Do Cartilage Repair Procedures Prevent Degenerative Meniscus Changes?

Longitudinal $T_{1\rho}$ and Morphological Evaluation With 3.0-T MRI

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Background: Cartilage repair (CR) procedures are widely accepted for treatment of isolated cartilage defects in the knee joint. However, it is not well known whether these procedures prevent degenerative joint disease.

Hypothesis: Cartilage repair procedures prevent accelerated qualitative and quantitative progression of meniscus degeneration in individuals with focal cartilage defects.

Study Design: Cohort study; Level of evidence, 2.

Methods: Ninety-four subjects were studied. Cartilage repair procedures were performed on 34 patients (osteochondral transplantation, n = 16; microfracture, n = 18); 34 controls were matched. An additional 13 patients received CR and anterior cruciate ligament (ACL) reconstruction (CR&ACL), and 13 patients received only ACL reconstruction. Magnetic resonance imaging at 3.0-tesla with $T_{1\rho}$ mapping and sagittal fat-saturated intermediate-weighted fast spin echo (FSE) sequences was performed to quantitatively and qualitatively analyze menisci (Whole-Organ Magnetic Resonance Imaging Score [WORMS] assessment). Patients in the CR and CR&ACL groups were examined 4 months (n = 34; n = 13), 1 year (n = 21; n = 8), and 2 years (n = 9; n = 5) after CR. Control subjects were scanned at baseline and after 1 and 2 years; ACL patients after 1 and 2 years.

Results: At baseline, global meniscus $T_{1\rho}$ values (mean ± SEM) were higher in individuals with CR (14.2 ± 0.5 ms; $P = .004$) and in individuals with CR&ACL (17.1 ± 0.9 ms; $P < .001$) when compared with controls (12.8 ± 0.6 ms). After 2 years, there was a statistical difference between $T_{1\rho}$ at the overlying meniscus above cartilage defects (16.4 ± 1.0 ms) and $T_{1\rho}$ of the subgroup of control knees without cartilage defects (12.1 ± 0.8 ms; $P < .001$) and a statistical trend to the CR group (13.3 ± 1.0 ms; $P = .09$). At baseline, 35% of subjects with CR showed morphological meniscus tears at the overlying meniscus; 10% of CR subjects showed an increase in the WORMS meniscus score within the first year, and none progressed in the second year. Control subjects with (without) cartilage defects showed meniscus tears in 30% (5%) at baseline; 38% (19%) increased within the first year, and 15% (10%) within the second year.

Conclusion: This study demonstrated more severe meniscus degeneration after CR surgery compared with controls. However, progression of $T_{1\rho}$ values was not observed from 1 to 2 years after surgery. These results suggest that CR may prevent degenerative meniscus changes.

Keywords: cartilage repair; meniscus; $T_{1\rho}$; WORMS; 3.0-T MRI

Articular cartilage defects have limited potential to regenerate and are associated with the early onset of osteoarthritis (OA).8 Over the past decade, cartilage repair (CR) has been increasingly used to treat focal cartilage defects of the knee.35 The most common technique is microfracture (Mfx), which is used for smaller lesions that do not affect the subchondral bone. For larger regions, besides autologous chondrocyte implantation, osteochondral transplantation (OCT) is the procedure of choice.41

Noninvasive magnetic resonance imaging (MRI) is the most important diagnostic tool for monitoring the postoperative course of these patients.43,44 The current standard in clinical practice is 1.5-T MRI of the knee,20,29 but evidence suggests that 3.0-T MRI may be more advantageous, yielding a stronger magnetic field strength, which allows for thinner sections, higher plane spatial resolution, and increased signal-to-noise ratio. In addition, 3.0-T MRI is more sensitive in diagnosing meniscus lesions, a known contributor to the early onset of OA.1,40
Quantitative $T_{1p}$ relaxation time measurements reflect early degenerative changes in the biochemical composition of cartilage, such as proteoglycan loss and increase in water content. It has recently also been applied to quantitatively and noninvasively detect meniscus degeneration. Although the exact factors that contribute to a higher meniscus $T_{1p}$ in subjects with OA and a lower meniscus $T_{1p}$ in healthy subjects are not yet clear, 1 study found a positive correlation between cartilage degeneration and increased $T_{1p}$ values in the meniscus.

Several studies have examined results after CR on a descriptive level. The challenge remains to demonstrate that CR can prevent joint degeneration beyond other methods by clinically validating imaging outcomes. A few studies have used 3.0-T MRI for follow-up, but little is known about meniscus degeneration as an outcome parameter after CR. However, evaluation of the effect of meniscus degeneration is crucial to ensure quality control and the development of future treatment guidelines in patients after CR.

As $T_{1p}$ relaxation time measurements of CR tissue have been described previously, the purpose of this study was to evaluate meniscus degeneration, as measured by morphological assessment and quantitative $T_{1p}$ meniscus measurements, at multiple longitudinal time points in patients who received CR surgery compared with controls. We hypothesized that patients who underwent CR would have higher meniscus $T_{1p}$ values, indicating more degenerative meniscus changes at baseline, but no further meniscus degeneration during follow-up.

MATERIALS AND METHODS

Subjects

Ninety-four subjects were analyzed in this study. Thirty-four subjects were treated with cartilage repair procedures (CR group) for isolated posttraumatic or degenerative full-thickness cartilage defects in the knee (graded III and IV according to the International Cartilage Repair Society [ICRS] classification). A control cohort (control group; $n = 34$) was recruited that was matched for sex and for Kellgren-Lawrence (KL) score. Thirteen additional subjects received CR as well as anterior cruciate ligament (ACL) reconstruction (CR&ACL group). A final additional 13 subjects received only ACL reconstruction (ACL group). The study was approved by the local Institutional Review Board and conducted in accordance with the Committee for Human Research at the University of California–San Francisco (UCSF). All subjects gave written informed consent before participation in the study. Data were prospective and nonrandomized.

Surgery

The indication for CR surgery was made in consultation with the patient and confirmed during arthroscopy of the affected knee joint. Exclusion criteria for CR procedures were as follows: uncontained large defects of several joint regions, significant degenerative changes of the affected joint (KL score $>2$), noncorrectable ligamentous instability, varus or valgus malalignment of $>5^\circ$, muscle loss, presence of inflammatory or metabolic disorders, obesity (body mass index $>30$ kg/m$^2$), and age $>55$ years. Additional exclusion criteria for this study were MR contraindications and retropatellar CR. None of the patients received CR at 2 sites, nor did any receive revision surgery during the observation period. The indication for ACL reconstruction was subacutecomplete ACL rupture by clinically diagnosed anterior-posterior laxity (Lachman grades 2 to 3) with confirmation by MRI.

All procedures were performed by a single surgeon (C.B.M.). Microfracture was used for smaller lesions ($<3$ cm$^2$). For mostly larger defects, patients received OCT. The cartilage defect area was debrided until its edges were completely surrounded by healthy cartilage. Microfracture surgery was performed during arthroscopy as previously described. The cartilage defects treated by OCT (using the Osteochondral Autograft Transfer System [OATS]; Arthrex Inc, Naples, Florida) were assessed arthroscopically and subsequently treated by an arthrolysis of the knee. Osteochondral grafts were harvested from the nonweight-bearing, nonarticulating intercondylar notch region of the trochlea of the same knee during surgery. A mean ($\pm$ SD) of $2.0 \pm 1.0$ transplanted cylinders was used. The ACL reconstruction was performed with single-bundle hamstring or patellar tendon graft. During the postoperative period, weightbearing was limited to 15 kg for 6 weeks (3 wk if only ACL reconstruction) and was gradually increased to reach full weightbearing after 8-12 weeks. Subjects underwent physical therapy to strengthen the joint during follow-up.

Imaging

Standard standing anteroposterior plain radiographs of the knee were obtained in all subjects at baseline. All subjects were scanned with a 3.0-T Signa HDx MR scanner (GE Healthcare, Milwaukee, Wisconsin) using an 8-channel phased array transmit/receive knee coil (Invivo, Orlando, Florida). For semiquantitative Whole-Organ Magnetic Resonance Imaging Score (WORMS) assessment, an intermediate-weighted fat-saturated fast spin echo (FSE) sequence (repetition time [TR]/echo time [TE] = 4300/51 ms, field of view [FOV] = 14 cm, matrix =

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512 × 256, slice thickness = 2.5 mm, gap = 0.5 mm) was used. Sagittal 3D T1w sequences were used to quantify the meniscus relaxation time. A spin-lock technique was followed by a spoiled gradient recalled (SPGR) acquisition using transient signals evolving toward steady state with the following parameters: repetition time/echo time (TR/TE) = 9.3/3.7 ms, time of recovery = 1500 ms, field of view (FOV) = 14 cm, matrix = 256 × 192, slice thickness = 3 mm, bandwidth = 31.25 kHz, views per segment = 48, time of spin-lock (TSL) = 0/10/40 ms, frequency of spin-lock (FSL) = 500 Hz. Parallel imaging with array spatial sensitivity technique (ASSET) was performed with an acceleration factor of 2.

Images were obtained at the clinically important time points of 4 months (4.0 ± 1.1 mo; 34/34 CR subjects: n = 16 OCT, n = 18 Mfx; 13/13 CR&ACL subjects: n = 2 OCT, n = 11 Mfx) and 1 year after CR (11.8 ± 2.8 mo; 21/34 CR subjects: n = 10 OCT, n = 11 Mfx; 8/13 CR&ACL subjects: n = 2 OCT, n = 6 Mfx). The MR studies were obtained 2 years (24.6 ± 1.2 mo) after surgery in 9 of 34 CR subjects (n = 5 OCT, n = 4 Mfx) and 5 of 13 CR&ACL subjects (n = 2 OCT, n = 3 Mfx). Control subjects without ACL reconstruction (n = 5 OCT, n = 4 Mfx) and 5 of 13 CR&ACL subjects (n = 2 OCT, n = 6 Mfx) were scanned 1 and 2 years after surgery (see the Appendix, available in the online version of this article at http://ajs.sagepub.com/supplemental/).

Image Analysis

Images were evaluated separately by 2 musculoskeletal radiologists (P.M.J., 4 y of experience; L.N., 6 y of experience); if scores were not identical, consensus reading by both radiologists and another independent radiologist (T.M.L., 22 y of experience) was performed. Images were reviewed on picture archiving communication system (PACS) workstations (Agfa, Ridgefield Park, New Jersey). Regarding plain knee radiographs, subjects with a KL score of more than 2 were excluded from CR surgery and from this study. A UCSF-modified WORMS system, as presented in Table 1, was used to assess morphological abnormalities. The medial and lateral menisci were separated into the following compartments: anterior horn, meniscus body, and posterior horn. For prevalence analysis, “no meniscus defect,” “simple tear,” and “complex tear” were differentiated. For progression analysis, any increase of entire meniscus WORMS score was considered as “progression.” Controls were divided into subjects with bone marrow lesions (BMLs) of the compartment with cartilage repair and those without morphological cartilage defect. Bone marrow lesions (BMLs) of the compartment with cartilage repair were graded according to the WORMS score and separated into BMLs ≤2 cm (WORMS score ≤2) and BMLs >2 cm (WORMS score 3).

The T1w sequences were transferred to a remote workstation (SPARC; Sun Microsystems, Mountain View, California) and analyzed by using software developed at our institution with an interactive display language (IDL; Research Systems, Boulder, Colorado) environment. Segmentation of the anterior and posterior horns of the medial and lateral meniscus in every section was performed by 1 radiologist and supervised by a senior radiologist.

### Table 1

Morphological Meniscus and Cartilage Grading and Definitions Based on WORMS Scoring

<table>
<thead>
<tr>
<th>Group</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Meniscus Grading</td>
<td></td>
</tr>
<tr>
<td>WORMS grade of meniscus parts</td>
<td></td>
</tr>
<tr>
<td>0 = normal meniscus</td>
<td></td>
</tr>
<tr>
<td>1 = intrasubstance abnormalities</td>
<td></td>
</tr>
<tr>
<td>2 = nondisplaced meniscus tear</td>
<td></td>
</tr>
<tr>
<td>3 = displaced or complex tear</td>
<td></td>
</tr>
<tr>
<td>4 = complete meniscus destruction/maceration</td>
<td></td>
</tr>
<tr>
<td>Total WORMS grade</td>
<td></td>
</tr>
<tr>
<td>0 = grade 0 in all meniscus parts</td>
<td></td>
</tr>
<tr>
<td>1 = no grade &gt;1 in any part</td>
<td></td>
</tr>
<tr>
<td>2 = grade 2 in 1 part</td>
<td></td>
</tr>
<tr>
<td>3 = grade 2 in &gt;1 part</td>
<td></td>
</tr>
<tr>
<td>4 = grade 3 in 1 or more parts</td>
<td></td>
</tr>
<tr>
<td>5 = grade 4 in 1 part</td>
<td></td>
</tr>
<tr>
<td>6 = grade 4 in &gt;1 part</td>
<td></td>
</tr>
<tr>
<td>Prevalence analysis</td>
<td></td>
</tr>
<tr>
<td>No meniscus tear</td>
<td>entire meniscus grade of ≤2 (no tear)</td>
</tr>
<tr>
<td>Simple meniscus tear</td>
<td>entire meniscus grade of 2 (nondisplaced tear)</td>
</tr>
<tr>
<td>Complex meniscus tear</td>
<td>entire meniscus grade of &gt;2 (complex tear)</td>
</tr>
<tr>
<td>Progression analysis</td>
<td></td>
</tr>
<tr>
<td>No progression</td>
<td>no increase of the entire meniscus grade over time</td>
</tr>
<tr>
<td>Progression</td>
<td>increase of the entire meniscus grade over time</td>
</tr>
</tbody>
</table>

| B. Cartilage Grading         |                                                                           |
| WORMS cartilage score        |                                                                           |
| 0 = no cartilage abnormality |                                                                           |
| 1 = intrasubstance cartilage abnormalities |                                                                           |
| >1 = morphological cartilage lesion with volume loss |                                                                           |
| Group                        |                                                                           |
| WORMS 0 or 1 = no cartilage defect |                                                                           |
| WORMS >1 = cartilage defect  |                                                                           |

*WORMS, Whole-Organ Magnetic Resonance Imaging Score.
*Anterior horn, posterior horn, and body of each meniscus was individually assessed.
*Medial and lateral meniscus were assessed separately.

Sagittal imaging precluded the meniscus body segmentation. The T1w images were reconstructed by fitting the T1w images pixel by pixel using a Levenberg Marquardt mono-exponential fitting algorithm developed in-house.

Reproducibility Measurements

Reproducibility was calculated in a randomly selected sample of 10 image datasets for each compartment. For WORMS measurements, each subregion of the images was graded twice, by 2 radiologists on 2 separate occasions. Linear weighted Cohen κ values were calculated. Interobserver κ was 0.89 for cartilage defects. Intraobserver κ was 0.91 and 0.95. For bone marrow abnormalities, interobserver κ was 0.80, and intraobserver κ was 0.81 and 0.87. Interobserver κ was 0.80 for meniscus defects. Intraobserver κ was 0.89 and 0.95. The mean coefficient of
of the mean (SEM) unless stated otherwise.

**Statistical Analysis**

Mean $T_{1p}$ values were calculated for both menisci and globally (mean of the value for medial and lateral menisci) from the segmented regions of interest. Statistical processing was performed with JMP software, version 9 (SAS Institute, Cary, North Carolina). Statistics were obtained applying multivariate regression models that adjusted in 1 model for KL score, sex, and age, by adding these variables as covariates for each of the analyses. For $T_{1p}$ value measurements, 1-way analysis of variance (ANOVA) and 2-way Student $t$ test were applied. For morphological analysis, the Mann-Whitney $U$ test was used. Results were considered as significantly different if $P < .05$. Values in the Results section are presented as mean ± standard error of the mean (SEM) unless stated otherwise.

**RESULTS**

**Subject Characteristics**

Of the 94 subjects in this study, 34 were treated with only CR (21 male, 13 female), 13 with CR and ACL reconstruction, and 13 with only ACL reconstruction. The CR group and control group ($n = 34$) were matched for sex and KL score (Table 2). Age was significantly different between the CR and the control group (mean ± SD, 35 ± 11 y vs 47 ± 11 y, respectively). Cartilage repair was performed 20 of 34 times at the medial femoral condyle, 10 of 34 times at the lateral femoral condyle, and 4 of 34 times at the trochlea (only Mfx). Screening controls for cartilage defects revealed that 13 of 34 control subjects had cartilage defects (medial, 7/34; lateral, 6/34) at baseline.

**Baseline Meniscus $T_{1p}$ Analysis**

At baseline, patients without surgery (control group) had the lowest $T_{1p}$ values (global $T_{1p}$: 12.8 ± 0.6 ms) (Table 3, Figure 1). Considering both menisci separately, the medial meniscus showed slightly higher values than the lateral meniscus in controls at baseline (13.1 ± 0.6 ms vs 12.5 ± 0.6 ms, $P = .07$). The CR group showed a significantly higher global $T_{1p}$ value of 14.2 ± 0.5 ms ($P < .001$) vs controls). The CR&ACL group showed the highest $T_{1p}$ values 4 months after surgery (17.1 ± 0.9 ms; $P < .001$ vs controls).

In comparing $T_{1p}$ values of the overlying meniscus above the cartilage repair regions with the overlying meniscus above untreated cartilage defect regions in the control subgroup without cartilage defects, no significant difference was detected at baseline (14.7 ± 0.7 ms vs 14.8 ± 0.9 ms) (Figure 2). However, differences with a statistical trend were found between the control subgroup with cartilage defects and the global meniscus $T_{1p}$ of the control subgroup without cartilage defects (12.5 ± 0.8 ms; $P = .06$), and a significant difference was found between the CR group and the control subgroup without cartilage defects ($P = .001$). In contrast, for each of the 4 separately segmented meniscus parts, the difference in $T_{1p}$ between the CR group and the control group was not significant at baseline because of different CR locations.

**Meniscus $T_{1p}$ at Follow-up**

Global meniscus $T_{1p}$ in the CR group did not increase in the first (14.1 ± 0.7 ms) or second year (13.2 ± 0.9 ms) after surgery (Figure 1). Global $T_{1p}$ values in the control group were stable during follow-up, 13.0 ± 0.6 ms after 1 year and 13.1 ± 0.6 ms after 2 years. The CR&ACL group did not show a further increase over time but still showed a significant difference from the control group after 2 years ($P = .04$).

In the subgroup of controls without cartilage defects ($n = 21$), global $T_{1p}$ values were stable over time, and there was no significant difference in $T_{1p}$ of the overlying

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**TABLE 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Overall</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients</td>
<td>94</td>
<td>34</td>
</tr>
<tr>
<td>Sex (male:female)</td>
<td>53:41</td>
<td>19:15</td>
</tr>
<tr>
<td>Age ± SD, y</td>
<td>40 ± 12</td>
<td>47 ± 11</td>
</tr>
<tr>
<td>Side (right:left)</td>
<td>56:38</td>
<td>20:14</td>
</tr>
<tr>
<td>KL score (0:1:2)</td>
<td>29:52:13</td>
<td>11:18:5</td>
</tr>
</tbody>
</table>

**TABLE 3**

<table>
<thead>
<tr>
<th>Surgery Type</th>
<th>$n$</th>
<th>Global $T_{1p}$, Mean ± SEM, ms</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No surgery</td>
<td>34</td>
<td>12.8 ± 0.6</td>
<td>.99</td>
</tr>
<tr>
<td>CR</td>
<td>34</td>
<td>14.2 ± 0.5</td>
<td>.004b</td>
</tr>
<tr>
<td>CR&amp;ACL</td>
<td>13</td>
<td>17.1 ± 0.9</td>
<td>&lt;.001b</td>
</tr>
</tbody>
</table>

*ACL, anterior cruciate ligament; CR, cartilage repair; KL, Kellgren-Lawrence; SD, standard deviation.

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variation (%), determined for $T_{1p}$ measurements of the meniscus in our laboratory, was 4.1%.5,53

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Study Group

<table>
<thead>
<tr>
<th></th>
<th>CR</th>
<th>ACL</th>
<th>ACL&amp;CR</th>
</tr>
</thead>
</table>
| Relapse in 20 of 34 times at the medial femoral condyle, and 4 of 34 times at the trochlea (only Mfx). Screening controls for cartilage defects revealed that 13 of 34 control subjects had cartilage defects (medial, 7/34; lateral, 6/34) at baseline.

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**Note:**

- **TABLE 2:** Epidemiological Data of the Analyzed Groups
- **TABLE 3:** Global Meniscus $T_{1p}$ Relaxation Time Values After CR and After ACL Reconstruction and CR Versus Without Surgery
- **Figure 1:** Global $T_{1p}$ values in the control group were stable during follow-up, 13.0 ± 0.6 ms after 1 year and 13.1 ± 0.6 ms after 2 years. The CR&ACL group did not show a further increase over time but still showed a significant difference from the control group after 2 years ($P = .04$).
- **Figure 2:** In the subgroup of controls without cartilage defects ($n = 21$), global $T_{1p}$ values were stable over time, and there was no significant difference in $T_{1p}$ of the overlying
meniscus above the cartilage repair region (n = 9) after 2 years (12.1 ± 0.8 ms vs 13.3 ± 1.0 ms; \( P = .11 \)) (Figure 2). However, there was a statistical trend toward a difference between \( T_1 \) of the overlying meniscus above the untreated cartilage defect (16.4 ± 1.0 ms) after 2 years (\( P = .09 \)) and a statistical difference between \( T_1 \) of the overlying meniscus above the untreated cartilage defect and global \( T_1 \) of the control subgroups without cartilage defects after 2 years (\( P < .001 \)).

Absolute \( T_1 \) progression was also calculated between the different time points and showed the same trend, but no statistically significant difference (\( P > .05 \)).

Comparison of Mfx and OCT in the CR Group

Subjects with Mfx (n = 18) showed higher \( T_1 \) at the overlying meniscus than OCT subjects (n = 16) (Figure 3). \( T_1 \) decreased at the 1- and 2-year time points in subjects with OCT. In subjects with Mfx, \( T_1 \) decreased only in the second year of follow-up. However, these results did not show any significant difference.

Correlation of Bone Marrow Lesions With Meniscus \( T_1 \)

At baseline, CR subjects with BMLs ≤2 cm (correlating with a WORMS score ≤2) showed slightly higher \( T_1 \) values at the overlying meniscus (15.5 ± 1.3 ms; 14/34) than CR subjects with BMLs >2 cm (14.1 ± 1.0 ms; 20/34; \( P = .09 \)). However, after 2 years, BMLs ≤2 cm (n = 4) were associated with lower \( T_1 \) values than BMLs >2 cm (n = 5; 12.1 ± 1.8 ms vs 14.5 ± 2.1 ms; \( P = .10 \)). Presence of large BMLs 1 year after CR was not significantly associated with meniscus \( T_1 \) after 2 years (\( P = .20 \)).

ACL Reconstruction

Patients with only ACL reconstruction (ACL group, n = 13) had a global meniscus \( T_1 \) value of 14.3 ± 0.8 ms 1 year after surgery (\( P = .03 \) vs control group). The medial meniscus showed lower \( T_1 \) values than the lateral meniscus (13.8 ± 0.8 ms vs 14.6 ± 0.8 ms, \( P = .20 \)). In patients with only ACL reconstruction, both the medial and lateral meniscus showed higher \( T_1 \) values at the 2-year follow-up time point compared with the 1-year time point (medial: 15.7 ± 1.0 ms; \( P = .03 \); lateral: 15.7 ± 0.9 ms; \( P > .05 \)). The absolute difference of the \( T_1 \) values between the 2 time points was higher in the medial meniscus. At the 2-year time point, global meniscus \( T_1 \) in the ACL group (n = 13) was significantly higher than in the CR group (n = 34; \( P = .009 \)).

Morphological Meniscus Lesions at Baseline

At baseline, 15% (5/34) and 20% (7/34) of the CR group had simple and complex morphological meniscus tears, respectively, at the overlying meniscus (Table 4 and Figure 4).
The control subgroup without cartilage defects (21/34) showed significantly fewer meniscus tears (0% [0/21] simple tears; 5% [1/21] complex tears; \( P = .001 \)). The control subgroup with untreated cartilage defects (13/34; 15% (2/13) simple tears; 15% (2/13) complex tears) showed no significant difference of meniscus tears compared to the CR group \( (P = .84) \), but significantly more meniscus tears than the control subgroup without cartilage defects \( (P = .006) \).

The control subgroup without cartilage defects (21/34) showed significantly fewer meniscus tears (0% [0/21] simple tears; 5% [1/21] complex tears; \( P = .001 \)). The control subgroup with untreated cartilage defects (13/34; 15% (2/13) simple tears; 15% (2/13) complex tears) showed no significant difference of meniscus tears compared to the CR group \( (P = .84) \), but significantly more meniscus tears than the control subgroup without cartilage defects \( (P = .006) \). The CR&ACL group showed more meniscus tears than all other groups (medial meniscus 92% [12/13]; lateral meniscus 69% [9/13]). Subjects in the ACL group (only ACL reconstruction) had medial meniscus tears in 35% (5/13) and lateral meniscus tears in 31% (4/13) at 1 year after surgery.

### Table 4
Incidence (in percentages) of Morphological Meniscus Defects in Different Groups

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>No Defect</th>
<th>Simple Tear</th>
<th>Complex Tear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartilage repair</td>
<td>34</td>
<td>65</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>No surgery (all controls)</td>
<td>34</td>
<td>85</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>Control subgroup with cartilage defects</td>
<td>13</td>
<td>70</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Control subgroup without cartilage defect</td>
<td>21</td>
<td>95</td>
<td>0</td>
<td>5</td>
</tr>
</tbody>
</table>

*In the cartilage repair group, the overlying meniscus above the cartilage repair region was analyzed. In the control subgroup with cartilage defect, the overlying meniscus above the defect was analyzed. In the control subgroup without cartilage defect, the meniscus with the higher Whole-Organ Magnetic Resonance Imaging Score (WORMS) was considered.

### Table 5
Morphological Meniscus Changes Measured by WORMS Scoring Between 2 Time Points

<table>
<thead>
<tr>
<th>Group; Time Points, y</th>
<th>n</th>
<th>Progression, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR; 0-1</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>CR; 1-2</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Control; 0-1</td>
<td>34</td>
<td>26</td>
</tr>
<tr>
<td>Control; 1-2</td>
<td>34</td>
<td>12</td>
</tr>
<tr>
<td>Control subgroup with defect; 0-1</td>
<td>13</td>
<td>38</td>
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<tr>
<td>Control subgroup with defect; 1-2</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Control subgroup without defect; 0-1</td>
<td>21</td>
<td>15</td>
</tr>
<tr>
<td>Control subgroup without defect; 1-2</td>
<td>21</td>
<td>10</td>
</tr>
</tbody>
</table>

*WORMS, Whole-Organ Magnetic Resonance Imaging Score; CR, cartilage repair.

*Percentage of subjects who showed an increase in the entire meniscus grading for the overlying meniscus above the cartilage repair region or the cartilage defect region, respectively. In controls without cartilage defect, any increase of either meniscus was considered as progression.

### Figure 4
Prevalence of morphological meniscus lesions. Green indicates no meniscus lesions; yellow, simple; and red, complex meniscus lesions. (A) Lesions at the overlying meniscus above cartilage repair regions in the cartilage repair group (CR) and above cartilage defects in the control subgroup with cartilage defect (Defect) were compared with the control subgroup without cartilage defect (No). (B) Lesions at the medial (MM) and lateral (LM) meniscus in the group with reconstruction of the anterior cruciate ligament (ACL; 1 y after surgery) and the group with combined CR and ACL surgery (CR&ACL), respectively.

### Figure 5
\( T_1 \rho \) color maps of the anterior and posterior horn of the medial meniscus of 1-y and 2-y follow-up time points, overlaid with the first-echo images. (A) Control subject with cartilage defect at the medial femoral condyle, who did not receive a cartilage repair (CR) procedure. (B) CR subject with osteochondral transplantation at the medial femoral condyle. Blue color indicates low, and red color indicates high meniscus \( T_1 \rho \) values. Subjects with untreated cartilage lesions showed a greater increase in \( T_1 \rho \) values over time compared with the subjects with CR.
Progression of Morphological Meniscus Lesions

Any increase in the entire WORMS score was considered as progression of morphological meniscus lesions (Table 5). During follow-up, 10% of the CR group (2/21) showed an increase at the overlying meniscus in the first postoperative year; none progressed in the second postoperative year (0/9). Within the subgroup of control subjects without cartilage defects, 19% (4/21) increased in the first and 10% (2/21) increased in the second year. Within the subgroup with untreated cartilage defects, 38% (5/13) increased in the first and 15% (2/13) increased in the second year. However, the differences between the groups were not significant (P > .05). In the CR&ACL group, 14% and 29% of subjects, respectively, showed an increase at the medial and lateral meniscus within the first postoperative year. Within the second year, 20% showed an increase at the medial and 20% at the lateral meniscus. An increase of morphological meniscus lesions was found in 19% of subjects with ACL surgery between the first and second postoperative year.

DISCUSSION

This longitudinal study analyzed meniscus degeneration as an outcome parameter after cartilage reconstruction procedures. Noninvasive MRI is used for monitoring the postoperative course of these patients to ensure quality control and development of future treatment guidelines. In this study, evaluation of the menisci was performed semiquantitatively by morphological analysis (WORMS) and quantitatively by meniscus $T_{1p}$ relaxation time measurements at several time points during a 2-year 3.0-T MRI follow-up. Four months after surgery, patients with CR and ACL reconstruction had a significantly higher meniscus $T_{1p}$ than controls, whereas $T_{1p}$ was the highest in subjects who received both surgeries. During follow-up, individuals with only ACL reconstruction and controls with cartilage defects showed a further increase in $T_{1p}$ values, whereas $T_{1p}$ values in CR subjects did not increase (Figure 5). In consideration of the methodological limitations, these findings suggest that individuals with CR surgery may benefit from this procedure, as it appears to prevent meniscus degeneration and potentially, the early onset of OA.

Apart from autologous chondrocyte implantation, $T_{1p}$ and OCT are 2 alternatively applied CR procedures. However, the outcome after these procedures with respect to prevention of further degenerative changes and early onset of OA of the knee is unclear. Most studies have evaluated clinical outcomes, and few have considered using MRI at follow-up. However, meniscus evaluation remains an important parameter with respect to evaluation of progression of early and advanced OA. In fact, previous studies have used meniscus evaluation to assess the risk of OA as an outcome after surgery, particularly ACL reconstruction. Evaluating the menisci, we confirmed previously reported findings that there are more simple and complex meniscus defects in individuals who have undergone ACL and CR surgery. Cartilage defects usually coincide with degeneration of the overlying meniscus, as confirmed in our study.
supports the presumption that a persisting BML is associated with outcome after CR.\textsuperscript{52} However, BMLs after 1 year did not predict 2-year meniscus T\textsubscript{1rho}.

Meniscus integrity is crucial for proper knee joint functioning and shock-absorption. An influence of meniscus lesions on further OA progression has been observed.\textsuperscript{53} Meniscus defects and OA have also been associated with higher and less homogeneous cartilage T\textsubscript{2} relaxation time values.\textsuperscript{15} Our study showed that patients with CR demonstrated improved meniscus T\textsubscript{1rho} values over time, which suggests that CR plays a role in halting OA progression as a postoperative outcome. In this context, in particular the findings regarding control subjects with and without morphological cartilage defects seem important. Subjects with untreated morphological cartilage defects had higher T\textsubscript{1rho} values at follow-up time points than at baseline, whereas controls without defects and CR subjects did not.

Meniscus T\textsubscript{1rho} in subjects with only ACL reconstruction (ACL group) increased over time. It is known that although the ACL is reconstructed, kinematics may not be completely restored. Anterior-posterior tibial translation is usually well restored, whereas rotational stability was observed to be still pathological after ACL reconstruction.\textsuperscript{13,46} Therefore, ACL-reconstructed subjects still suffer from increased degeneration of the knee, as detected by T\textsubscript{1rho} in our study. One year after surgery, particularly in the lateral meniscus, the ACL group showed higher T\textsubscript{1rho} values, which is consistent with previous T\textsubscript{1rho} findings,\textsuperscript{53} as well as clinical MR findings that result from the kissing bone bruise. However, during the second year after ACL reconstruction, T\textsubscript{1rho} values increased more at the medial meniscus than at the lateral meniscus, indicating a faster degeneration of the medial meniscus after ACL reconstruction, probably because of rotational instability.\textsuperscript{3} In control patients, the medial meniscus showed slightly higher T\textsubscript{1rho} values and more morphological meniscus lesions, which is consistent with prior studies.\textsuperscript{45} We found that patients with combined ACL and CR procedures showed the highest T\textsubscript{1rho} values, with slightly lower values at follow-up. This result supports previously reported findings of reasonable outcomes for combined surgery.\textsuperscript{7}

There are several limitations of the present study. First, not all patients came back for 1- and 2-year follow-up. The low rate of follow-up was the result of a young patient clientele with high mobility, who are leaving the area and are not able to attend for follow-up visits, as well as limited scan times at our institution and missing or not reaching the right follow-up time point. Second, age was significantly different between the groups; since age is known as 1 of the most important risk factors for OA, results were adjusted for this parameter. Third, hamstring and patellar tendon grafts (bone-tendon-bone, BTB) were not differentiated, since the focus of this study was on CR and the number of subjects in each group would have been too small for further analysis. In the ACL group, 9 patients received BTB grafts and 4 patients received hamstring grafts; in the CR&ACL group, 4 patients received BTB grafts and 9 patients received hamstring grafts. It may be interesting to evaluate the influence of different techniques in future studies. Fourth, results were not adjusted for lower limb alignment, which could potentially also slightly influence the results. However, subjects with an axis deviation >5° were excluded. Finally, only 1 clinical sequence was used, because of scan-time limitations.

CONCLUSION

In this study we used 3.0-T MRI meniscus T\textsubscript{1rho} relaxation time measurements along with morphological meniscus assessment in a cross-sectional, 2-year longitudinal analysis of individuals who underwent cartilage resurfacing procedures and compared the findings with normal controls. Meniscus T\textsubscript{1rho} values were higher in individuals with CR or cartilage defects at baseline compared with individuals without defects. Although T\textsubscript{1rho} did not increase at the follow-up time points in CR patients, increasing T\textsubscript{1rho} values were detected in patients with untreated cartilage defects or ACL reconstruction. Compared with controls, morphological meniscus defects showed a lower progression during the second year of follow-up after CR. These results suggest that patients with focal cartilage defects may benefit from cartilage repair procedures with regard to prevention of further meniscus matrix degeneration and consequently, prevention of early OA in the knee.

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