# Compressed Sensing Magnetic Resonance Imaging (CS-MRI) for Accelerated Knee MR Imaging

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# Disclosures

- The images for the cases using the CS-MRI sequence and data presented in this educational exhibit are from a study funded by Canon Medical Systems USC, Inc.
- Hung P. Do, PhD is an employees of Canon Medical System USA, Inc.
- The authors have no other conflicts of interest


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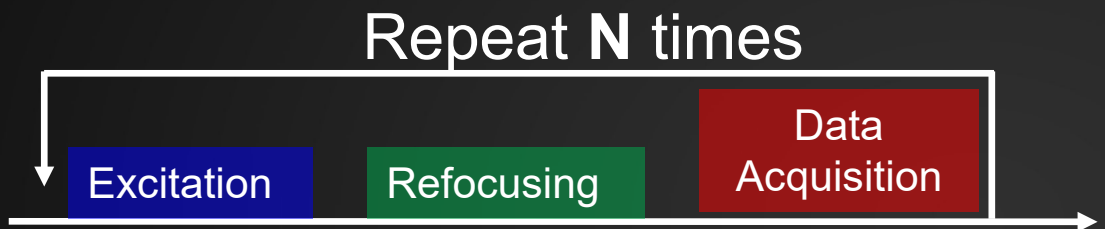
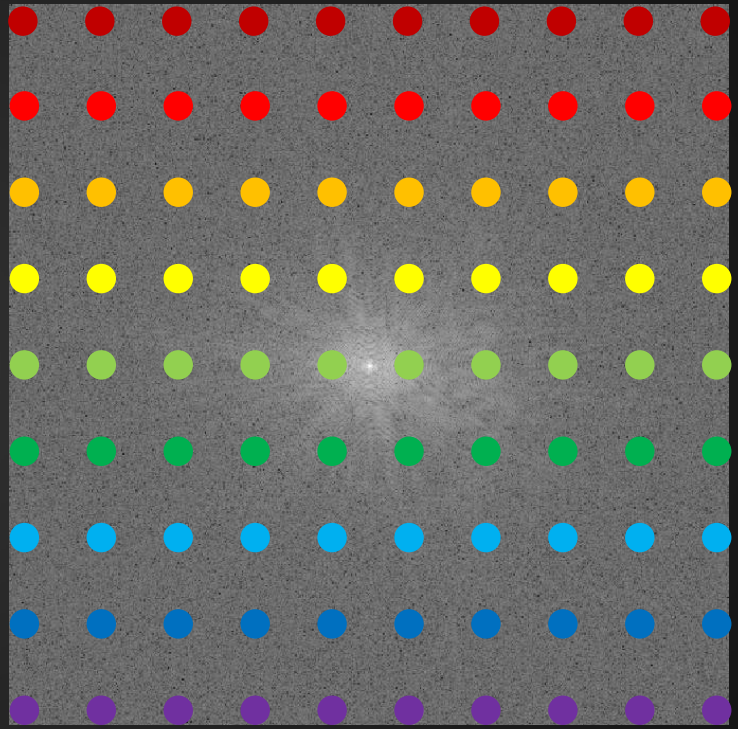
# Background

- Accelerated MRI data acquisition techniques have therefore been the subject of much research and interest
- Parallel imaging (PI) is one approach to speed MRI acquisition time, but acceleration factors greater than two cannot be reliably achieved without compromising imaging quality
- 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
- Compressed sensing has successfully been applied for a variety of clinical applications, including MRI of the brain, liver, spine, heart, prostate, breast, and knee with acceleration factors from 2 to 12.5

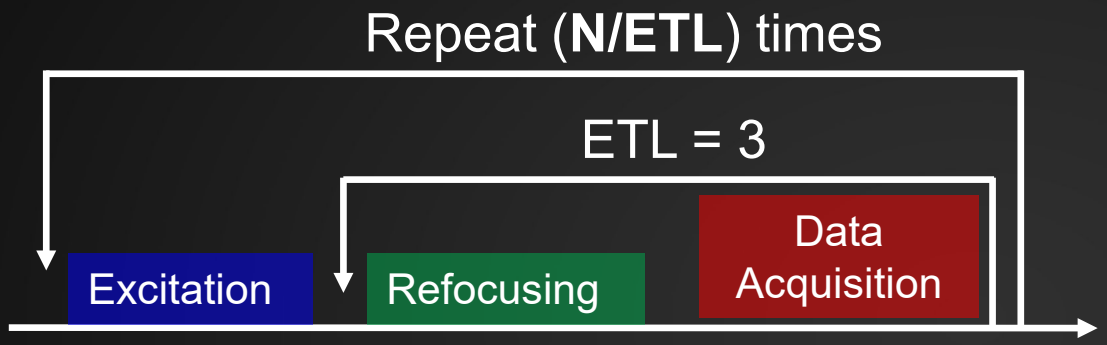
# 2D Spin Echo sequence

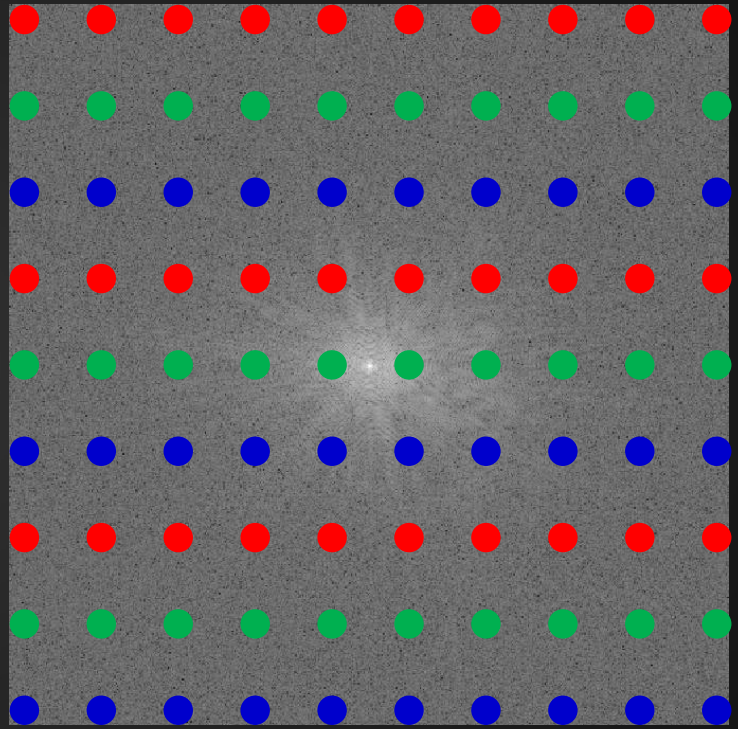


K-space

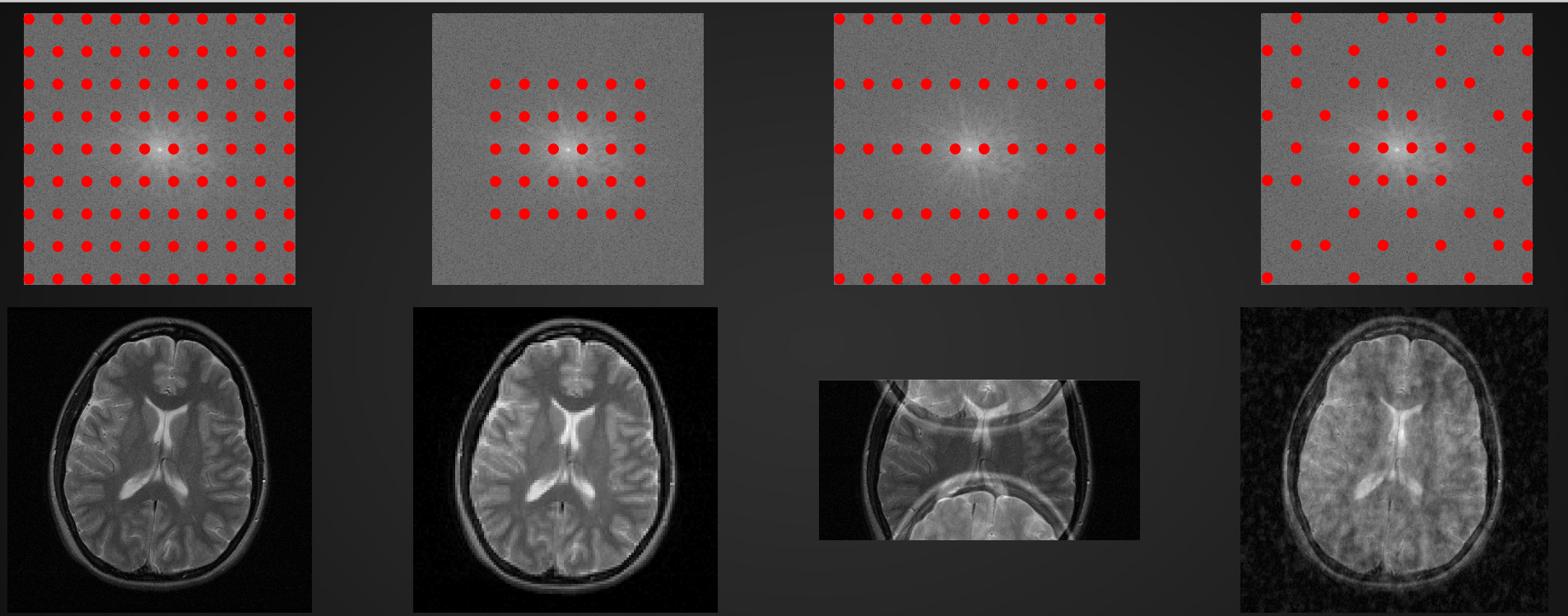
# 2D Fast Spin Echo (FSE) sequence



K-space

# Going faster by acquiring less data



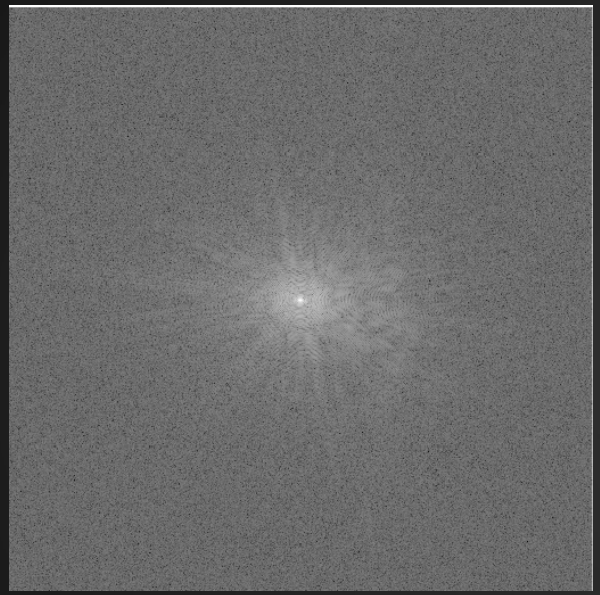
Fully-sampled

Low resolution

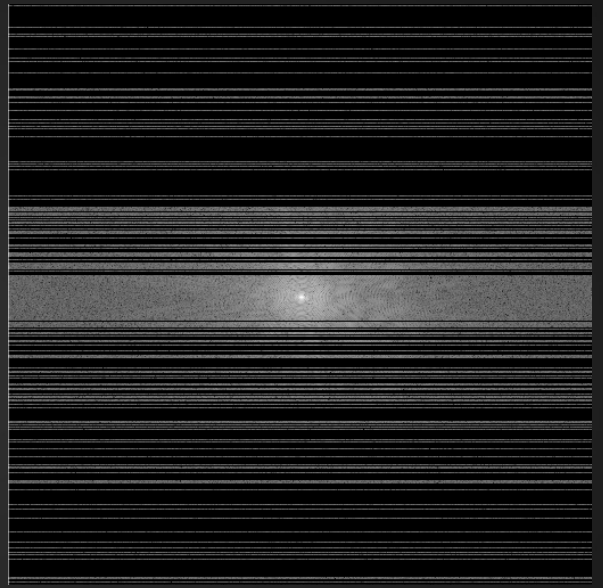
Parallel Imaging

Compressed Sensing (CS)

# Sampling Pattern used in this Work



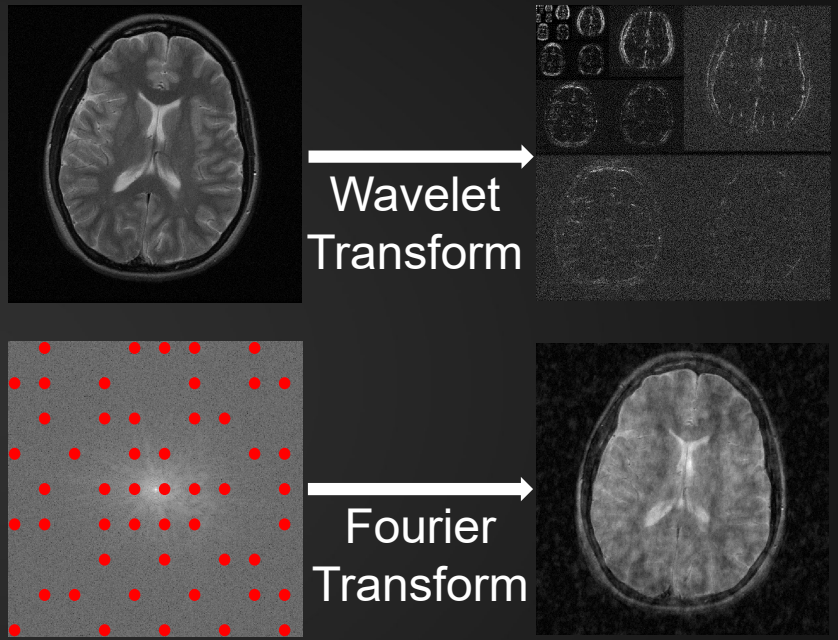
Fully-sampled 2D FSE



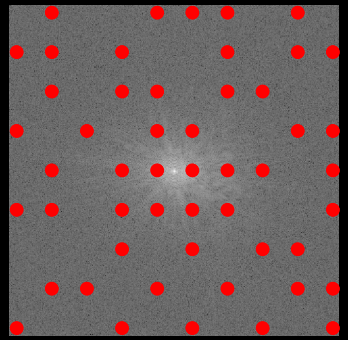
CS under-sampled 2D FSE

# Three Ingredients of CS

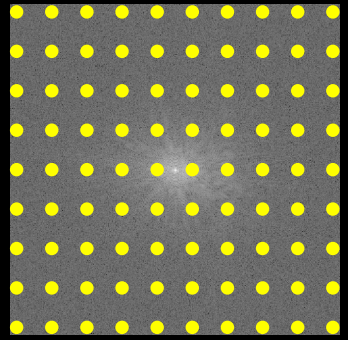
- Sparsity – Compressibility of images
  - MR images are generally not sparse but their transforms may
- Incoherent under-sampling
  - Resulting in noise like artifacts
- Non-linear iterative reconstruction
  - Enforcing data consistency and promoting sparsity via denoising



# Non-linear iterative reconstruction



Data consistency

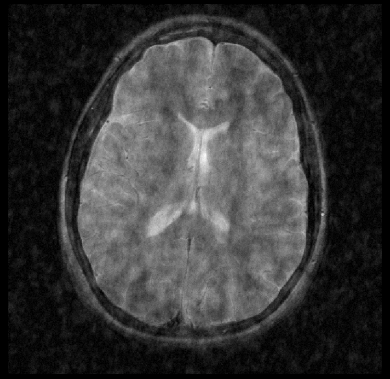


Inverse FFT

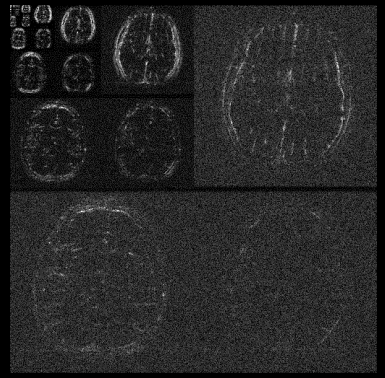
**Iterate** to enforce data consistency and promote sparsity

Inverse FFT

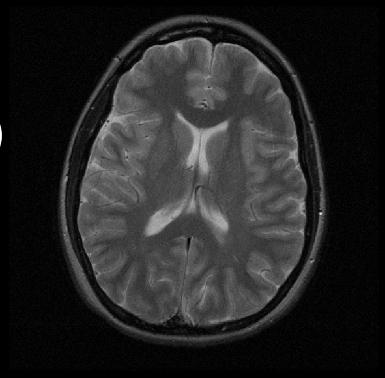
FFT



Sparsity transform



"Denoising" (thresholding)



# Pilot Study to Evaluate Quality of FSE vs CS MRI

- In a pilot study at our institution, 10 clinical patients scheduled for knee 3T MRI examinations (on a Canon Vantage Titan MRI scanner) were prospectively enrolled into the study
- In addition to the routine 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 (with sequence parameters and scan time on next slides)
- These images were then anonymized and 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 to 5, 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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# Sequence parameters

| | Axial PD FS | Coronal T1 | Sagittal T2 FS |
|---|---|---|---|
| Echo train length (ETL) | 7 | 2 | 9 |
| Echo time (TE) | 44 ms | 11 ms | 55 ms |
| Repetition Time (TR) | 3108 ms | 525 ms | 3516 ms |
| Flip angle | 90 | 90 | 90 |
| Number of excitations | 2 | 1 | 1 |
| Matrix size | 224 x 384 | 192 x 448 | 384 x 192 |
| Field of view (FOV) | 16 x 17.4 cm | 16 x 17.4 cm | 16 x 17.4 cm |
| Slice thickness | 3 mm | 3 mm | 3 mm |
| Interslice gap | 1 mm | 1 mm | 1 mm |
| Number of slices | 30 | 24 | 24 |

# Scan Times

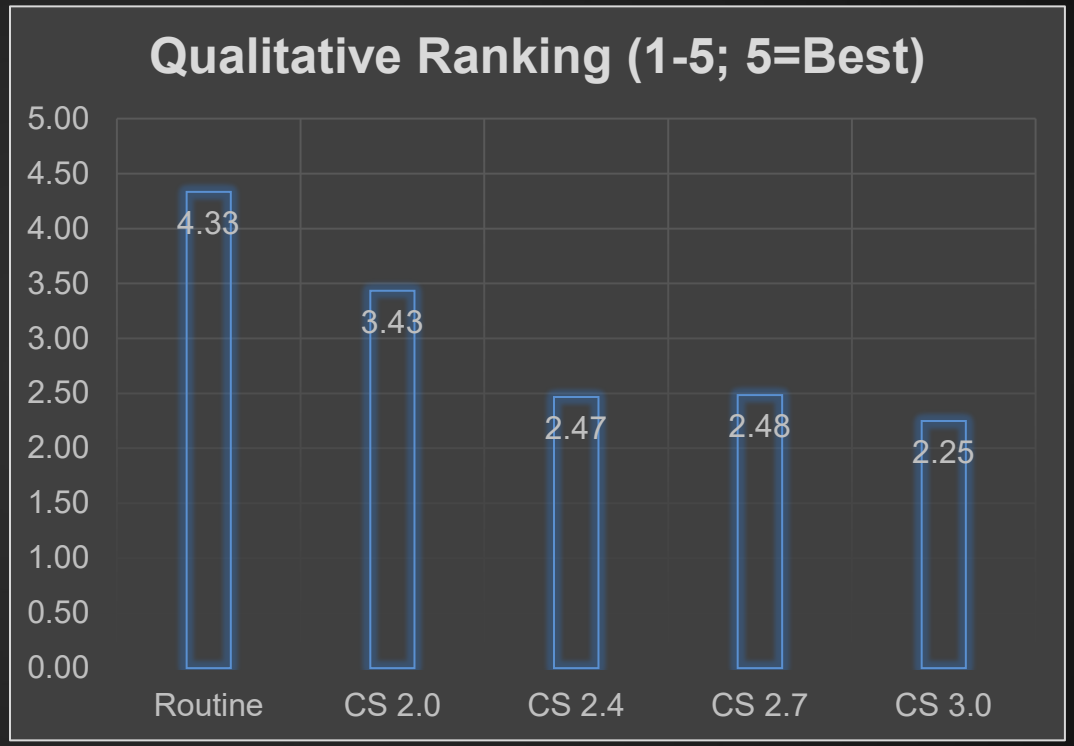
| | Axial PD FS | Coronal T1 | Sagittal T2 FS |
|---|---|---|---|
| Standard FSE | 04:52 | 04:30 | 02:52 |
| CS 2.0 | 02:48 | 02:16 | 02:16 |
| CS 2.4 | 02:20 | 01:56 | 01:52 |
| CS 2.7 | 02:08 | 01:42 | 01:40 |
| CS 3.0 | 01:55 | 01:32 | 01:34 |

# Inter-reader Agreement

- Inter-reader agreement was assessed by calculating prevalence and bias adjusted kappa (PABAK) with 95% confidence intervals for each sequence and ranking/quality score, as well as combined for each sequence (axial PD FS, coronal T1 and sagittal T2 FS) and for the routine versus each CS rate factor and 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 to 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

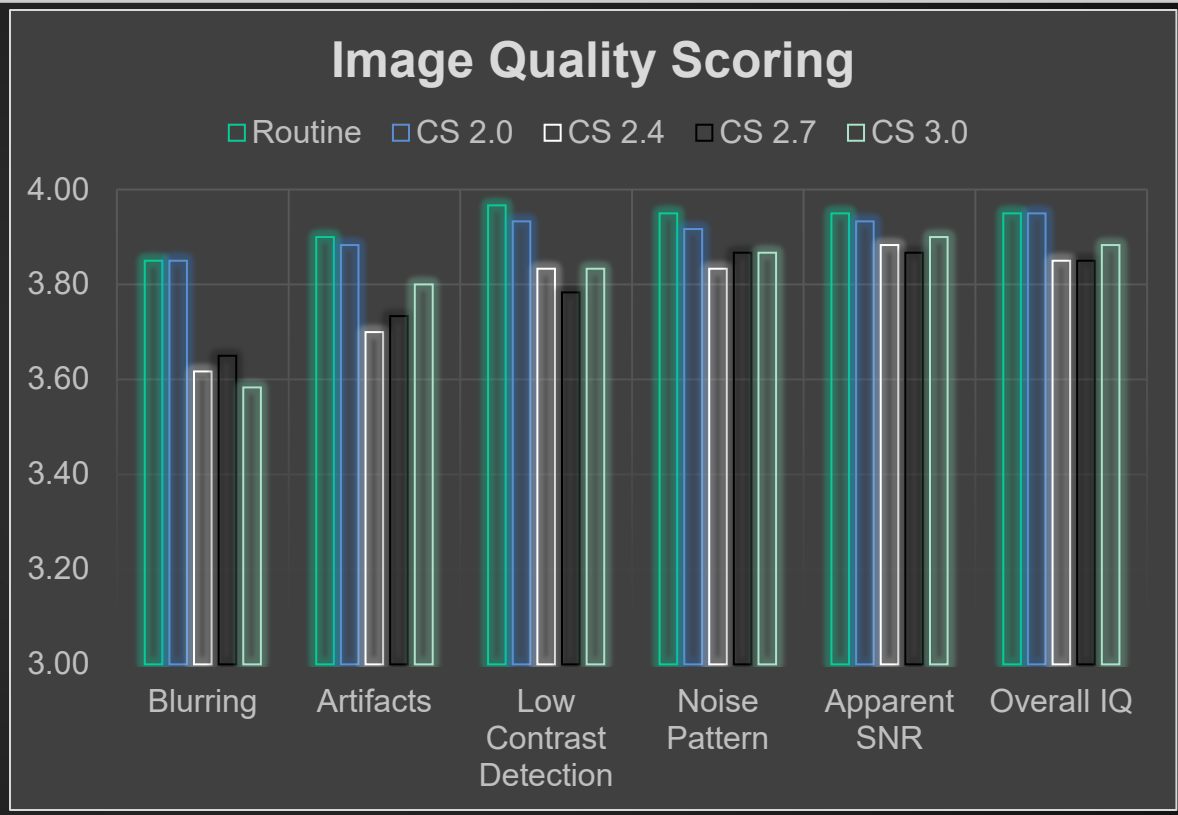
# Qualitative Rankings FSE vs CS MRI

- Inter-reader agreement for the qualitative ranking was poor
  - The poor inter-reader agreement for the qualitative ranking is probably because there was good inter-reader agreement for the routine FSE sequence, which received a statistically higher rating compared to the CS-MRI sequences
  - Although the CS-MRI sequence with an acceleration factor of 2.0 was overall rated higher than the other CS-MRI acceleration factors by both readers, there was little difference between the mean qualitative rankings for CS acceleration factors 2.4, 2.7, and 3.0, which likely contributed to the poor overall inter-reader agreement
  - Such wide variation in the qualitative rankings for CS acceleration factors 2.4 to 3.0 between readers suggests that any differences between these different acceleration factors were subtle or insignificant



# Quality Scores FSE vs CS MRI

- Inter-reader agreement for the quality scores was fair for blurring and moderate for artifacts, but good for all other quality score categories (low contrast detection, noise pattern, signal-to-noise ratio, and overall quality)
- Both readers rated the quality scores in every category for each obtained sequence as either good or very good
- Both readers agreed that all imaging performed was of diagnostic quality

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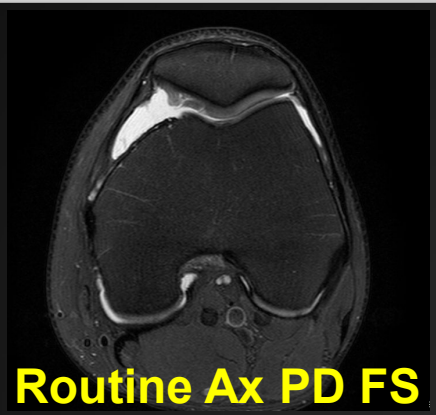
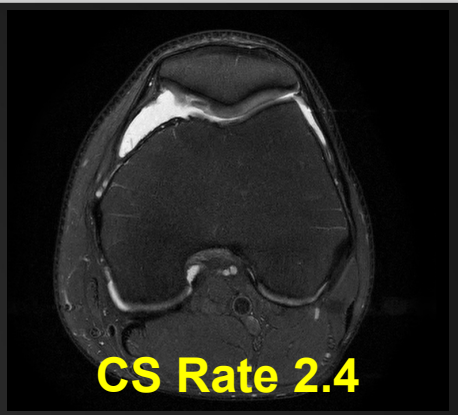
# Case 1: 42-year-old man with chondromalacia patellae



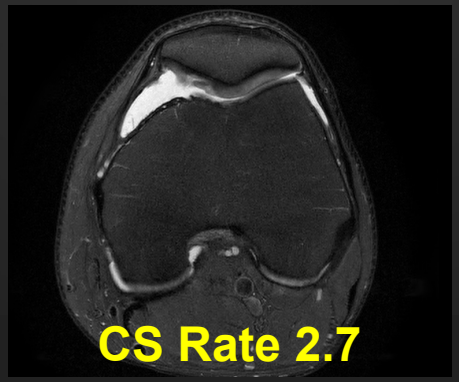

Acquisition Time: 4:52


Acquisition Time: 2:48

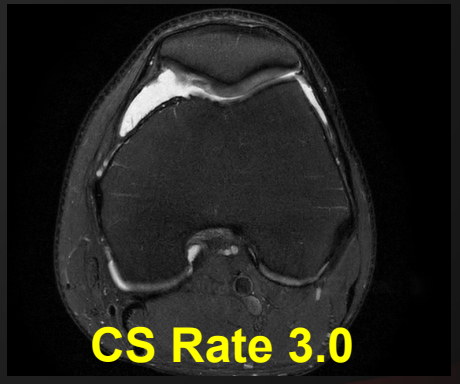



Acquisition Time: 2:20

Grade 3 chondral fissuring and delamination of the medial patellar facet is clearly demarcated with similar quality with acquisition time savings of up to 60.6% with CS rate 3.0

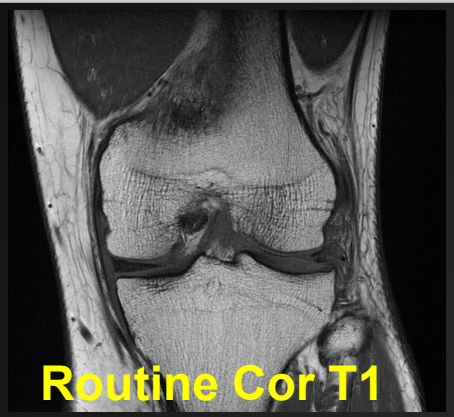



Acquisition Time: 2:08



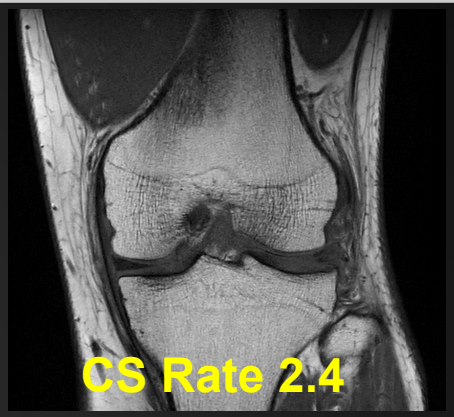

Acquisition Time: 1:55

# Case 2: 37-year-old man with lateral meniscal tear




Acquisition Time: 4:30


Acquisition Time: 2:16




Acquisition Time: 1:56

Lateral meniscal tear pattern is slightly more defined on the routine FSE sequence, but the diagnostic quality is maintained even up to a CS rate of 3.0


Acquisition Time: 1:42


Acquisition Time: 1:32

# Case 3: 22-year-old man with lateral trochlear chondrosis

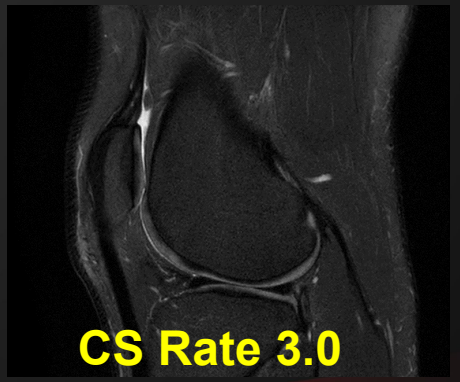

Acquisition Time: 2:52


Acquisition Time: 2:16


Acquisition Time: 1:52

Signal alteration (low grade chondrosis) of the lateral trochlear cartilage is slightly more defined on the routine FSE sequence, but the diagnostic quality is maintained even up to a CS rate of 3.0


Acquisition Time: 1:40




Acquisition Time: 1:34

# Limitations & Future Investigations

- This pilot study 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 to routine sequences
- Also plan to apply compressed sensing technique to speed and test other routine sequences (PD, STIR, T2, and T1 FS pre- and post-contrast) and to advanced MRI sequences such as 3D isotropic sequences and cartilage mapping sequences

# Potential Time Savings of CS-MRI

- Time savings for each sequence range from
  - 36 seconds (at a CS acceleration factor of 2.0 compared to the routine sagittal T2 FS sequence) to
  - 2 minutes and 58 seconds (at a CS acceleration factor of 3.0 compared to the routine coronal T1 sequence)
- Replacing just three routine FSE sequences (axial PD FS, coronal T1, and sagittal T2 FS) with CS-MRI sequences would result in an overall time savings of
  - 4 minutes and 54 seconds at a CS acceleration factor of 2.0
  - 7 minutes and 13 seconds at a CS factor of 3.0

# Potential Uses of CS-MRI

- The time savings by applying compressed sensing to the routinely obtained sequences as part of a knee MRI could be used to
  - Increase patient throughput
  - Obtain higher resolution images
  - Obtain three-dimensional isovoxel images
  - Add additional sequences such as T2 mapping or other cartilage mapping sequences without affecting diagnostic quality

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