceleration factors of 2.4, 2.7, and 3.0 for reader 2 and the average between both readers ($P < 0.01$), but not for reader 2 or compared with the CS-MRI sequence with an acceleration factor of 2.0. Other overall statistically significant differences were seen for artifacts for CS 2.4 ($P < 0.01$) and CS 2.7 ($P = 0.02$), but not for CS 2.0 or 3.0 and for low contrast noise detection for CS 2.4 ($P = 0.04$), 2.7 ($P < 0.01$), and 3.0 ($P = 0.04$). For noise pattern, signal-to-noise ratio, and overall quality, there were no significant overall differences between the quality scores for the routine FSE and any of the CS-MRI sequences for either reader or the average between them.

Discussion

This study shows that CS can be applied to different MRI knee sequences (PD FS, T₁, and T₂ FS) and imaging planes (axial, coronal, and sagittal) with time savings ranging from 36 s (at a CS acceleration factor of 2.0 compared with the routine sagittal T₂ FS sequence) to 2 min and 58 s (at a CS acceleration factor of 3.0 compared with the routine coronal T₁ sequence). Replacing all three of the routine FSE sequences evaluated in this study (axial PD FS, coronal T₁, and sagittal T₂ FS) sequence with CS-MRI sequences would result in an overall time savings of 4 min and 54 s at a CS acceleration factor of 2.0 and up to 7 min and 13 s at a CS factor of 3.0.

Table 4 Overall mean quality scores for routine fast spin echo (FSE) vs compressed sensing (CS)-MRI sequences and contrast test *P*-values

	Blurring		Artifacts		Low contrast detection		Noise pattern		Signal-to-noise ratio		Overall quality	
	Mean	<i>P</i>	Mean	<i>P</i>	Mean	<i>P</i>	Mean	<i>P</i>	Mean	<i>P</i>	Mean	<i>P</i>
Reader 1												
Routine	3.93		4.00		4.00		4.00		4.00		4.00	
CS 2.0	4.00	0.3	3.93	0.19	3.87	0.12	3.93	0.28	3.97	0.43	4.00	N/A
CS 2.4	3.90	0.61	3.93	0.19	3.83	0.05	3.90	0.11	3.97	0.43	4.00	N/A
CS 2.7	3.97	0.61	3.97	0.51	3.83	0.05	3.93	0.28	3.97	0.43	4.00	N/A
CS 3.0	3.87	0.3	3.97	0.51	3.83	0.05	3.93	0.28	3.97	0.43	4.00	N/A
Reader 2												
Routine	3.77		3.80		3.93		3.90		3.90		3.90	
CS 2.0	3.70	0.58	3.83	0.79	4.00	0.44	3.90	1.00	3.90	1.00	3.90	1.00
CS 2.4	3.33	<0.01	3.47	<0.01	3.83	0.25	3.77	0.17	3.80	0.3	3.70	0.06
CS 2.7	3.33	<0.01	3.50	0.02	3.73	0.02	3.80	0.3	3.77	0.16	3.70	0.06
CS 3.0	3.30	<0.01	3.63	0.18	3.83	0.25	3.80	0.3	3.83	0.49	3.77	0.2
Average												
Routine	3.85		3.90		3.97		3.95		3.95		3.95	
CS 2.0	3.85	1.00	3.88	0.81	3.93	0.61	3.92	0.57	3.93	0.75	3.95	1.00
CS 2.4	3.62	<0.01	3.70	<0.01	3.83	0.04	3.83	0.05	3.88	0.21	3.85	0.06
CS 2.7	3.65	<0.01	3.73	0.02	3.78	<0.01	3.87	0.15	3.87	0.12	3.85	0.06
CS 3.0	3.58	<0.01	3.80	0.15	3.83	0.04	3.87	0.15	3.90	0.34	3.88	0.2

N/A; not applicable.

Inter-reader agreement for the qualitative ranking was poor. The poor inter-reader agreement for the qualitative ranking is probably because there was little difference between the mean qualitative rankings for CS acceleration factors 2.4, 2.7, and 3.0 leading to wide variation in the qualitative rankings for CS acceleration factors 2.4–3.0 between readers. This suggests that any differences between these different acceleration factors were subtle or insignificant.

Inter-reader agreement for the quality scores was fair for blurring and moderate for artifacts; however, it was good for all other quality score categories (low contrast detection, noise pattern, signal-to-noise ratio, and overall quality). The lower inter-reader agreement for the quality scores for blurring and artifacts also likely resulted from reader 2 documenting more overall statistically significant differences for these categories (Table 4), especially for the axial PD FS sequence, whereas reader 1 did not demonstrate a statistically significant difference for the quality scores for any of the categories overall or for any of the separate sequences. The overall rankings and scores also demonstrate more statistically significant differences between the readers, likely due to the increased power by increasing the number of measurements in this manner.

Despite these differences, both readers rated the quality scores in every category for each obtained sequence (the routine FSE and each CS-MRI acceleration factor for each of the axial PD FS, coronal T₁, and sagittal T₂ FS sequences for all 10 patients) as either good or very good. Both readers agreed that all imaging performed as part of this study was of diagnostic quality, even at CS acceleration factors of up to 3.0.

A limitation of this study is that it was not designed to evaluate diagnostic performance. Future investigations are planned to evaluate how readers perform when diagnosing meniscal and ligament tears and cartilage lesions when using CS-MRI compared with routine sequences with arthroscopic correlation. Additional limitations of this study include the small sample size (10 patients, 30 sequences) and a qualitative rather than a quantitative evaluation of the signal-to-noise ratio. Future investigations would benefit from a larger sample size and quantitative measurement of contrast-to-noise ratio. There was also no assessment of intra-reader agreement in this study. Future investigations of the benefits of combining parallel imaging with compressed sensing techniques would also be useful.

Conclusion

The time savings by applying CS to the routinely obtained MRI sequences as part of a knee 3T MRI could be used to increase patient throughput, obtain higher resolution or three-dimensional isovoxel images, or add additional sequences such as T₂ mapping or other cartilage mapping sequences.

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Conflicts of Interest

George R. Matcuk received pilot funding grant support from Canon Medical Systems USA, Inc. The remaining authors declare that they have no other conflicts of interest.

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