Comparison of 1.5- and 3.0-T MR Imaging for Evaluating the Articular Cartilage of the Knee Joint[1]

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Purpose: To retrospectively compare the diagnostic performance of 1.5- and 3.0-T magnetic resonance (MR) imaging protocols for evaluating the articular cartilage of the knee joint in symptomatic patients.

Materials and Methods: This HIPAA-compliant study was performed with a waiver of informed consent from the institutional review board. The study group consisted of 200 symptomatic patients undergoing MR examination of the knee at 1.5 T (61 men, 39 women; mean age, 38.9 years) or 3.0 T (52 men, 48 women; mean age, 39.1 years), who also underwent subsequent arthroscopic knee surgery. All MR examinations consisted of multiplanar fast spin-echo sequences with similar tissue contrast at 1.5 and 3.0 T. All articular surfaces were graded at arthroscopy by using the Noyes classification system. Three musculoskeletal radiologists retrospectively and independently graded all articular surfaces seen at MR imaging by using a similar classification system. The sensitivity, specificity, and accuracy of the 1.5- and 3.0-T MR protocols for detecting cartilage lesions were determined by using arthroscopy as the reference standard. The *z* test was used to compare sensitivity, specificity, and accuracy values at 1.5 and 3.0 T.

Results: For all readers combined, the respective sensitivity, specificity, and accuracy of MR imaging for detecting cartilage lesions were 69.3%, 78.0%, and 74.5% at 1.5 T ($n = 241$) and 70.5%, 85.9%, and 80.1% at 3.0 T ($n = 226$). The MR imaging protocol had significantly higher specificity and accuracy ($P < .05$) but not higher sensitivity ($P = .73$) for detecting cartilage lesions at 3.0 T than at 1.5 T.

Conclusion: A 3.0-T MR protocol has improved diagnostic performance for evaluating the articular cartilage of the knee joint in symptomatic patients when compared with a 1.5-T protocol.

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Accurate cartilage assessment in patients undergoing magnetic resonance (MR) imaging of the knee is clinically important. With promising new treatment options available for patients with osteoarthritis and posttraumatic cartilage defects, there is an increasing need for the detection of early morphologic changes in articular cartilage (1–4). Identifying focal and diffuse cartilage loss can also explain the etiology of joint pain in many symptomatic patients and is an important prognostic factor for determining the long-term success of anterior cruciate ligament and meniscal surgery (5–7).

The main limitation of current MR protocols for evaluating the articular cartilage of the knee joint is their inability to identify early cartilage degeneration and superficial posttraumatic cartilage defects, which may progress to more advanced osteoarthritis (7–18). The low sensitivity of these protocols is primarily attributed to suboptimal spatial resolution (19). However, additional factors, such as partial volume averaging and inadequate tissue contrast, also play important roles in limiting their sensitivity (11,20,21).

The use of high–field-strength 3.0-T MR imaging systems is becoming widespread in clinical practice and has the potential to improve clinical cartilage imaging. These 3.0-T systems can produce images of articular cartilage with higher spatial resolution and thinner section thickness than can 1.5-T systems without sacrificing signal-to-noise ratio (SNR) or prolonging acquisition time. By using optimized protocols, 3.0-T systems can also create images with greater contrast-to-noise ratios (CNRs) between articular cartilage and adjacent joint structures (22,23).

Previous experimental studies comparing 1.5- and 3.0-T MR imaging systems for helping detect cartilage lesions in animal and human cadaver joints have shown an improved diagnostic performance of 3.0-T systems (22,24–27). However, no previous study has documented the advantages of 3.0-T systems for clinical cartilage imaging. Thus, this study was performed to retrospectively compare the diagnostic performance of 1.5- and 3.0-T MR protocols for evaluating the articular cartilage of the knee joint in symptomatic patients.

Advances in Knowledge

- We noted significantly higher specificity (78.0% at 1.5 T and 85.9% at 3.0 T) and accuracy (74.5% at 1.5 T and 80.1% at 3.0 T) but not higher sensitivity (69.3% at 1.5 T and 70.5% at 3.0 T) for detecting cartilage lesions in the knee joint at 3.0 T than at 1.5 T.
- We noted significantly higher agreement at 3.0 T ($\kappa = 0.566$) than at 1.5 T ($\kappa = 0.459$) between the cartilage grades assigned at arthroscopy and MR imaging.

Materials and Methods

Study Group

The retrospective study was performed in compliance with Health Insurance Portability and Accountability Act regulations, with approval from our institutional review board, and with a waiver of informed consent.

The study group comprised 100 symptomatic patients (mean age, 38.9 years; range, 16–63 years) that consisted of 61 men (mean age, 38.4 years; range, 17–63 years) and 39 women (mean age, 39.5; range, 16–60 years), who underwent MR of the knee at 1.5 T; and another 100 symptomatic patients (mean age, 39.1 years; range 15–65 years) that consisted of 52 men (mean age, 39.0 years; range, 16–65 years) and 48 women (mean age, 40.4 years; range, 15–64 years), who underwent MR examination of knee at 3.0 T, and also underwent subsequent arthroscopic knee surgery. The study group was selected by an author (R.K.) by using a database of clinical MR examinations of the knee performed at our institution between July 2006 and March 2007. The author selected the first 100 consecutive patients in the database evaluated at 1.5 and 3.0 T who underwent subsequent arthroscopic surgery. No patient was excluded from the study on the basis of any factor, including age, sex, history of prior knee surgery, severity of articular cartilage degeneration, or MR image quality.

Implication for Patient Care

- MR imaging at 3.0 T improves cartilage assessment in symptomatic patients.

MR Examinations

All 200 patients in the study group underwent MR examinations performed with either 1.5- or 3.0-T imagers (HDx; GE Healthcare Systems, Waukesha, Wis) by using eight-channel phased-array extremity coils (Precision TXRX Knee Array; In Vivo, Orlando, Fla). The decision on whether to evaluate a patient at 1.5 T or 3.0 T was made solely on the basis of imager availability and screening criteria, such as patient size and presence of ferromagnetic implanted devices not approved for use with 3.0-T imagers, and not subjective factors, such as the clinical indication of the MR examination, the patient's age or level of athletic activity, or the preference of the referring physician or radiologist. All patients were evaluated by using one of the following imaging protocols at our institution: *(a)* a frequency-selective fat-suppressed T2-weighted fast spin-echo sequence, *(b)* a coronal T1-weighted fast spin-echo sequence, *(c)* a coronal frequency-selective fat-suppressed intermediate-weighted fast spin-echo sequence, *(d)* a sagittal intermediate-weighted fast spin-echo sequence, or *(e)* a sagittal frequency-selective fat-suppressed T2-weighted fast spin-echo sequence. Table 1 compares the imaging

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Abbreviations:
CNR = contrast-to-noise ratio
SNR = signal-to-noise ratio

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parameters of the sequences in the 1.5- and 3.0-T protocols.

The 1.5- and 3.0-T MR protocols used at our institution were developed by a fellowship-trained musculoskeletal radiologist (A.A.D.S., with >26 years clinical experience). The MR protocols were not optimized for cartilage imaging but were instead designed to provide comprehensive joint assessment in a clinically feasible 30-minute examination. Repetition time and echo time were chosen according to the manufacturer's recommendations to achieve T1- and T2-weighted contrast levels at 1.5 and 3.0 T. The increased SNR efficiency of the 3.0-T imager was used to increase spatial resolution and decrease section thickness when possible while maintaining adequate image quality. Imaging parameters were optimized by using multiple volunteers before the sequences were performed on clinical patients. The image quality and tissue contrast of each sequence in the MR protocols were subjectively assessed by all seven musculoskeletal radiologists at our institution (R.K., D.G.B., K.W.D., A.A.D.S., and three nonauthors) prior to their implementation in clinical practice.

Arthroscopic Knee Surgery

Arthroscopic knee surgery was performed in all 200 patients in the study group within 2 months (range, 3–59 days; mean, 19.1 days) of their MR examination. The indications for surgery were debridement or repair of a meniscal tear ($n = 117$), anterior cruciate ligament reconstruction ($n = 33$), anterior cruciate ligament reconstruction and debridement or repair of a meniscal tear ($n = 45$), or debridement of an articular cartilage lesion ($n = 5$). All arthroscopic knee surgery was performed by one of three experienced orthopedic surgeons (L.D.K. and two nonauthors, each with 8–20 years clinical experience in sports medicine). All articular surfaces of the knee joint were graded at arthroscopy by using the Noyes classification system (grade 0 =

Table 1

Comparison of Imaging Parameters for Sequences in 1.5- and 3.0-T MR Protocols

	Fast Spin-Echo Imaging Sequence									
	Axial T2 Weighted*		Coronal T1 Weighted		Coronal Intermediate Weighted*		Sagittal Intermediate Weighted		Sagittal T2 Weighted*	
Imaging Parameter	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T
Repetition time (msec)	4000	2200	550	1000	1000	2000	1888	2000	4000	5300
Echo time (msec)	80	80	20	20	40	30	15	20	80	80
Matrix size	256 × 224	448 × 224	256 × 224	384 × 224	256 × 224	384 × 224	256 × 224	384 × 224	256 × 192	384 × 224
Field of view (cm)	18	18	14	14	14	14	14	14	14	14
Section thickness (mm)	4	4	3	3	4	3	3	2	3	3
Voxel volume (mm^3)	2.24	1.28	1.03	0.68	1.38	0.68	1.03	0.45	1.20	0.70
Bandwidth (kHz)	20.8	41.7	20.8	41.7	20.8	41.7	31.2	31.2	20.8	41.7
Echo train length	15	21	4	6	6	8	4	4	10	20
No. of signals acquired	2	4	2	2	2	2	2	2	2	3
Imaging time (min)	2:11	3:20	2:28	1:54	2:35	1:56	4:38	3:26	2:48	3:16

* Fat-suppressed imaging.

Table 2

SNR Efficiency for MR Protocol Sequences

	SNR Efficiency					
	Cartilage		Synovial Fluid		Bone Marrow	
Fast Spin-Echo Imaging Sequence	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T
Axial T2 weighted*	3.6 ± 1.2	2.7 ± 0.4	32.1 ± 10.0†	22.6 ± 6.5†	3.0 ± 0.8	3.2 ± 0.7
Coronal T1 weighted	4.6 ± 1.6	4.4 ± 1.2	4.8 ± 1.2	5.4 ± 1.2	10.9 ± 3.5	12.1 ± 3.0
Coronal intermediate weighted*	5.3 ± 1.9	4.2 ± 1.8	10.5 ± 2.7	8.7 ± 2.4	2.2 ± 0.7	2.0 ± 0.5
Sagittal intermediate weighted	3.5 ± 0.9	3.6 ± 0.7	4.6 ± 1.4	4.9 ± 1.5	8.3 ± 2.6	9.0 ± 2.2
Sagittal T2 weighted*	1.8 ± 0.6	1.5 ± 0.4	12.0 ± 3.2	14.0 ± 4.9	1.8 ± 0.5	2.1 ± 0.8

Note.—Measurements were obtained from 10 patients with arthroscopically normal cartilage evaluated by using the 1.5-T protocol and from 10 patients with arthroscopically normal cartilage evaluated by using the 3.0-T protocol. Data are the mean ± standard deviation.

* Fat-suppressed imaging.

† Significant difference at $P < .05$.

normal, grade 1 = cartilage softening, grade 2A = superficial partial-thickness cartilage defect <50% of total articular surface thickness, grade 2B = deep partial-thickness cartilage defect >50% of total articular surface thickness, and grade 3 = full-thickness cartilage defect) (28). The orthopedic surgeons were aware of the MR imaging findings of all patients at the time of arthroscopy.

Image Analysis

Ten patients with arthroscopically normal cartilage imaged with the 1.5-T MR imaging protocol and 10 patients with arthroscopically normal cartilage imaged with the 3.0-T protocol were randomly chosen from the 200 patients in the study group. These 20 patients were selected by an author (R.K.) by using consecutive medical record numbers to minimize case selection bias. The SNR efficiency of articular cartilage, synovial fluid, and subchondral bone marrow and the CNR efficiency between articular cartilage and synovial fluid and subchondral bone marrow for each sequence in the MR protocols of these 20 patients were measured by using a previously described technique (29). SNR efficiency and CNR efficiency values were respectively calculated by using the following equations:

$$\text{SNR efficiency} = \frac{Signal \times 0.655}{\sigma_{background} \times \sqrt{scan\ time}};$$

$$\text{CNR efficiency} = \frac{|Signal_{tissue\ 1} - Signal_{tissue\ 2}| \times 0.655}{\sigma_{background} \times \sqrt{scan\ time}},$$

where the factor 0.655 in Equations 1 and 2 accounts for the fact that the SNR efficiency and CNR efficiency measurements were obtained by using magnitude images (30), and $\delta_{background}$ is the standard deviation of the background noise.

Review of MR Examinations

The MR examinations of all 200 patients in our study were retrospectively and independently reviewed by three fellowship-trained musculoskeletal radiologists (R.K., D.G.B., and K.W.D., with 6, 8, and 10 years clinical experience, respectively). The radiologists combined all sequences in the MR protocol to grade all articular surfaces of the knee joint by using a modified Noyes classification system (grade 0 = normal cartilage, grade 1 = increased T2 signal intensity of morphologically normal cartilage not oriented at 55° to the external magnetic field, grade 2A = superficial partial-thickness cartilage defect <50% of total articular surface thickness, grade 2B = deep partial-thickness cartilage defect >50% of total articular surface thickness, and grade 3 = full-thickness cartilage defect) (11,13,16). The radiologists were unaware of the surgical findings of each patient when reviewing their MR examinations.

Table 3

CNR Efficiency for MR Sequence Protocols

	CNR Efficiency Measurements			
	Cartilage-Fluid		Cartilage–Bone Marrow	
Fast Spin-Echo Sequence	1.5 T	3.0 T	1.5 T	3.0 T
Axial T2 weighted*	28.8 ± 9.4†	19.8 ± 6.5†	1.0 ± 0.8	0.6 ± 0.4
Coronal T1 weighted	0.4 ± 0.3†	1.3 ± 0.7†	6.3 ± 2.3	7.3 ± 2.4
Coronal intermediate weighted*	5.2 ± 1.1	4.5 ± 1.8	3.1 ± 1.3	2.2 ± 1.6
Sagittal intermediate weighted	1.2 ± 0.5	1.5 ± 1.2	4.8 ± 1.8	5.4 ± 1.9
Sagittal T2 weighted*	10.2 ± 2.7	12.5 ± 4.8	0.2 ± 0.2	0.7 ± 0.7

Note.—Measurements were obtained from 10 patients with arthroscopically normal cartilage evaluated by using the 1.5-T protocol and from 10 patients with arthroscopically normal cartilage evaluated by using the 3.0-T protocol. Data are the mean ± standard deviation.

* Fat-suppressed imaging.

† Significant difference at $P < .05$.

Statistical Analysis

All statistical analyses were performed by using software (R, version 2.3.1; R Foundation for Statistical Computing, Vienna, Austria). For all statistical tests, differences between the 1.5- and 3.0-T MR protocols were considered to be significant if the *P* value was less than .05.

The Fisher exact test was used to compare the proportion of men and women evaluated by using both imaging protocols. The two-sample *t* test was used to compare the mean age of all patients, the mean age of male patients, the mean age of female patients, and the mean interval between the MR examination and arthroscopic knee surgery for patients evaluated by using both imaging protocols.

The average SNR efficiency of articular cartilage, synovial fluid, and subchondral bone marrow and the average CNR efficiency between articular cartilage and synovial fluid and subchondral bone marrow were calculated for each sequence in both imaging protocols. The two-sampled *t* test was used to compare the SNR efficiency and CNR efficiency values for both protocols.

The distribution of the arthroscopic grades of cartilage lesions in the knee joint for patients evaluated by using both protocols was compared. The *t* test was used to compare the proportion of cartilage lesions of each grade on each articular surface of the knee joint for patients evaluated by using both protocols.

By using arthroscopy as the reference standard, the sensitivity, specificity, and accuracy of both imaging protocols for helping detect each grade of cartilage lesion in the knee joint were calculated and classified as either negative for disease (ie, grade 0) or positive for disease (ie, MR grades 1–4). Standard errors were calculated by using a bootstrapping method for patients to account for dependence within patients among the six articular surfaces and among the three readers. Given the standard errors, the *z* test was used to compare sensitivity, specificity, and accuracy of both protocols.

The κ statistic was used to measure

Table 4

Comparison of Distribution of Cartilage Lesions on Articular Knee Joint Surfaces

	No. of Cartilage Lesions on Each Articular Surface													
	Patella		Trochlea		Medial Femoral Condyle		Lateral Femoral Condyle		Medial Tibial Plateau		Lateral Tibial Plateau		All Surfaces	
Cartilage Grade	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T
0	46	45	62	66	45	47	75	79	73	75	58	62	359	374
1	2	1	0	0	5	3	0	4	3	0	4	4	14	12
2A	14	14	15	13	16	18	14	11	12	13	16	14	87	83
2B	33	35	19	16	27	28	10	4	12	10	20	18	121	111
3	5	5	4	5	7	4	1	2	0	2	2	2	19	20

interobserver agreement for determining the presence of cartilage lesions by using both protocols when both normal and abnormal articular cartilage were seen at arthroscopy. Interobserver agreement was assessed, according to the recommendations of Landis and Koch (31), as follows: $\kappa = 0–0.20$ indicates slight agreement; $\kappa = 0.21–0.40$, fair agreement, $\kappa = 0.41–0.60$, moderate agreement; $\kappa = 0.61–0.80$, substantial agreement; $\kappa = 0.81$ to less than 1.00, almost perfect agreement; and $\kappa = 1.00$, perfect agreement. Standard error was calculated by using a bootstrapping method for patients to account for dependence within patients among the six articular surfaces and among the three readers. Interobserver agreement was considered to be significantly positive if the ratio of κ value to standard error was greater than two. Given the standard errors, the z test was used to compare κ values for both protocols.

Weighted κ statistics were used to measure the degree of agreement between the grade assigned to each articular surface at arthroscopy and the grade assigned at MR imaging for both protocols (16). The proportions of cartilage lesions that were graded identically or within one grade of each other when seen at arthroscopy and at MR imaging were calculated for both protocols. The standard error was calculated by using a bootstrapping method for patients to account for dependence within patients among the six articular surfaces and among the three readers. Given the standard errors, the z test was used to compare differences in the weighted κ values and the proportion of correctly graded cartilage lesions for both protocols.

Figure 1

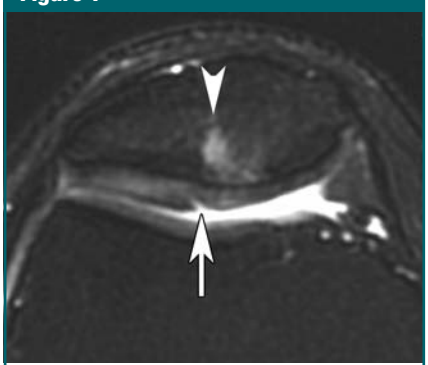


Figure 1: Axial 1.5-T MR image of knee in 43-year-old woman shows surgically confirmed grade 2A cartilage lesion on lateral facet of patella. Note small fluid-filled cartilage fissure (arrow) in lateral facet of patella; adjacent subchondral bone marrow edema (arrowhead).

Figure 2

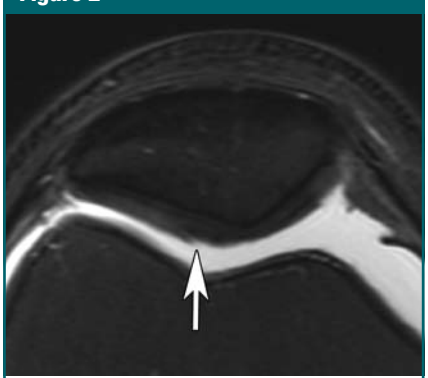


Figure 2: Axial 3.0-T MR image of knee in 31-year-old woman shows surgically confirmed grade 2A cartilage lesion on lateral facet of patella. Note small fluid-filled cartilage fissure (arrow) in lateral facet of patella.

Results

Comparison of Patients Evaluated by Using 1.5- and 3.0-T MR Protocols

There was no significant difference between patients evaluated by using both imaging protocols with regard to the proportion of men to women ($P = .29$), the mean age of all patients ($P = .71$), the mean age of the men ($P = .84$), the mean age of the women ($P = .82$), or the mean interval between the MR examination and arthroscopic surgery ($P = .55$).

Comparison of Image Quality of 1.5- and 3.0-T MR Protocols

The SNR efficiency of articular cartilage (range, 1.8–5.3 at 1.5 T and 1.5–4.4 at 3.0 T), synovial fluid (range, 4.6–32.1 at 1.5 T and 4.9–22.6 at 3.0 T), and subchondral bone marrow (range, 1.8–10.9 at 1.5 T and 2.0–12.1 at 3.0 T) was similar ($P = .07–.47$) for most sequences in both protocols despite the reduction in voxel volume for the 3.0-T sequences. However, there was a significantly higher SNR efficiency ($P < .05$) of synovial fluid for the axial fat-suppressed T2-weighted fast spin-echo sequence in the 1.5-T protocol (32.1 at 1.5 T and 22.6 at 3.0 T) (Table 2).

The CNR efficiency between articular cartilage and synovial fluid (range, 0.4–28.8 at 1.5 T and 1.3–19.8 at 3.0 T) and between articular cartilage and subchondral bone marrow (range, 0.2–6.3 at 1.5 T and 0.6–7.3 at 3.0 T) was similar ($P = .07–.47$) for most sequences in both pro-

tocols. However, there was significantly higher CNR efficiency between articular cartilage and synovial fluid for the axial fat-suppressed T2-weighted fast spin-echo sequence in the 1.5-T protocol (28.8 at 1.5 T and 19.8 at 3.0 T) and for the coronal T1-weighted fast spin-echo sequence in the 3.0-T protocol (0.4 at 1.5 T and 1.3 at 3.0 T) (Table 3).

Comparison of Diagnostic Performance of 1.5- and 3.0-T MR Imaging Systems

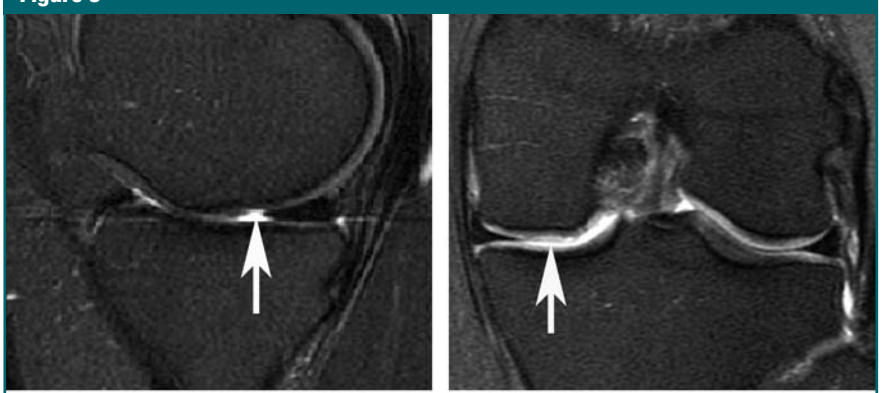
There was no significant difference (P = .201 to more than .999) in the proportion of cartilage lesions of each grade on each articular surface of the knee joint at arthroscopy for patients evaluated by using both imaging protocols (Table 4).

For all readers, the respective sensitivity, specificity, and accuracy for detecting all grades of cartilage lesions in the knee joint by using MR imaging was 69.3% (501 of 723), 78.0% (840 of 1077), and 74.5% (1341 of 1800) at 1.5 T and 70.5% (478 of 678), 85.9% (964 of 1122), and 80.1% (1442 of 1800) at 3.0 T (Figs 1–4). The respective sensitivity for detecting cartilage lesion grades 1, 2A, 2B, and 3 by using MR imaging was 40.5% (17 of 42), 50.2% (131 of 261), 82.4% (299 of 363), and 94.7% (54 of 57) at 1.5 T and 41.7% (15 of 36), 48.6% (121 of 249), 85.0% (283 of 333), and 98.3% (59 of 60) at 3.0 T. For all readers, there was no significant difference (P = .460–.871) in the sensitivity of both imaging protocols for helping detect each grade of cartilage lesions in the knee joint. However, the 3.0-T protocol had a significantly higher specificity and accuracy ($P < .05$) for helping detect all grades of cartilage lesions (Table 5).

There was fair interobserver agreement for determining the presence of cartilage lesions by using MR imaging when normal articular cartilage was seen at arthroscopy (κ = 0.250–0.299 at 1.5 T and κ = 0.260–0.322 at 3.0 T), and moderate interobserver agreement when abnormal articular cartilage was seen at arthroscopy (κ = 0.491–0.577 at 1.5 T and κ = 0.465–0.558 at 3.0 T. There was no significant difference (P = .171–.965) in interobserver agreement between the imaging protocols for determining the presence of cartilage lesions (Table 6).

The 3.0-T MR protocol had significantly higher agreement ($P < .05$) than did the 1.5-T protocol between the grades assigned at arthroscopy and at MR imaging (for all readers, κ = 0.459 at 1.5 T and κ = 0.566 at 3.0 T) (Table 7). The 3.0-T MR protocol also had a significantly higher ($P < .05$) proportion of cartilage lesions graded identically (28.1% at 1.5 T and 35.1% at 3.0 T for all readers) or within one grade of the arthroscopic grade (66.7% at 1.5 T and 71.1% at 3.0 T for all readers) (Table 8).

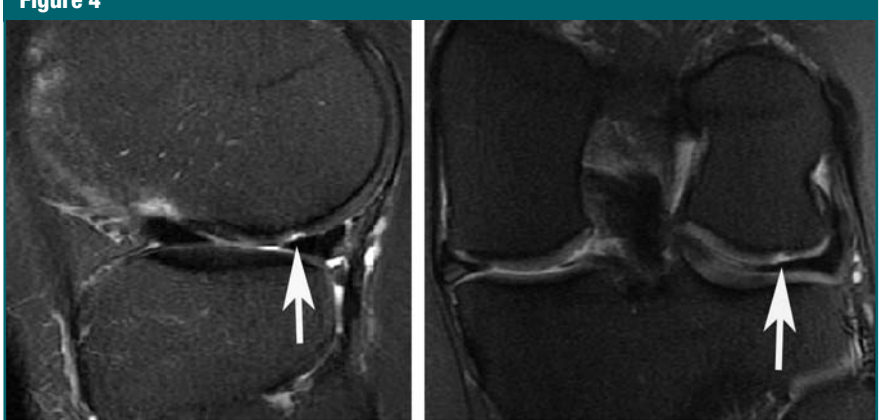
Figure 3



a. b.

Figure 3: **(a)** Sagittal and **(b)** coronal 1.5-T MR images of knee in 37-year-old man show surgically confirmed grade 2A cartilage lesion on medial femoral condyle. Note partial-thickness cartilage defect (arrow) in medial femoral condyle.

Figure 4



a. b.

Figure 4: **(a)** Sagittal and **(b)** coronal 3.0-T MR images of knee in 45-year-old man show surgically confirmed grade 2A cartilage lesion on lateral femoral condyle. Note partial-thickness cartilage defect (arrow) in lateral femoral condyle.

Discussion

Our study results showed that a 3.0-T MR imaging protocol does not have significantly higher sensitivity than a 1.5-T protocol for helping detect cartilage lesions in the knee joint in symptomatic patients. The results of our study disagree with the findings of previous experimental studies that used animal and human cadaver models (22,26). Masi et al (22) found that a fat-suppressed intermediate-weighted fast spin-echo

Table 5

Characteristics of MR Protocols for Detecting Grades of Cartilage Lesions in the Knee Joint

Reader and Cartilage Lesion Grade	Sensitivity		Specificity		Accuracy	
	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T
Reader 1						
1	57.1, 8/14 (17.7)	58.3, 7/12 (13.6)	54.9, 322/586 (3.6)	64.6, 380/588 (3.2)	55.0, 330/600 (3.5)	64.5, 387/600 (3.1)
2A	56.3, 49/87 (5.9)	47.0, 39/83 (6.6)	56.5, 290/513 (3.6)	66.0, 341/517 (3.2)	56.5, 339/600 (2.9)	63.3, 380/600 (2.8)
2B	86.8, 105/121 (4.4)	82.9, 92/111 (3.6)	65.1, 312/479 (3.3)	74.8, 366/489 (3.0)	69.5, 417/600 (2.5)	76.3, 458/600 (2.5)
3	89.5, 17/19 (6.8)	100.0, 20/20 (0.0)	56.1, 326/581 (3.5)	66.4, 385/580 (2.8)	57.2, 343/600 (2.8)	67.5, 1222/1800 (2.8)
All	74.3, 179/241 (4.1)	69.9, 158/226 (3.4)	74.1, 266/359 (3.0)	84.8, 317/374 (2.4)	74.2, 445/600 (2.2)	79.2, 475/600 (1.8)
Reader 2						
1	35.7, 5/14 (17.0)	41.7, 5/12 (13.7)	52.2, 306/586 (3.3)	60.5, 356/588 (3.2)	51.8, 311/600 (3.3)	60.2, 361/600 (3.1)
2A	55.2, 48/87 (5.7)	54.2, 45/83 (3.7)	53.8, 276/513 (3.4)	62.9, 325/517 (3.4)	54.0, 324/600 (2.8)	61.7, 370/600 (3.1)
2B	86.0, 104/121 (4.2)	83.8, 93/111 (2.8)	62.3, 298/479 (2.9)	70.6, 345/489 (2.9)	67.0, 402/600 (2.2)	73.0, 438/600 (2.4)
3	100.0, 19/19 (0.0)	95.0, 19/20 (5.1)	54.2, 315/581 (3.2)	62.4, 362/580 (3.1)	55.7, 334/600 (3.0)	63.5, 381/600 (2.9)
All	73.0, 176/241 (3.9)	71.7, 162/226 (3.7)	69.6, 250/359 (2.9)	79.9, 299/374 (2.6)	71.0, 426/600 (2.1)	76.8, 461/600 (2.0)
Reader 3						
1	28.6, 4/14 (12.1)	25.0, 3/12 (12.1)	69.8, 409/586 (3.1)	69.2, 407/588 (3.0)	68.8, 413/600 (3.1)	68.3, 410/600 (2.9)
2A	39.1, 34/87 (5.3)	44.6, 37/83 (6.0)	71.3, 366/513 (3.2)	71.6, 370/517 (3.0)	66.7, 400/600 (2.8)	67.8, 407/600 (2.7)
2B	74.4, 90/121 (5.1)	88.3, 98/111 (2.7)	81.0, 388/479 (2.4)	82.4, 403/489 (2.5)	79.7, 478/600 (2.1)	83.5, 501/600 (2.1)
3	94.7, 18/19 (4.5)	100.0, 20/20 (0.0)	71.9, 418/581 (3.0)	71.7, 416/580 (2.8)	72.7, 436/600 (2.9)	72.7, 436/600 (2.7)
All	60.6, 146/241 (3.9)	69.9, 158/226 (3.3)	90.3, 324/359 (1.8)	93.0, 348/374 (1.5)	78.3, 470/600 (1.9)	84.3, 506/600 (1.5)
All Readers						
1	40.5, 17/42 (12.5)	41.7, 15/36 (9.1)	59.0, 1037/1758 (3.1)	64.8, 1143/1764 (2.9)	58.6, 1054/1800 (3.1)	64.3, 1158/1800 (2.8)
2A	50.2, 131/261 (4.7)	48.6, 121/249 (5.3)	60.6, 932/1539 (3.2)	66.8, 1036/1551 (3.0)	59.1, 1063/1800 (2.6)	64.3, 1157/1800 (2.6)
2B	82.4, 299/363 (4.0)	85.0, 283/333 (2.8)	69.5, 998/1437 (2.6)	75.9, 1114/1467 (2.4)	72.1, 1297/1800 (2.0)	77.6, 1397/1800 (1.9)
3	94.7, 54/57 (3.4)	98.3, 59/60 (1.7)	60.8, 1059/1743 (3.0)	66.8, 1163/1740 (2.7)	61.8, 1113/1800 (2.8)	67.9, 1222/1800 (2.5)
All	69.3, 501/723 (3.4)	70.5, 478/678 (2.9)	78.0, 840/1077 (2.1)*	85.9, 964/1122 (1.6)*	74.5, 1341/1800 (1.6)*	80.1, 1442/1800 (1.4)*

Note.—Data are the mean, expressed as a percentage, followed by the numbers used to calculate the mean; numbers in parentheses are the standard error.

* Significant difference at $P < .05$.

Table 6

Interobserver Agreement for Determining Presence of Cartilage Lesions in the Knee Joint by Using MR

Articular Cartilage Seen at Arthroscopy	κ Value					
	Readers 1 and 2		Readers 1 and 3		Readers 2 and 3	
	1.5 T	3.0 T	1.5 T	3.0 T	1.5 T	3.0 T
Normal cartilage	0.299 (0.054)	0.322 (0.058)	0.290 (0.057)	0.294 (0.070)	0.250 (0.053)	0.260 (0.063)
Abnormal cartilage	0.540 (0.062)	0.551 (0.061)	0.491 (0.062)	0.558 (0.067)	0.577 (0.054)	0.465 (0.062)

Note.—Agreement determined when both normal and abnormal articular cartilage were seen at arthroscopy. Data are the mean; numbers in parentheses are the standard error. No significant difference at $P < .05$.

sequence had higher sensitivity at 3.0 T than at 1.5 T for detecting 29 artificially created cartilage lesions in porcine knee joints. In addition, Barr et al (26) found that a fat-suppressed intermediate-weighted fast spin-echo sequence had higher sensitivity at 3.0 T than at 1.5 T for detecting 14 cartilage lesions in human cadaver ankle joints. However, Fischbach et al (25) found that a fat-suppressed intermediate-weighted fast spin-echo sequence did not have higher sensitivity at 3.0 T than at 1.5 T for detecting 12 artificially created cartilage lesions in ovine knee joints.

The differences between our findings and the findings of Masi et al (22) and Barr et al (26) can partly be explained by differences in the MR protocols used in those studies. In our study, the sequences performed at 3.0 T had higher spatial resolution and, in some cases, decreased section thickness than those performed at 1.5 T. The reduction in voxel volume of the 3.0-T sequences resulted in a significant decrease in SNR efficiency and CNR efficiency values for only the axial fat-suppressed T2-weighted fast spin-echo sequence. The higher spatial resolution and decreased

section thickness of the 3.0-T sequences in our study did not improve the detection of cartilage lesions in the knee joint. However, the spatial resolution of the sequences in the 3.0-T protocol was well below the 0.15 × 0.15–mm resolution needed to help detect early morphologic changes in articular cartilage (19). Thus, it is not surprising that the higher spatial resolution of the 3.0-T sequences did not improve the detection of superficial cartilage lesions, while deep cartilage lesions were probably equally well visualized with the spatial resolutions of both imaging sequences.

In the studies performed by Masi et al (22) and Barr et al (26), the sequences performed during the 1.5- and 3.0-T examinations had identical spatial resolution and section thickness. Thus, the higher sensitivity of the 3.0-T sequences for helping detect cartilage lesions was most likely secondary to the superior SNR and CNR of the 3.0-T images. However, the superior SNR and CNR of 3.0-T images may improve the detection of cartilage lesions only when sequences with high spatial resolution and small section thickness are used. Link et al (24) compared the ability of high-resolution (spatial resolution, 0.19 × 0.26 mm; section thickness, 2 mm) and low-resolution (spatial resolution, 0.31 × 0.45 mm; section thickness, 3 mm) fat-suppressed intermediate-weighted fast spin-echo sequences performed at 1.5 and 3.0 T for detecting 84 artificially created cartilage lesions in porcine knee joints. The superior SNR and CNR of the 3.0-T images significantly ($P < .05$) improved the diagnostic performance of only the high-resolution sequences. However, with an acquisition time of almost 10 minutes, such a high-resolution sequence would be difficult to incorporate in MR protocols owing to time constraints and the high likelihood for patient motion artifact. Most MR protocols in clinical practice use sequences with spatial resolution and section thickness similar to the sequences used in our study and similar to the low-resolution sequence used in the study performed by Link et al (24).

Comparison of our study with previous studies raises questions about how the higher SNR efficiency of 3.0-T MR imaging systems should be used to improve the detection of cartilage lesions in patients undergoing MR imaging of the knee. Additional studies need to be performed to determine how interrelated variables such as spatial resolution, section thickness, SNR, and CNR between cartilage and adjacent joint structures should be optimized on 3.0-T systems to maximize cartilage lesion detection while maintaining clinically feasible imaging times.

In our study, the 1.5- and 3.0-T MR protocols had relatively low sensitivity for detecting superficial cartilage lesions in the knee joint. However, our sensitivity values for detecting cartilage lesions did fall within the range of previously reported values for fast spin-echo sequences (grade 1 = 12.5%–88.9% and grade 2A = 22.6%–95.0%) (11,13,16–18). Our study suggests that MR protocols, even when performed at 3.0 T, may be inadequate for evaluating patients with suspected cartilage abnormalities especially those for whom cartilage repair procedures are being considered. In these situations, intermediate- and T2-weighted fast spin-echo sequences optimized for cartilage imaging with higher spatial resolution, decreased section thickness, and longer acquisition times should be used for cartilage assessment. Incorporating dedicated cartilage imaging sequences, such as a fat-suppressed three-dimensional spoiled gradient-recalled acquisition, in the protocol may also improve the detection and characterization of cartilage lesions in this patient population.

Our study showed that a 3.0-T protocol has significantly higher specificity and accuracy than a 1.5-T protocol for detecting cartilage lesions in the knee joint in symptomatic patients. Two previous experimental studies that used animal and human cadaver models have compared the specificity of both imaging systems for helping detect cartilage lesions. Schroder et al (27) compared the specificity of fat-suppressed intermediate-weighted fast spin-echo and fat-suppressed two- and three-dimensional spoiled gradient-recalled acquisition sequences performed at 1.5 and 3.0 T for helping detect 12 artificially cre1ated cartilage lesions in ovine knee joints. The 3.0-T fat-suppressed three-dimensional spoiled gradient-recalled acquisition sequence had the highest specificity (95.6%), while the other sequences had specificity values that were inferior by no more than 2.5%. Barr

Table 7

Agreement between Grades Assigned to Articular Surfaces at Arthroscopy and at MR

	Weighted κ Value	
Reader	1.5 T	3.0 T
1	0.456 (0.035)	0.546 (0.035)
2	0.405 (0.033)	0.520 (0.033)
3	0.524 (0.035)	0.637 (0.035)
All	0.459 (0.024)	0.566 (0.023)

Note.—Data are the mean; numbers in parentheses are the standard error. Significant difference at $P < .05$.

Table 8

Proportion of Cartilage Lesion Grades Seen at MR and at Arthroscopy

	Cartilage Lesions (%)			
	MR and Arthroscopic Grades Identical		MR and Arthroscopic Grades within One Grade of Each Other	
Reader	1.5 T	3.0 T	1.5 T	3.0 T
1	28.2, 68/241 (0.3)	33.2, 75/226 (0.3)	69.7, 168/241 (0.4)	70.8, 160/226 (0.4)
2	27.8, 67/241 (0.3)	34.1, 77/226 (0.4)	68.5, 165/241 (0.4)	71.2, 161/226 (0.4)
3	28.2, 68/241 (0.4)	38.1, 86/226 (0.4)	61.8, 149/241 (0.4)	71.2, 161/226 (0.3)
All	28.1, 203/723 (0.2)	35.1, 238/678 (0.3)	66.7, 482/723 (0.3)	71.1, 482/678 (0.3)

Note.—Data are the mean, expressed as a percentage, followed by the numbers used to calculate the mean; numbers in parentheses are the standard error. Significant difference at $P < .05$.

et al (26) found no significant difference in the specificity of fat-suppressed intermediate-weighted fast spin-echo sequences performed at 1.5 and 3.0 T for helping detect 14 cartilage lesions in human cadaver ankle joints.

Our study showed that a 3.0-T protocol is significantly more accurate than a 1.5-T protocol for assigning a grade to articular surfaces and to cartilage lesions in the knee joint in symptomatic patients. Two previous experimental studies that used animal knee models have compared the ability of both imaging systems for determining the exact depth of cartilage lesions. Schroder et al (27) found that a fat-suppressed intermediate-weighted fast spin-echo sequence performed at 3.0 T did not provide superior determination of the exact depth of 12 artificially created cartilage lesions in ovine knee joints when compared with the same sequences performed at 1.5 T. However, in a larger study, Link et al (24) found that fat-suppressed intermediate-weighted fast spin-echo sequences provided superior determination of the exact depth of 84 artificially created cartilage lesions in porcine knee joints when performed at 3.0 T than when performed at 1.5 T.

In our study, there was no significant difference between the 1.5- and 3.0-T MR protocols in interobserver agreement for determining the presence of cartilage lesions in the knee joint. Unlike previous studies that reported a single κ value for interobserver agreement, we chose to report separate κ values for normal and abnormal articular cartilage seen at arthroscopy. This can partly explain why our κ values for interobserver agreement were lower than those reported in previous studies investigating fast spin-echo sequences for evaluating the articular cartilage of the knee joint (13,16). When a single κ value is used to measure interobserver agreement, high reader sensitivity and specificity naturally make the κ value high, which is a combined effect of high sensitivity and specificity and an association of misdiagnoses among readers. By reporting separate κ values for normal and abnormal articular cartilage seen at arthroscopy, we were able to separate these two effects and determine if there were similar misdiagnoses among readers regarding the presence of cartilage lesions.

Our study had several limitations; one was that the 1.5- and 3.0-T MR imaging protocols were performed in different patient populations. The proportion of cartilage lesions of each arthroscopic grade on each articular surface of the knee joint was similar for patients evaluated by using both protocols. However, the exact size and location of the cartilage lesions may have differed between the two patient populations which may have been a source of bias. Another limitation of our study was that both protocols were not optimized for evaluating articular cartilage and used sequences with different imaging parameters at 1.5 and 3.0 T . Furthermore, the MR protocols did not include dedicated cartilage imaging sequences, such as fat-suppressed three-dimensional spoiled gradient-recalled acquisition. Additional limitations of our study were its retrospective nature; selection bias, in that only patients with arthroscopic correlation were included in the study group; interpretation bias owing to inability to blind readers with regard to the MR protocol used for cartilage assessment; and the use of an imperfect reference standard in arthroscopy.

In conclusion, our study showed that a 3.0-T MR protocol has improved diagnostic performance for evaluating the articular cartilage of the knee joint in symptomatic patients when compared with a 1.5-T protocol. A 3.0-T protocol has higher specificity and accuracy but not higher sensitivity than a 1.5-T protocol for detecting cartilage lesions in the knee joint. A 3.0-T protocol also has greater accuracy for assigning a grade to articular surfaces and to grading cartilage lesions. However, a 3.0-T protocol does not have higher interobserver agreement than a 1.5-T protocol for determining the presence of cartilage lesions.

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