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Fast Comprehensive Single-Sequence Four-Dimensional Pediatric Knee MRI With T_2 Shuffling

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Abstract

Purpose: To develop and clinically evaluate a pediatric knee magnetic resonance imaging (MRI) technique based on volumetric fast spin-echo (3DFSE) and compare its diagnostic performance, image quality, and imaging time to that of a conventional 2D protocol.

Materials and Methods: A 3DFSE sequence was modified and combined with a compressed sensing-based reconstruction resolving multiple image contrasts, a technique termed T_2 Shuffling (T_2 Sh). With Institutional Review Board (IRB) approval, 28 consecutive children referred for 3T knee MRI prospectively underwent a standard clinical knee protocol followed by T_2 Sh. T_2 Sh performance was assessed by two readers blinded to diagnostic reports. Interpretive discrepancies were resolved by medical record chart review and consensus between the readers and an orthopedic surgeon. Image quality was evaluated by rating anatomic delineation, with 95% confidence interval. A Wilcoxon rank-sum test assessed the null hypothesis that T_2 Sh structure delineation compared to conventional 2D is unchanged. Intraclass correlation coefficients were calculated for interobserver agreement. Imaging time of the conventional protocol and T_2 Sh was compared.

Results: There was 81% and 87% concordance between T_2 Sh reports and diagnostic reports, respectively, for each reader. Upon consensus review, T_2 Sh had 93% sensitivity and 100% specificity compared to clinical reports for detection of clinically relevant findings. The 95%

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confidence interval of diagnostic or better rating was 95–100%, with 34–80% interobserver agreement. There was no significant difference in structure delineation between T_2 Sh and 2D, except for the retinaculum ($P < 0.05$), where 2D was preferred. Typical imaging time for T_2 Sh and the conventional exam was 7 and 13 minutes, respectively.

Conclusion: A single-sequence pediatric knee exam is feasible with T_2 Sh, providing multiplanar, reformattable 4D images.

Magnetic resonance imaging (MRI) is an important tool in pediatric imaging based on its ability to provide superior soft-tissue contrast and lack of ionizing radiation. However, the often lengthy exam times continue to be challenging for the pediatric population, compounded by other factors such as patient anxiety and discomfort.

Volumetric variants of fast spin-echo (FSE)¹ have been proposed to streamline and expedite joint MRI, based on potential reformattability into multiple planes.^{2–4} However, in clinical practice standard 2D imaging still predominates,⁵ largely due to blurring artifacts in the volumetric images. This is likely due to long echo trains required for scan efficiency of volumetric imaging, which leads to image blurring due to T_2 decay.¹ This work evaluates a redesigned volumetric FSE acquisition⁶ that randomizes echo train view orderings and resamples positions in k -space at multiple echo times to compensate for T_2 decay, thereby reducing blurring. This roughly 7-minute acquisition effectively supports a four-dimensional reconstruction, producing images corresponding to each echo time within the echo train, and thus with image contrast varying from proton density (PD) to heavy T_2 weighting. Therefore, a single acquisition can provide multiple sets of sagittal images with isotropic resolution, which can be reformatted to axial, coronal, and arbitrary oblique planes. This technique, termed T_2 Shuffling (T_2 Sh), has the potential to considerably streamline joint MRI, which may be especially advantageous in pediatric imaging.⁷

Thus, the purpose of this study is to test the hypothesis that T_2 Sh can suffice as a single-sequence, rapid pediatric knee protocol with reduced imaging time.

Materials and Methods

T_2 Sh Technique

A volumetric fast spin-echo sequence with variable refocusing flip angles (CUBE) was modified to randomize the echo train view ordering and resample positions in k -space at multiple echo times. The revised acquisition requires a modified compressed sensing iterative reconstruction and results in sharp images at each echo time. The overall methodology is referred to as T_2 Shuffling (T_2 Sh) and shown in Fig. 1a.⁶

Data Acquisition

The echo train phase encode ordering was chosen such that at each echo time the sampling follows an undersampled variable density Poisson disc distribution, which is known to be suitable for compressed sensing and parallel imaging.⁸ An exception to the rule is the first two echoes, which are typically discarded in product sequences. The data in these echoes covered the central portion of k -space (18-by-18) and were used for parallel imaging

autocalibration of the ESPIRiT maps.⁹ Figure 1b shows the sampling patterns at each echo time, and their use for calibration and reconstruction. The echo train length (ETL) was set to 82 for the study.

Reconstruction

Prior to the study, a T_2 -map of an adult volunteer's knee was acquired and used to simulate a distribution of signal evolutions with variable refocusing flip angles using the Extended Phase Graph Algorithm.¹⁰ A basis representing the relaxation curves subspace was formed through principal component analysis.¹¹ A compressed sensing-based iterative reconstruction employing parallel imaging⁹ is performed on the subspace coefficient images by solving the following optimization problem:

$$\min_{\alpha} \frac{1}{2} \|y - E\Phi\|_2^2 + \lambda_1 \sum_r \|R_r(\alpha)\|_* + \lambda_2 \|\Psi\alpha\|_1$$

where α are the recovered subspace coefficient images, y are the acquired multichannel data, E is the forward operator containing the sampling pattern and coil sensitivities, and Φ is a matrix representing the basis functions spanning the subspace of the relaxation curves. Locally low rank regularization is used to exploit the spatiotemporal correlations within local patches of the image (full description available in Ref.⁶). L1-Wavelet regularization is also applied to enforce sparsity of the image coefficients in the Wavelet domain. After solving Eq. [1], the relaxation curve time series images (80 in total) are constructed by computing $x = \Phi\alpha$. The images depict the changing contrast of the signal relaxation curves, starting at PD weighting and progressing to full T_2 weighting contrast.

Implementation

The reconstruction was implemented in the C programming language using the Berkeley Advanced Reconstruction Toolbox.¹² The regularization parameters λ_1 and λ_2 were experimentally tuned and kept constant for all reconstructions. To reduce reconstruction time, a software coil compression¹³ was applied to compress the eight channels of data to six virtual channels. As the full reconstruction is computationally intensive, for the purpose of clinical workflow, an initial linear reconstruction with no regularization was solved and transmitted to the scanner console within 10 minutes to verify that the scan was successful. In order to manage diagnosis, only three of the 80 reconstructed images at effective echo times of 27 msec, 63 msec, and 98 msec were transmitted to the picture archiving and communication system (PACS). The reconstruction parameters are summarized in Table 1.

Patient Recruitment and MRI Protocol

This prospective study was approved by our Institutional Review Board and complied with the Health Insurance Portability and Accountability Act. The exclusion criterion was any clinical issue that required gadolinium-based contrast-enhanced imaging. Written informed consent/assent was obtained from all parents/subjects. Twenty-eight consecutive pediatric patients (mean age 14 years, 11 male, 17 female) satisfying the inclusion criterion of referral to our children's hospital for clinical knee MRI exams were recruited. Two patients had

requests for bilateral knee MRIs, resulting in 30 scans from May to August, 2015. Subjects underwent our institution's standard clinical knee MRI protocol followed by the T_2 Sh experimental sequence.

All scans were performed on a clinical 3T MRI scanner (MR750, GE Healthcare, Milwaukee, WI) with an 8-channel knee coil. T_2 Sh scan parameters include repetition time (TR) of 1400 msec, ETL of 82, bandwidth of 62.5 kHz, $16 \times 14.4 \times 14.4\text{cm}^3$ field of view (FOV), 288×288 matrix, 0.6mm isotropic resolution, 85% fat suppression efficiency, 240 sagittal source slices reconstructed to 472 slices, with total scan time of ~7 minutes.

Our institution's standard clinical 2D FSE knee protocol consists of coronal T_1 -weighted, sagittal PD, fat-suppressed axial PD, and fat-suppressed sagittal and coronal T_2 -weighted images. The scan parameters include 14 cm FOV, 2.5 mm slice thickness, and 0.5 mm slice gap. Other parameters vary by sequence and are summarized in Table 2. Scan and planning time for 2D sequences totaled ~20 minutes.

Image Analysis

The T_2 Sh images were reconstructed at three effective echo times corresponding to PD, intermediate, and T_2 -weighted contrasts and reviewed on a multiplanar reformat capable workstation (Osirix; Pixmeo, Geneva, Switzerland). Although the source images were acquired at 0.6 mm slice thickness in the sagittal plane, they were reviewed at a slice thickness format of 2.5 mm in sagittal, axial, and coronal planes in a similar fashion as the conventional 2D images. To evaluate the diagnostic performance of T_2 Sh, two radiologists (S.B. and S.V., 5 and 15 years' experience, respectively), blinded to both the clinical history as well as the 2D imaging, independently interpreted each case, forming a structured diagnostic report based solely on the T_2 Sh images. To avoid recall bias, this was performed prior to an image quality evaluation that is described next.

Each reader then independently evaluated T_2 Sh image quality. The quality of delineation of nine anatomic structures were rated on a five-point scale from nondiagnostic to outstanding quality, detailed in Table 3. Then T_2 Sh was compared to conventional 2D and the delineation of the nine anatomic structures, as well as the appearance of bone marrow and joint fluid at different contrasts, were rated on a relative scale (Table 3). To validate the apparent image contrast of the T_2 Sh images, for five cases signal intensities of muscle, cartilage, meniscus, bone marrow, and joint fluid were measured on T_2 Sh reconstructions at 10 effective echo times. Regions of interests were placed over the semimembranosus muscle, posterior articular cartilage of the medial femoral condyle, posterior horn of the medial meniscus, marrow space of the medial femoral condyle, and anterior joint fluid.

Statistical Analysis

Using the clinical diagnostic report based on conventional 2D sequences as the standard of reference, the sensitivity, specificity, and accuracy of the T_2 Sh structured reports were calculated based on the number of clinically relevant concordant findings. Clinically relevant findings included meniscal pathology, ligament and tendon injury, cartilage defect, focal bony and soft-tissue lesions, bone marrow edema/contusion, and intra-articular bodies. Findings present on both T_2 Sh structured reports and diagnostic reports were classified as

concordant. Findings present on diagnostic reports and not present on T_2 Sh structured reports were classified as false negatives. Findings detected on T_2 Sh but not identified in diagnostic reports were classified as false positives. The proportion of concordant findings between the T_2 Sh structured interpretations and diagnostic reports was calculated with 95% confidence interval (CI).

After this initial analysis, the two readers and an orthopedic surgeon (J.Y.) conducted a consensus review of both conventional 2D and T_2 Sh images as well as a chart review encompassing all orthopedic clinic notes, rheumatology clinic notes, orthopedic procedures, physical therapy clinic notes, and imaging exams. The rationale for consensus review was that diagnostic reports were imperfect as the sole reference standard, and as arthroscopy is less often implemented in the pediatric population than in adults,¹⁴ a consensus review would better establish a panel standard, as well as to determine the detection of pathologic findings on T_2 Sh images. The consensus data were used to recalculate sensitivity, specificity, accuracy, and 95% CI for concordance. 95% CI for proportion of diagnostic or better rating was calculated for T_2 Sh structure delineation. A Wilcoxon rank-sum test assessed the null hypothesis that the relative quality of T_2 Sh structure delineation compared to conventional 2D is unchanged. Intraclass correlation coefficients (ICCs) were calculated at a 5% significance level to evaluate interobserver agreement.

RESULTS

Of the 30 cases reviewed, there were 10 cases without relevant clinical findings. There were nine findings of meniscal abnormalities, including one case of discoid lateral meniscus and one of postsurgical partial meniscectomy. There were 10 instances of ligamentous or tendon abnormalities, three cartilage defects, five focal bone or soft-tissue lesions consisting of osteochondroma, osteonecrosis, soft-tissue nodule, two cases of osteochondral defects, three joint bodies, four joint effusions, and 13 cases with findings of posttraumatic bone marrow edema, contusion, or fracture. There were nine cases with more than one clinically relevant finding.

For reader 1, there was 81% (95% CI of 70–92%) concordance between T_2 Sh structured reports and diagnostic reports, with a sensitivity of 77%, specificity of 100%, and accuracy of 81%. For reader 2, there was 87% (95% CI of 78–96%) concordance, with a sensitivity of 84%, specificity of 91%, and accuracy of 85%.

There were 10 discrepancies between T_2 Sh structured reports and diagnostic reports by either reader and four discrepancies by both readers. On consensus review of the discrepancies, three discrepant findings, a lateral meniscus posterior horn tear, a focal patellar cartilage defect, and discoid lateral meniscus, were less well visualized on T_2 Sh compared to conventional 2D, even in retrospect. Of the remaining discrepancies, all missed findings were equally visualized on T_2 Sh and 2D sequences on consensus review. The discrepant findings and consensus results are detailed in Table 4. Four findings were missed by both readers: one case of medial retinaculum avulsion, one lateral meniscus posterior horn tear, and two cases of joint bodies. Of those missed findings, only the case of the lateral

meniscus tear was considered to be less delineated on T_2 Sh on review while the other three were equally delineated.

Figure 2 shows T_2 Sh and conventional 2D images of a medial retinaculum avulsion, which was not initially described in the T_2 Sh structured report, but seen with similar delineation on T_2 Sh and conventional 2D sequences. Figure 3 shows two cases of joint bodies not prospectively identified on T_2 Sh, but easily visualized upon consensus review. A subtle tear of the lateral meniscus is shown in Fig. 4. While this was not prospectively identified on the T_2 Sh structured report, it is apparent that this can be visualized to a similar degree on T_2 Sh and 2D images.

Figure 5 shows a tear of the posterior horn of the lateral meniscus that was not as well seen on the T_2 Sh sagittal source images compared to conventional 2D, due to difference in the prescribed axis of imaging—oriented to the magnet for T_2 Sh (thus oblique to the knee) and oriented to the knee on 2D FSE. In this case, the patient's leg was externally rotated. When the T_2 Sh sagittal images were reformatted relative to the orientation of the knee during the consensus review, the tear could be easily seen (Fig. 5c). A case of MCL injury was initially categorized as a false positive as it was identified on T_2 Sh but not described on the clinical diagnostic report. However, on consensus review, it was apparent that abnormal signal along the deep fibers of the MCL was present both on the T_2 Sh and 2D images, and thus likely a false negative of the diagnostic report. Using the consensus data, there was 94% concordance between T_2 Sh and conventional 2D (95% CI of 88–100%), with a sensitivity of 93%, specificity of 100%, and accuracy of 94%.

Figure 6a shows the distribution of T_2 Sh structure delineation ratings for both readers. Quality of delineation of the 9 anatomic structures was at least diagnostic in all cases for both readers (95% CI of a diagnostic or better rating is between 95–100%), except in one case where delineation of the medial collateral ligament (MCL), lateral collateral ligament (LCL), and retinaculum was limited (however, 95% CI is 90–100% for a diagnostic quality delineation for these three structures). The most frequent rating given for all anatomic structures was outstanding, 17–27 cases out of 30 for reader 1 and 22–28 out of 30 cases for reader 2. Interobserver agreement was moderate or strong (ICC 0.53–0.79) for all structures except for the posterior collateral ligament, medial meniscus, and cartilage, where there was fair agreement (ICC 0.33–0.43).

There was no significant difference in relative quality of structure delineation between T_2 Sh and conventional 2D except for the retinaculum (Wilcoxon rank-sum test, $P < 0.05$), where 2D was preferred for both readers. Figure 6b shows the spectrum of ratings for both readers, with the predominant score being that of no difference between T_2 Sh and conventional 2D. Additionally, while there is no statistically significant difference, the menisci may be delineated to better advantage on T_2 Sh, as shown in Fig. 7, where a radial tear of the lateral meniscus is more conspicuous in the axial plane with T_2 Sh compared to conventional 2D.

The change in signal intensity of joint fluid, bone marrow, cartilage, muscle, and meniscus over 10 effective echo time reconstructions ranging from PD to heavy T_2 -weighting is shown in Fig. 8, expressed as a percentage of the initial signal, with superimposed simulated

signal relaxation curves for meniscus and cartilage. The relative signal changes of the different tissue types are in close agreement with the expected contrast-equivalent effective echo times.¹⁰ The deviation between measured and simulated meniscus signal change on the later echoes is probably from magnitude operation on noise.

Additional examples of T_2 Sh are shown in the Supporting Information. Supporting Fig. 1 shows T_2 Sh and conventional 2D T_2 -weighted sagittal images of the knee. Subtle T_2 high signal along the inferior pole of the patella suggesting Sinding-Larsen Johansson syndrome, while not initially described on the T_2 Sh structured report, is equally seen on both sequences. Ghosting from popliteal artery pulsation artifact frequently seen on conventional 2D images is not present on T_2 Sh. Supporting Fig. 2 shows a discoid lateral meniscus that was not initially described by one reader on the T_2 Sh structured report, but is equally delineated on T_2 Sh and conventional 2D, and may be visualized to better advantage on the T_2 Sh axial reformatted images. Supporting Fig. 3 shows a complex lateral meniscus tear well delineated on T_2 Sh, reformattable in arbitrary planes to show the different components of the tear. Supporting Fig. 4 shows an osteochondral lesion of the lateral femoral condyle demonstrated on T_2 Sh and conventional 2D. Irregularity of the articular cartilage is well delineated on T_2 Sh and a small focus of adjacent subchondral bone marrow edema is seen equally well on T_2 Sh and conventional 2D. The same case is shown as movies in the sagittal source image, as well as coronal and axial reformats (Supporting Videos 1–3). Finally, in Supporting Videos 4 and 5 the four-dimensional nature of the image data is highlighted by showing reformats in various planes at arbitrary echo times.

Discussion

There have been many studies on the clinical implementation of volumetric FSE methods for knee imaging,^{2,15–17} including incorporating sparsity-based methods.¹⁸ Our work seeks to further improve image quality, with the additional capability to provide reconstructions at multiple effective echo times in one acquisition, suggesting the feasibility of a single-sequence pediatric knee MRI protocol based on a new technique called T_2 Shuffling. This technique accounts for T_2 decay during the long echo trains of volumetric fast spin-echo and thereby mitigates T_2 decay-related blurring that has historically limited adoption of the volumetric approach in joint imaging.

Our consensus data show high diagnostic accuracy for T_2 Sh. That most of the discrepancies on retrospective review were equally well seen on T_2 Sh and conventional 2D, as evidenced in the above figures, suggests that these are likely attributable to readers' experience levels with this approach to imaging and also highlights the value of clinical history and comparison studies. For example, one case of joint body had prior MRIs and radiographs showing this finding, which were not available to the blinded readers. Additionally, most of the discrepant findings were isolated to individual readers, with only four findings missed by both readers. This may also suggest that factors other than those related to the T_2 Sh technique and image quality have contributed to our assessment of diagnostic performance. Moreover, the pathologies that posed diagnostic challenges for T_2 Sh in our study, namely, lateral meniscus tears and intra-articular bodies, would benefit from interpretation with full clinical history and capability to reformat into oblique planes.^{19,20}

Nonetheless, there were a few discrepancies that were thought to be related to the T_2 Sh technique, although not necessarily due to deficiencies in image quality. A case of lateral meniscus tear was seen in retrospect on T_2 Sh but not as easily perceived compared to the conventional 2D images. This was felt to be due to external rotation of the patient's leg; as the T_2 Sh sequence is prescribed in a true sagittal plane, evaluation of the meniscus was limited compared to proper oblique prescription for the 2D images. This was confirmed by viewing T_2 Sh images in a sagittal plane relative to the knee, which clearly delineated the tear.

One case of patellar cartilage defect was less obviously seen on T_2 Sh compared to conventional 2D, in part due to the presence of a hemarthrosis, where the signal of cartilage matched the complex signal of the hemorrhagic joint fluid on T_2 Sh, decreasing the conspicuity of the cartilaginous defect. Lastly, a finding of discoid lateral meniscus was not prospectively noted on T_2 Sh by one reader. The MRI diagnosis of discoid meniscus is typically based on counting the number of standard sagittal 2D slices on which the body of the meniscus is visualized. However, when interpreting a volumetric sequence, this feature becomes less apparent due to the much increased number of slices. These examples illustrate some of the inherent differences of this volumetric sequence compared to conventional 2D and suggest a learning curve in interpreting these images.

Our results show that the image quality of T_2 Sh is not inferior to conventional 2D sequences, with high quality delineation of anatomic structures, even those which are primarily viewed on reformatted planes. The isolated case where delineation of the MCL, LCL, and retinaculum was limited on T_2 Sh was thought to be due to patient body habitus, for which T_2 Sh was not optimized, but compensated in conventional 2D FSE. The higher in-plane resolution of 2D imaging could also explain the discrepancy in image quality. However, other artifacts such as the commonly encountered popliteal artery pulsation artifact, which manifests as ghosting on 2D FSE, was reduced to mild localized blurring on T_2 Sh. While T_2 Sh yields an image quality that is comparable to 2D FSE, it does have a qualitatively different appearance due to its volumetric nature, and a period of acclimation can be expected. The isotropic nature of T_2 shuffling has a potential to be more advantageous in the evaluation of complex pathology where it can be reformatted in arbitrary planes and with high spatial resolution.

Our results demonstrate the potential for the application of T_2 Sh as a single-sequence comprehensive knee MRI protocol, with multiplanar reformattable images in PD, intermediate, and T_2 -weighted reconstructions. The prospect of a fast, single-sequence MRI protocol is especially well suited for pediatric imaging, improving the likelihood for high-quality scans and decreasing the need for sedation. Although the volumetric sequence is lengthier than any single 2D sequence, and hence there may be a higher chance of motion during the scan, motion artifacts did not appear to limit the images. Although we investigated the performance of a single fat-suppressed sequence in evaluating knee MRI exams, there may be a strong preference among some practitioners to obtain at least one nonfat-suppressed sequence. In our own practice, since the completion of our study, and based on our resulting confidence in the performance of T_2 Sh, we have fully implemented and reduced to clinical practice a rapid knee protocol consisting of a single nonfat-

suppressed 2D coronal T_1 scan (4 min) and T_2 Sh, which is with fat suppression. The total imaging time of the two-sequence protocol is ~11 minutes. We will evaluate this protocol for a period of time to gain further confidence prior to eliminating the 2D sequence.

One current limitation of the technique is the reconstruction time required, ~60 minutes for T_2 Sh, which does not permit image quality assurance prior to discharging a patient from the imaging suites. We have implemented a fast reconstruction of ~10 minutes to allow for quality assurance without significant impact on workflow. We note that since the completion of the study, we have introduced further technical improvements to reduce the reconstruction time to ~20 minutes, and are continuing to explore additional approaches to speed reconstruction. An additional consideration in the potential clinical implementation of T_2 Sh is the requirement of a PACS with an integrated capability to view volumetric data in arbitrary obliquities. Nevertheless, we have implemented an expanded clinical role for T_2 Sh as the sole acquisition for fat-suppressed axial, sagittal, and coronal PD and T_2 -weighted knee images and are broadening its role in our pediatric musculoskeletal MRI protocols.

An additional limitation of our study is that readers could not be blinded to the sequence, given its manifest volumetric nature. A second limitation is the small sample size in this pilot study. Additionally, our gold standard was necessarily imperfect due to the paucity of arthroscopic data.

In conclusion, we have shown that T_2 Shuffling in the clinical setting produces sharp, multicontrast images in a single acquisition, with similar diagnostic performance as conventional 2D FSE and noninferior image quality, and shows potential for realization of a single-sequence pediatric knee MRI.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIGURE 1:

(a) Overview of the T_2 Shuffling (T_2 Sh) method. The echo trains sample k -space phase encodes in a randomly ordered fashion, and a linear reconstruction leads to reduced image blur at the cost of noise-like incoherent artifacts. The artifacts are iteratively suppressed in a compressed sensing-based reconstruction, and the images are reconstructed at each effective echo time along the echo train. (b) The sampled phase encodes at each echo time. The first two echoes are used for ESPIRiT parallel imaging calibration. The remaining 80 echo times are reconstructed with T_2 Sh.

FIGURE 2:

A 15-year-old boy with medial retinaculum avulsion. (a) T_2 Sh proton density (PD) axial reformat and (b) T_2 Sh T_2 -weighted (T_2 W) coronal reformat MRI images of the knee show a medial retinaculum avulsion and adjacent bone marrow edema (arrows) with similar delineation compared to (c) conventional 2D fast spin-echo (FSE) fat-suppressed (FS) PD axial and (d) FS T_2 W coronal images.

FIGURE 3:

Two cases of intra-articular bodies of the knee in a 19-year-old boy and a 14-year-old girl.

(a) Case 1 shows a small joint body (arrows) in the inferolateral joint space with deep infrapatellar bursitis, shown on T_2 Sh (top row) in PD axial reformatted, intermediate coronal reformatted, and T_2 W sagittal source images (left to right), with similar delineation compared to conventional 2D FSE (bottom row) FS PD axial, FS T_2 W coronal, and FS T_2 W sagittal images (left to right). Metal artifact from ACL graft is noted in the distal femur. (b) Case 2 shows a joint body (arrowheads) in the superolateral joint space with complex signal joint effusion. There is similar delineation between T_2 Sh (top row) PD axial reformatted, intermediate sagittal source, and T_2 W coronal reformatted images (left to right), and conventional 2D FSE (bottom row) FS PD axial, FS T_2 W sagittal, and FS T_2 W coronal images (left to right).

FIGURE 4:

A 16-year-old girl with lateral meniscus tear. Subtle tear of the lateral meniscus (arrows) is seen equally on (a-c) T_2 Sh PD, intermediate, and T_2 W coronal reformatted images and (d) conventional 2D FSE FS T_2 W coronal knee MRI.

FIGURE 5:

Tear of the posterior horn of the lateral meniscus in a 15-year-old girl. Lateral meniscus tear (arrow) is well seen on (a) the 2D FSE FS T_2W sagittal image but not well visualized on (b) the T_2Sh T_2W sagittal source image at the same level, likely due to the orientation of the prescribed axis of image acquisition shown on the inset generated from the axial reformatted image of the same dataset. (c) Reformatted T_2Sh T_2W sagittal image reoriented relative to the knee (see c inset) shows the lateral meniscus tear (arrow).

FIGURE 6: Frequency of scores for each anatomic structure for (a) T_2 Sh structure delineation and (b) relative structure delineation between T_2 Sh and conventional 2D. Note the higher frequency of higher ratings in both instances. For (a), there were no cases with a rating of 1 (nondiagnostic); therefore, this category was not included.

FIGURE 7:

A 16-year-old girl with a radial tear of the lateral meniscus. (a-c) T_2 Sh T_2 W sagittal, intermediate coronal reformatted, and PD axial reformatted images with similar delineation of anatomic structures compared to (d-f) 2D FSE FS T_2 W sagittal, FS T_2 W coronal, and FS PD axial images. The radial tear of the lateral meniscus (arrows) is well visualized on the T_2 Sh PD axial reformatted image (c).

FIGURE 8: Measured signal decay across 10 effective echo times for joint fluid, bone marrow, cartilage, muscle, and meniscus with superimposed simulated signal decay for cartilage and meniscus.

TABLE 1.

T2 Shuffling (*T2Sh*) Reconstruction Parameters

	Full reconstruction	Initial reconstruction
Iterations	800	100
LLR Regularization Parameter	0.00065	—
LLR Block Size	8	—
L1-Wavelet Regularization Parameter	0.00021	—
Subspace Size	4	1
Approx. Reconstruction Time (min)	60	10

The reconstructions were performed on a dedicated machine with dual Intel Xeon E5–2600 CPUs and 128 GB RAM.

TABLE 2.

MRI Scan Parameters

	AX	PD	FS	COR	T2 FS	COR	T1	SAG	PD	SAG	T2 FS	T2 shuffling
TR (msec)	3000			3700		600		3000		3000		1400
TE (msec)	30			56		18		9		60		—
Echo spacing (msec)	—			—		—		—		—		5.7
Echo train length	6			8		3		8		6		82
Bandwidth (kHz)	50			41.6		50		41.6		31.25		62.5
Field of view (cm)	14			14		14		14		14		16
Matrix size	416×256			416×256		416×256		416×256		384×320		288×288
Slice thickness (mm)	2.5			2.5		2.5		2.5		2.5		0.6
Slice gap (mm)	0.5			0.5		0.5		0.5		0.5		50% overlap
Scan time (min)	2:30			4:00		2:30		2:00		2:30		7:00

TABLE 3.

Anatomic Structures Evaluated and Ratings Criteria

Structures evaluated
Anterior cruciate ligament (ACL)
Posterior cruciate ligament (PCL)
Medial meniscus
Lateral meniscus
Extensor mechanism
Medial collateral ligament (MCL)
Lateral collateral ligament (LCL)
Retinaculum
Cartilage
Fluid
Marrow
T2 shuffling structure delineation rating scale
1. Nondiagnostic—cannot see structure
2. Limited—can see structure but not evaluate for pathology
3. Diagnostic—can evaluate structure with some confidence
4. Good—can evaluate structure with high confidence
5. Outstanding—best quality of delineation
T2 shuffling and 2D comparison scale
-2- Conventional 2D more delineation
-1- Conventional 2D preferred
0. Same
1. T2 shuffling preferred
2. T2 shuffling more delineation

TABLE 4.

Discrepancies and consensus outcome

Discrepancy	Reader 1	Reader 2	Consensus outcome
Tibial plateau fracture	+		Similar delineation on T2Sh and 2D
MCL sprain (false positive)		+	Similar delineation on T2Sh and 2D
Medial retinaculum avulsion	+	+	Similar delineation on T2Sh and 2D (Fig. 2)
Patellar cartilage defect	+		Less well seen on T2Sh due to complex signal in hemorrhagic joint fluid
Medial retinaculum sprain		+	Similar delineation on T2Sh and 2D
Lateral meniscus posterior horn tear	+	+	Similar delineation on oblique sagittal reformats (Fig. 5)
Lateral meniscus central tear	+		Similar delineation on T2Sh and 2D (Fig. 4)
Post saucerization of lateral meniscus	+		Similar delineation on T2Sh and 2D
Infrapatellar ligament sprain		+	Similar delineation on T2Sh and 2D
Discoid lateral meniscus		+	Similar delineation but may be less obvious on T2Sh (Sup. Fig. 3)
Sinding-Larsen Johansson syndrome	+		Similar delineation on T2Sh and 2D (Sup. Fig. 1)
Joint bodies (3)	+++	++	Similar delineation on T2Sh and 2D (2 cases shown in Fig. 3)

⁺ indicates discrepancy by the reader.