Assessment of Low-Grade Meniscal and Cartilage Damage of the Knee at 7 T: A Comparison to 3 T Imaging With Arthroscopic Correlation

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Received for publication November 26, 2017; and accepted for publication, after revision, January 17, 2018.

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Conflicts of interest and sources of funding: none declared.

Supplemental digital contents are available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal’s Web site (www.investigativeradiology.com).

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ISSN: 0020-9996/18/5307-0390
DOI: 10.1097/RLI.0000000000000456

ORIGINAL ARTICLE

Objectives: The aim of this study was to compare the assessment of low-grade meniscal tears and cartilage damage in ultrahigh-field magnetic resonance imaging (MRI) at 7 T to routine clinical MRI at 3 T.

Materials and Methods: This study was approved by the local ethics committee, and written informed consent was obtained from each patient. Forty-one patients with suspected meniscal damage or mild osteoarthritis (Kellgren-Lawrence score, 0–2) received 7 T as well as routine clinical 3 T consecutively. The imaging protocol at both field strengths consisted of PD-weighted imaging with more than doubled resolution at 7 T. Images were read blinded regarding field strength and patient characteristics by 3 readers with different experience in musculoskeletal MRI (3 years, 6 years, and 10 years) according to a modified whole-organ MRI score of the knee in osteoarthritis and the Score of the International Cartilage Repair Society. Arthroscopic reports as a criterion standard were available for 12 patients. A multifactorial mixed model analysis was performed.

Results: The mean cumulated diagnostic score at 7 T was significantly closer to the criterion standard compared with 3 T in patients where criterion standard was available (P<0.001). In all 41 patients, the damages were rated more severely at 7 T reflected by a mean higher cumulative score in cartilage (P<0.001) and in the meniscus (P<0.001). No difference in interreader variability between 3 T and 7 T was observed. Imaging acquisition time was nearly identical.

Conclusions: Morphologic imaging of cartilage and meniscal damage of the knee in ultrahigh-field MRI at 7 T with PD-weighted T2E sequences seemed to have a significantly higher diagnostic accuracy than 3 T and can be performed with equal acquisition times while exploiting higher resolution of 7 T.

Key Words: MRI, MSK, knee, ultrahigh-field imaging

Invest Radiol 2018;53: 390–396

The number of magnetic resonance imaging (MRI) examinations is growing constantly with an increasing variety of different MR scanners and different MRI techniques being developed and implemented all over the world including third world countries.1 Within the field of MRI, a clear trend toward higher field strengths can be observed with the aim of gaining higher spatial resolution, faster image acquisition, or new imaging techniques that rely on a high signal or field-strength–related contrast. Until recently (October 2017), ultrahigh-field (UHF) MRI at 7 T and above was only applied in research but not in clinical imaging. Besides the impressive technical and scientific progress that has been realized with UHF imaging along with good patient comfort,2–4 there is still a strong need to evaluate whether this progress can be translated into substantial benefits for patients in a clinical setting compared with imaging with lower field strengths—especially regarding the increased efforts to install, operate, and maintain an UHF system.

Clinical evaluation of UHF-MRI potential has already showed some promising results mainly in the field of neuroradiologic imaging5–8 but also to some extent in musculoskeletal imaging, where the focus mainly lies on functional imaging techniques such as compositional cartilage imaging.9–12 Nevertheless, UHF-MRI also promises better conditions for morphologic imaging that should not be underestimated and need to be evaluated among other fields in musculoskeletal radiology.13,14

The aim of this study was to compare the assessment of low-grade cartilage and meniscal damage of the knee in UHF-MRI at 7 T to that of clinical routine MRI at 3 T using arthroscopy as a criterion standard in a subset of patients.
of MRI according to the clinical grading system of the International Cartilage Repair Society (ICRS) and meniscal lesions according to the same score that we used in MRI (see below). All arthroscopy findings were graded by C.S.

MR Scanners, RF Coils, and Imaging Protocols
Images were obtained with a Philips 3 T Scanner (Achieva, Philips, the Netherlands) with a standard 8-channel knee coil (Invivo, Gainesville, FL) and with a whole-body 7 T Scanner (Siemens Healthineers, Erlangen, Germany) employing a 28-channel receive knee coil with a local CP transmit coil (Quality Electrodynamics, Mayfield Village, OH).

The imaging protocol at both field strengths consisted of a vendor-provided but adapted PD-weighted fat saturated turbo spin echo (TSE) sequence with approximately twice the resolution at 7 T. The sequence is similar to comparable UHF sequences published in the literature by various musculoskeletal imaging groups that have shown these sequences to be feasible with higher signal-to-noise-ratio(s) than in clinical routine 3 T imaging. Detailed image acquisition parameters are given in Table 1.

Assessment of Cartilage and Meniscal Damage
Images were read blinded regarding field strength and patient characteristics in a randomized order of the examinations by 3 readers with different experience in musculoskeletal MRI (3 years, 6 years, and 10 years) (S.P., B.F., and F.F.).

For cartilage reading, the knee was divided into 14 regions according to the whole-organ MRI score of the knee in osteoarthritis (WORMS), and every single lesion was graded separately depending on the severity of the lesion according to the grading system of the ICRS. In situ delaminations of cartilage were not assessed in this study.

For meniscal reading, the menisci were divided into 6 regions according to a modified WORMS. Every single lesion was graded separately depending on the severity of the lesion as degenerative changes, simple tears, complex tears (more than one orientation in space), and dislocated tears and/or volume loss (Fig. 2).

In addition, for every region in cartilage as well as in the menisci, a diagnostic confidence score from 1 (very insecure) to 5 (very sure) was obtained regardless whether a lesion was found to be present or not.

Finally, subjective image quality including imaging artifacts had to be rated by all 3 readers on a 5-point scale from 1 (very bad) to 5 (excellent).

Statistical Analysis
To avoid unnecessary multiple testing, considering the 12 or 6 different locations in cartilage and meniscus, respectively, in separate analyses, we decided to carry out a summary analysis over all these locations. The different locations in the same patient cannot necessarily be considered as independent observations; we added the scores over the different locations per patient in the analysis with all 41 patients. Analogously, we added the absolute differences between the MRI assessments and criterion standard assessment over the different locations in the 12 patients with available arthroscopy. These summary constructs were then considered as dependent variables in the mixed model analyses. In addition, we conducted the same calculations for every single

### TABLE 1. Imaging Acquisition Parameters of the Used MR Sequences

<table>
<thead>
<tr>
<th>Seq.</th>
<th>TR, ms</th>
<th>TE, ms</th>
<th>Flip</th>
<th>FS</th>
<th>Parallel</th>
<th>ETL</th>
<th>ES, ms</th>
<th>Phase</th>
<th>NEX</th>
<th>BW, Hz</th>
<th>FOV, mm</th>
<th>Matrix, mm × mm</th>
<th>Voxel, mm × mm</th>
<th>No.</th>
<th>Slices</th>
<th>Time, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 T</td>
<td>PD-TSE</td>
<td>5961</td>
<td>30.0</td>
<td>90°</td>
<td>SPAIR</td>
<td>2</td>
<td>15</td>
<td>9.5</td>
<td>2</td>
<td>178.1</td>
<td>160 × 160</td>
<td>420 × 300</td>
<td>0.38 × 0.53 × 2</td>
<td>45</td>
<td>04:10</td>
<td></td>
</tr>
<tr>
<td>7 T</td>
<td>PD-TSE</td>
<td>4400</td>
<td>26.0</td>
<td>150°</td>
<td>CHESS</td>
<td>2</td>
<td>5</td>
<td>12.8</td>
<td>1</td>
<td>222</td>
<td>120 × 120</td>
<td>480 × 456</td>
<td>0.3 × 0.3 × 2</td>
<td>38</td>
<td>04:30</td>
<td></td>
</tr>
</tbody>
</table>

TR indicates time of repetition; TE, echo time; Flip, flip angle; FS, fat saturation; Parallel, parallel Imaging factor; ETL, echo train length; ES, echo spacing; Phase, phase encoding direction; NEX, number of excitations; BW, bandwidth; FOV, field of view; Time, acquisition time.
RESULTS

Mixed Model Analysis of Grading Results

In the mixed model analysis of all 41 patients, field strength as a factor was highly significant ($P < 0.001$) in the diagnosis of cartilage damages as well as in the diagnosis of meniscal damages. The mean diagnostic cumulative score of all 41 patients averaged over all readers was 4.85 at 3 T and 9.15 at 7 T for cartilage lesions and 3.9 at 3 T and 4.59 at 7 T for meniscus lesions (Fig. 3). Every single region in cartilage (14 of 14) and in 4 of 6 regions (meniscus), the mean single region scores at 7 T were also significantly higher than those at 3 T (see Supplementary Material, Supplemental Digital Content 1, http://links.lww.com/RLI/A377).

Furthermore, field strength was also highly significant ($P < 0.001$) in the analysis of the mean absolute differences of the MR findings to arthroscopic observations in the 12 patients where arthroscopy was available revealing a mean absolute difference of the MR findings to arthroscopy in cartilage lesions at 3 T of 9.92 and at 7 T of 2.81 and in meniscus lesions of 2.19 at 3 T and 1.0 at 7 T (Fig. 4). In every region in cartilage (14 of 14) and in 2 of 6 regions (meniscus), the mean single region absolute differences to criterion standard at 7 T were also significantly lower than those at 3 T (see Supplementary Material, Supplemental Digital Content 1, http://links.lww.com/RLI/A377).

Moreover, field strength was also highly significant ($P < 0.001$) in the analysis of the absolute cumulative diagnostic scores in these 12 patients with a mean cumulative score of 4.58 at 3 T and 10.75 at 7 T in cartilage lesions. This indicates that 3 T as well as 7 T are generally underestimating cartilage damage but 7 T is underestimating damages significantly less. In meniscus lesions, the analysis of the cumulative scores of the 12 patients is less conclusive (mean score of 4.08 in arthroscopy, 4.61 at 3 T and 4.81 at 7 T ($P = 0.594$)).

Example images from 3 T and 7 T are shown in Figures 5, 6, and 7.

Reader as a factor was only significant in grading of meniscus lesion in the analysis of all 41 patients ($P = 0.005$). Nevertheless, an interaction effect of reader and field strength was observed in grading of cartilage lesions of all 41 patients ($P = 0.018$). This interaction effect indicates that the difference between the 3 T and 7 T assessment varied significantly among the 3 readers from 0.61 to 0.78 (Table 2).

Field strength did not influence diagnostic confidence scores as the mean diagnostic confidence score of all 3 readers was 4.45 at 3 T and 4.44 at 7 T (cartilage) and 4.72 at 3 T and 4.76 at 7 T (meniscus) revealing no significant difference between 3 T and 7 T (cartilage: $P = 0.954$; meniscus: $P = 0.241$).

![FIGURE 3. Mean diagnostic cumulative score of all 41 patients averaged over all readers in cartilage (A) and in meniscus (B). In the mixed model analysis of all 41 patients, field strength as a factor was highly significant ($P < 0.001$). In all 41 patients, damages were rated more severely at 7 T reflected by a mean higher cumulative score (all regions of 1 knee added) of 9.15 in cartilage damage (vs 4.85 in 3 T) and of 4.59 in meniscal damage (vs 3.9 in 3 T). Error bars represent 95% confidence interval.](http://www.investigativeradiology.com)
In total, averaged over all 3 readers and summarizing all WORMS regions of meniscus and cartilage (14 regions for cartilage, 6 regions for meniscus) in cartilage 3 T diagnosed 83.0% with no lesion, 7.0% with ICRS grade-1 lesions, 3.8% with ICRS grade-2 lesions, 4.6% with ICRS grade-3 lesions, and 1.5% with ICRS grade-4 lesion compared with 7 T with 60.0%, 26.2%, 4.9%, 6.6%, and 2.2%, respectively (Fig. 8). In meniscus, 3 T diagnosed 74.0% with no lesion, 6.5% with degenerative changes, 6.0% with simple tears, 7.9% complex tears, and 5.7% with dislocated tears compared with 7 T with 66.7%, 10.2%, 9.3%, 7.7%, and 6.2%, respectively (Fig. 8). These findings indicate that the biggest difference between 3 T and 7 T was observed in ICRS grades 0 and 1, implying that 7 T detected more ICRS grade 1 damages than 3 T (see Figs. 5, 6, and 7).

In the 12 patients where criterion standard was available, estimated sensitivities for the detection of cartilage damage was significantly higher at 7 T (92.3%) than at 3 T (88.6%) (P < 0.0001) as well as for the detection of meniscus damage (99.1% at 7 T vs 96.6% at 3 T) (P = 0.0065). No significant difference was found in the specificities between 3 T and 7 T in the detection of cartilage damage (99.5% in 7 T vs 96.6% in 3 T) (P = 0.0654) as well as in the detection of meniscus damage (91.4% in 7 T vs 95.2% in 3 T) (P = 0.1227).

Interreader Variability

There was no significant difference in interreader variability between 3 T and 7 T as the mean standard deviation over the 3 readers of all 41 patients at 3 T did not differ significantly from that at 7 T in cartilage lesions (P = 0.499) as well as in meniscus lesions (P = 0.850) with a mean standard deviation of all 3 readers of 1.21 at 3 T and of 1.35 at 7 T in cartilage lesions and of 0.87 at 3 T and of 0.83 at 7 T in meniscus lesions. Note that the standard deviation is based on the cumulative scores, that is, the sum of 14 or 6 regions for cartilage or meniscus, respectively.

The mean standard deviation of the confidence scores in meniscus lesions of the 3 readers of all 41 patients in 3 T did not differ significantly from the mean standard deviation of that in 7 T (P = 0.177) with a mean standard deviation of all 3 readers of 0.23 in 3 T and of 0.19 in 7 T.

The mean standard deviation of the confidence scores in cartilage lesions of the 3 readers of all 41 patients in 7 T was significantly lower (meaning higher diagnostic accuracy) than the mean standard deviation of that in 3 T (P < 0.001) with a mean standard deviation of all 3 readers of 0.18 in 7 T and of 0.38 in 3 T.

In the mixed model analysis of confidence scores, reader as a factor was significant in cartilage lesions (P = 0.007) as well as in...
meniscus lesions ($P = 0.028$) reflected by the highest mean confidence score in cartilage imaging of reader 3 (mean confidence score of 4.55), followed by reader 1 (4.43) and reader 2 (4.35) and in meniscus imaging by the highest mean confidence score of reader 3 (mean confidence score of 4.80), followed by reader 2 (4.72) and reader 1 (4.70). Confidence scores did not correlate with experience levels of the readers.

**Image Quality**

Subjective mean image quality averaged over all 3 readers including artifacts was judged with a mean score of 3.8 in 3 T and a mean score of 4.3 in 7 T on a 5-point scale from 1 (very bad) to 5 (excellent).

**DISCUSSION**

Despite the large potential of UHF-MRI in musculoskeletal imaging, protocols from 3 or 1.5 T cannot simply be transferred to 7 T without being adjusted substantially. After a thorough adaption process of all technical factors several studies in different centers since 2006 have shown, the capability of UHF MR at 7 T to perform high-resolution imaging of the ankle, wrist, and knee. Whereas those studies mainly focused on the feasibility and subjective image quality, further studies tried to quantify potential superiority of UHF-MRI by measuring SNR ratios or by implementing dedicated imaging sequences for cartilage imaging for instance. Another important step in bringing the benefits of UHF-MRI to practice was the development of dedicated coils with an increased sensitivity to exploit the higher SNR of UHF optimally. Finally, it still has to be explored that UHF-MRI can also bring substantial benefit to patients. So far, this has only been addressed in the study of Springer et al. and by the study of Stahl et al. The availability of arthroscopy with possible correlation to MR grading remains the biggest strength of this study although only available for 12 of 41 patients. The most important finding of this study is that in those 12 patients where arthroscopy was available the mean cartilage and meniscus gradings of every knee at 7 T were significantly closer to the criterion standard of arthroscopy than the findings at 3 T. Second, in a mixed model analysis of all 41 patients (adding patients with and without arthroscopy), field strength was a highly significant factor, revealing significantly higher grading scores for cartilage damage as well as for meniscal damage in 7 T than in 3 T. Combining these 2 results, presuming that there might be the same tendency in patients that did not receive arthroscopy than those that did receive arthroscopy, one may conclude that 7 T can diagnose cartilage and meniscal damages with a significantly higher accuracy.
the confidence scores in diagnosing cartilage defects depended on the diagnostic accuracy of the readers. Furthermore, the use of summary constructs over regions, as used in this study, can lead to counterbalancing effects of different regions (eg, two grade 1 lesions result in the same grading than one grade 2 lesion). This evaluation was chosen in this study to avoid the statistical problem of multiple testing, which would have arisen when considering
the single regions of the knee of 1 subject as independent observations. Another limitation is that this study only focused on cartilage and meniscal damage, whereas in clinical practice also other pathologies such as ligament injuries or the presence of bone marrow edema plays a crucial role. Finally, technical differences between scanners in field strength comparisons are difficult to be fully eliminated and may be larger than necessary in this study due to the use of scanners from different vendors. In conclusion, the results of this prospective in vivo study of MR cartilage and meniscus imaging indicates that morphologic imaging of the knee at 7 T provides superior diagnostic accuracy than at lower field strengths and that UHF-MRI of the knee with superior image quality and resolution is feasible with nearly identical image acquisition times compared with MRI at lower field strengths.

ACKNOWLEDGMENTS

The authors thank Frank Godenschweger, PhD, from the Department of Biomedical Magnetic Resonance from the Otto-von-Guericke University Magdeburg for his support.

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