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Accelerating knee MR imaging: Compressed sensing in isotropic three-dimensional fast spin-echo sequence

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ABSTRACT

Purpose: To compare image quality between compressed sensing (CS)-3D-fast spin-echo (FSE) and conventional 3D-FSE sequences for knee magnetic resonance imaging (MRI).

Methods: Knee MRI of 43 patients (male:female, 14:29; mean age, 53 years) were acquired using conventional and CS-3D-FSE with an acceleration factor of 1.5. Overall image quality was assessed by correlation coefficient, root-mean-square error (RMSE), and structural similarity (SSIM) index. Regional image quality was evaluated using signal-to-noise ratios (SNRs) and contrast-to-noise ratios (CNRs). Subjective image quality was evaluated using a four-point scale. Diagnostic agreement for meniscal lesions between the two sequences was evaluated.

Results: The scan time was reduced from 7:14–8:08 to 4:53–5:08 with CS. A strong positive correlation was observed between data of the two sequences (mean r = 0.880). The RMSE (mean, 126.861) and SSIM index (mean, 0.987) were acceptable. The SNRs and CNRs were not significantly different between the two sequences ($P > 0.05$, each). There were no significant differences in the evaluation of the menisci and cruciate ligaments, while the CS images demonstrated inferior quality of cartilage–subchondral bone delineation. Diagnostic agreement for meniscal lesions between the two sequences was very good (κ = 0.943–1).

Conclusion: Compressed sensing-3D-FSE knee MRI produces images of acceptable quality while reducing scan time.

1. Introduction

Magnetic resonance imaging (MRI) of the knee is an accurate and noninvasive technique for the evaluation of internal derangements [1]. Three-dimensional (3D) volumetric MRI with isotropic resolution allows for decreased partial volume artifacts with thin continuous sections as well as multiplanar reformatting capabilities [2]. Isotropic 3D sequences have provided similar diagnostic performance as conventional two-dimensional (2D) sequences for detecting knee joint pathology [3–5]. However, 3D MRI of the knee requires relatively longer scan times [6].

Rapid MRI data acquisition is essential in knee imaging because patients with knee pain tend to move, causing motion artifacts, especially when the scan time is long. Parallel imaging (PI) is one approach to accelerate MRI data acquisition. However, PI acceleration factors > 2 cannot be reliably achieved in clinical settings without compromising image quality [7].

Compressed sensing (CS), a more recent technique, was developed on the premise of reconstructing an image from an incompletely filled (i.e. undersampled) *k*-space, since the number of segments in the *k*-space is a direct determinant of image acquisition time [8]. This technique exploits the data redundancy (also known as sparsity) in MR images, which essentially allows less data to be acquired [9]. The combination of CS and PI afford even faster imaging, with the resultant image quality deemed acceptable.

Recently, several studies have examined the quality and diagnostic efficacy of CS images [7,10–15]. A few studies have examined the application of CS in 3D-fast spin-echo (FSE) MRI of the knee [16–19]. However, application of CS in 3D-FSE sequence that has true voxel isotropy remain limited and comparison between 3D-FSE sequences without CS and that with CS is confined to a specific sequence on scanner of a specific vendor.

The purpose of this study was to compare the image quality and assess the diagnostic agreement for meniscal lesions between the isotropic CS-3D-FSE and conventional 3D-FSE sequences in knee MRI. We hypothesized that isotropic 3D-FSE knee MRI using CS would decrease scan time, while yielding similar image quality and diagnostic performance when compared with a conventional isotropic 3D-FSE sequence.

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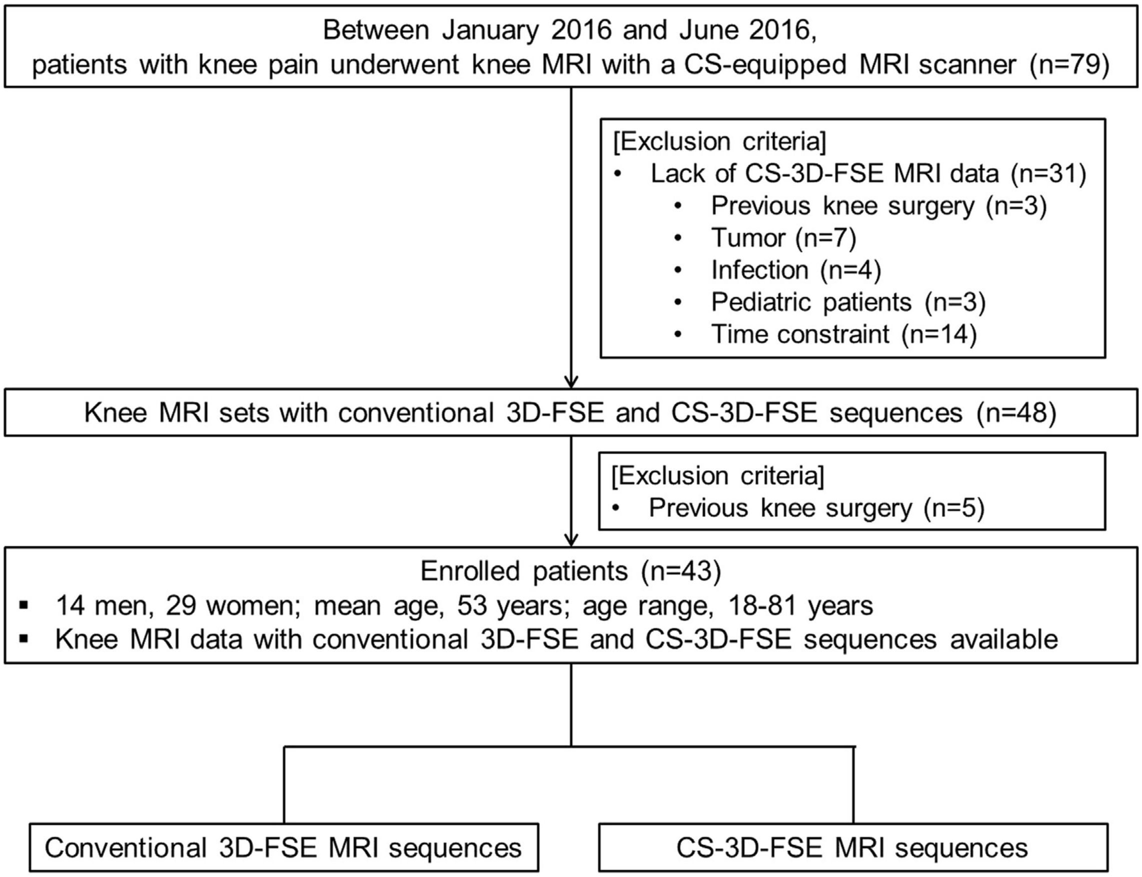

Fig. 1. Flow chart of patient enrollment.
MRI = magnetic resonance imaging, CS = compressed sensing, 3D = three-dimensional, FSE = fast spin-echo.

2. Materials and methods

2.1. Patients

The institutional review board of our hospital approved this single-center retrospective study and waived the requirement for informed consent. The inclusion criteria for this study were patients with symptomatic knee and knee MRI data with conventional 3D-FSE and CS-3D-FSE sequences available. Exclusion criteria included previous knee surgery, tumor, infection, pediatric patients under the age of 18, and lack of CS-3D-FSE MRI data available. We enrolled 43 symptomatic patients (male:female, 14:29; mean age, 53 years; range, 18–81 years) between January 2016 and June 2016. The flowchart of patient enrollment is summarized in Fig. 1.

2.2. Phantom study

To determine the optimal CS factor, a cylindrical unified phantom with NiCi (GE Healthcare, Waukesha, WI, USA) was scanned using various CS factors (range, 1.0–1.8). A line-of-interest (100 pixels) including the phantom, boundary, and background air was drawn on each image near the edge of the phantom. The edge response function (ERF) was calculated from a plot of image intensity across the edge of the phantom, using the following equation:

$$\mathrm{ERF} = \frac{(\mathrm{S_{max}} - \mathrm{S_{min}})}{(\mathrm{S_{max}} + \mathrm{S_{min}})}$$

S_{max} and S_{min} stand for the maximum and minimum signal intensity values of the line-of-interest placed at the edge of the phantom.

A sphere phantom (2,360,034; GE Healthcare, Milwaukee, WI, USA) was repetitively scanned twice using various CS factors which range from 1.1 to 1.9 in steps of 0.1. The "difference method" was used for signal-to-noise ratio (SNR) determination. For each CS acceleration factor, a sum image that added two repeated identical acquisitions and a difference image that subtracted the two identical acquisitions were reconstructed. Circular regions of interest (ROI), range 1162.5–1358.2 mm^2, were placed at the center of the sum and the difference images. The SNR_{diff} was calculated as the ratio of the mean signal intensity value of the ROI in the sum image to the standard deviation (SD) of the signal intensity in the difference image, divided by the factor $\sqrt{2}$ [20].

The SNR as well as the SNR/scanning duration ratio increased as the CS acceleration factor increased (Supplemental Table 1). The ERF at the edge of the phantom decreased, corresponding to the increase in the CS factor. However, the ERF showed a peak at 1.5, and dropped after 1.5 (Supplemental Fig. 1). The optimal CS acceleration factor for high ERF and adequate SNR/scanning duration ratio was determined to be 1.5.

2.3. Magnetic resonance imaging protocol

All MR image acquisitions were performed using a 3T MR system (Discovery MR750®, GE Healthcare, Waukesha, WI, USA) with a dedicated 8-channel HD transmit/receive knee coil. Sagittal MR images using the conventional fat-suppressed intermediate-weighted isotropic 3D-FSE Cube sequence were acquired followed by a repeat acquisition using identical MR parameters but with CS, with an acceleration factor of 1.5. Undersampling of *k*-space data was achieved by undersampling in both *ky* and *kz* phase-encoding directions using 2D Gaussian distribution. Spatial finite differences were used for the sparsifying transform. The *k*-space data of both conventional and CS-3D-FSE sequences were processed by PI reconstruction using the Autocalibrating Reconstruction for Cartesian (ARC™, GE Healthcare; ARC acceleration