Intraoperative validation of quantitative T2 mapping in patients with articular cartilage lesions of the knee

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**Summary**

Objective: The aim of this study was to compare T2 relaxation times of knee cartilage with intraoperative results for the assessment of early osteoarthritis (OA) and to define T2 values for the differentiation between healthy and degenerated cartilage.

Design: Twenty-one patients with cartilage lesions or moderate OA were examined using 3T magnetic resonance imaging (MRI). In this prospective study, a total of 882 regions of interest (ROIs) were examined by a sagittal, multi-echo, spin-echo T2 sequence and a morphological high-resolution three-dimensional, fat-saturated proton-density space sequence. Cartilage lesions were identified arthroscopically, graded by the International Cartilage Repair Society (ICRS) score in 42 defined ROIs per patient and consecutively compared with mean T2 values using analysis of variance and Spearman’s rank correlation test. Receiver operating characteristics (ROC) curves were developed to identify threshold T2 values to differentiate between the ICRS grades.

Results: A total of 882 ROIs were examined and graded in ICRS score 0 (67.3%), 1 (25.2%), 2 (6.2%) and the merged ICRS 3 and 4 (1.0%). T2 values increased with increasing grade of cartilage damage with a statistically significant positive correlation between T2 values and ICRS scores. A T2 value threshold of 47.6 ms was identified to differentiate between ICRS score 0 (normal) and all other grades (ROC curve analysis).

Conclusion: T2 mapping might provide a diagnostic tool for the detection of early knee-joint cartilage damage and for the non-invasive differentiation between ICRS grades by MRI in clinical practice.

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**Introduction**

The knee joint is one of the regions of the body that is most commonly prone to injury during sports and everyday activities. Joint injuries frequently lead to cartilage degeneration, which ultimately results in osteoarthritis (OA). The most frequently associated articular injuries in one study population included medial meniscus lesions (37%) and anterior cruciate ligament rupture (36%). To ensure successful treatment outcomes, the detection and quantification of early-stage pathological changes to knee cartilage using sensitive, non-invasive diagnostic procedures are necessary. Standard morphological magnetic resonance imaging (MRI) has become the accepted diagnostic tool for non-invasive evaluation of cartilage lesions. Moreover, emerging techniques including T2 mapping, delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) and chemical exchange saturation transfer (CEST) can be used to visualize microstructural and biochemical changes to the cartilage matrix even before morphological damage is visible. These sensitive methods could provide robust biomarkers for disease onset and progression and may prove to be indispensable when it comes to assessing alterations to the cartilage matrix and monitoring the effectiveness of pharmacological or surgical therapy. Quantitative T2 mapping is the only biochemical-based MRI technique that is currently available for use in clinical routine. Its relaxation times are particularly responsive to changes in cartilage water content, collagen composition, and tissue anisotropy. T2 mapping is particularly advantageous compared to other MRI techniques due to its clinical applicability. Quantitative T2 mapping has been used for years especially for the...
assessment of cartilage repair procedures of the knee. However, the correlation of its results with intraoperative findings has not yet been extensively investigated. Comparing T2 and morphological MRI sequences, Apprich et al. showed that T2 values directly correlate with the defect score of the International Cartilage Repair Society (ICRS) score, particularly in grade 1 and 2 lesions. T2 mapping has the potential to identify various grades of cartilage damage. Nevertheless, it remains unclear whether quantitative T2 mapping is suitable for quantification of cartilage damage in clinical practice. Previous studies have not clearly defined the correlation between T2 values and clinical methods of grading osteoarthritis, particularly in terms of intraoperative validation.

The aim of this prospective study was to compare quantitative cartilage T2 measurements with arthroscopically determined ICRS scores and to evaluate the sensitivity of T2 mapping in the presence of various grades of cartilage degeneration.

Materials and methods

Patients

We selected our study population from a group of 69 subjects who either suffered from non-traumatic degenerative knee disorders or traumatic knee injury and were scheduled to undergo surgery by the same orthopedic surgeon at the same orthopedic medical center between October 2012 and January 2013. The indication for arthroscopy was defined on the basis of the results of clinical examination and diagnostic imaging. Thirty patients with assumed severe OA (ICRS scores 3 and 4) diagnosed in X-ray and prior morphological MRI images were excluded. Of the remaining patients, 34 gave their informed consent to participate in this study. However, preoperative biochemical-based MRI was possible only in the case of 22 patients, one of whom had to be excluded because of image degradation caused by motion artifacts. We included the remaining 21 patients (9 females, 12 males; mean age 41.2 ± 12.65 years; age range 18–70 years; 10 left knees, 11 right knees) in the study. Ten patients had traumatic or degenerative meniscus lesions, eight patients had anterior cruciate ligament rupture and three patients suffered from knee pain of unclear cause. An average of 20 ± 6.7 days passed between biochemical-based MRI and arthroscopy. Ethical approval for this study was provided by the Clinical Ethics Committee of the local university.

Surgical assessment

Patients were evaluated intraoperatively by the same orthopedic surgeon (A.G., with 25 years of experience in knee arthroscopy) on the basis of ICRS scores and the ICRS Cartilage Injury Evaluation Package. ICRS scores ranged from grade 0 (normal cartilage) to grade 4 (defects extending into the subchondral bone). Size, number, and grade of cartilage lesions were recorded. This articular cartilage mapping system divides the knee into sections for the localization of lesions and provides a standardized form of knee joint cartilage evaluation (see Fig. 2(D)).

A junior imaging specialist (S.S., orthopedic surgeon with 2 years of experience in knee arthroscopy and MR imaging) together with a senior imaging specialist (G.W., orthopedic surgeon with 15 years of experience in knee arthroscopy and expert for biochemical MRI) preoperatively defined in cooperation with the surgeon (A.G.) the regions of interest (ROIs) on the cartilage surface. For each patient, 42 ROIs covering the whole articular surface were defined. The ROIs are shown in Fig. 2(D) and described in the following image analysis section. All lesions were documented by the mapping system and in arthroscopic images.

MR imaging

A 3.0 T MR scanner (Magnetom Skyra, Siemens Medical Solutions, Erlangen, Germany) with a gradient strength of 40 mT/m and a 15-channel knee array coil (IN vivo, Gainesville, FL, USA) were used for image acquisition. In order to standardize knee joint loading, patients had to rest in a horizontal position for 30 min prior to T2 mapping examination. Thereafter, images were acquired while patients were in a supine position. The knee joint was fully extended and fixed in a neutral rotation position in the center of the coil. Defined in the protocol was sagittal, multi-echo, spin-echo (SE) T2 image acquisition. High-resolution morphological MRI was also performed using a three-dimensional, isotropic, fat-saturated proton-density space sequence (PD-SPACE). MRI parameters for the applied sequences are shown in Table 1.

All sequences were acquired in the sagittal plane. For image acquisition, the menisci and the femoral intercondylar notch were used as anatomical landmarks. This ensured that all chosen slices in the MRI results corresponded with the areas selected for arthroscopic assessment based on the ICRS score sheet. In the PD-SPACE sequence, the imaging specialists defined the ROIs and copied them onto the T2 map. This step was considered critical for precise localization of the defined ROIs in the T2 sequence images. This clear form of orientation provided the basis for subsequent image analysis.

Image analysis

For ROI analysis, the MRI data sequences were transferred to a Syngo (Leonardo) workstation (Siemens Medical Solution, Erlangen, Germany). T2 maps were obtained using a pixelwise, mono-exponential non-negative least squares (NNLS) fit analysis. First, the morphological data sets were examined for any knee joint abnormalities or motion artifacts by the imaging specialists (S.S., G.W.).

In conformity with the surgical assessment, ROIs were defined in four sagittal planes: two through the medial and two through the lateral femoral condyle. Cartilage status was assessed in these four planes. We marked three regions of the femur and three regions of the tibia (anterior, central, and posterior). The anterior ROIs were set above and below the borders of the anterior meniscus horn, the posterior ROIs above and below the posterior meniscus horn, and the central ROIs above and below the mid portion of the meniscal body. The cartilage surface of the patella and the opposing trochlea was divided into three equal ROIs (proximal, central, and distal). The distal ROI of the trochlea was bordered by the anterior rim of the anterior meniscus horn (see Fig. 1). Articular cartilage status was analyzed in 42 ROIs per patient by T2 mapping.

First, the imaging specialist manually marked the respective ROI on a morphological image of the T2 sequence; this provided the best cartilage-to-bone and cartilage-to-joint fluid contrast (see

<table>
<thead>
<tr>
<th>Table 1</th>
<th>MR imaging protocols</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence</td>
<td>T2 map</td>
</tr>
<tr>
<td>Repetition time (ms)</td>
<td>1,200</td>
</tr>
<tr>
<td>Echo time (ms)</td>
<td>13.8, 27.6, 41.4, 55.2, 69.0, 82.8</td>
</tr>
<tr>
<td>Field of view (mm)</td>
<td>160 x 160</td>
</tr>
<tr>
<td>Pixel matrix</td>
<td>384 x 384</td>
</tr>
<tr>
<td>Pixel size (mm)</td>
<td>0.4 x 0.4 x 3.0</td>
</tr>
<tr>
<td>Slice thickness (mm)</td>
<td>0.6</td>
</tr>
<tr>
<td>Number of slices</td>
<td>12</td>
</tr>
<tr>
<td>Flip angle (°)</td>
<td>180</td>
</tr>
<tr>
<td>Bandwidth (Hz/pixel)</td>
<td>228</td>
</tr>
<tr>
<td>Scan time (min)</td>
<td>4.09</td>
</tr>
</tbody>
</table>
Fig. 1, lowest echo time). Subsequently, these ROIs were copied and pasted onto the T2 map for correct placement of ROIs within the appropriate cartilage zones. Finally, the mean values of the T2 relaxation times for each ROI were recorded.

In order to provide a better overview in the results section of this article, results for these 42 ROIs have been summarized in terms of the following six regional groups: central medial femoral condyle (CMFC), medial tibia plateau (MTP), central lateral femoral condyle (CLFC), lateral tibia plateau (LTP), patella and trochlea.

Statistical analysis

SPSS software v.23 for Windows (IBM Corp., Armonk, NY, USA) was used for statistical analysis. Based on the sample of 21 independent cases (patients), descriptive statistics employed mean T2 values with confidence intervals, medians, standard deviations (SD), and minimum and maximum T2 values for all 42 examined ROIs and ROI groups. The results of the Kolmogorov–Smirnov test and the Shapiro–Wilk test showed that it was not possible to assume normal distribution of ICRS scores or of measured T2 data. Hence Kruskal–Wallis non-parametric analysis of variance (ANOVA) was used to identify any statistically significant differences between the mean T2 values measured for each ICRS score for a specific ROI/ROI group. Here post hoc comparisons using the Kruskal–Wallis test were undertaken to determine which pairs of ROIs differed significantly in terms of T2 values. In order to quantify any correlations between T2 mapping values and ICRS scores, Spearman’s (non-parametric) rank correlation coefficient rho was calculated, and the corresponding P-values were used to identify ‘significant’ (P < 0.05) and ‘highly significant’ (P < 0.01) correlated pairs per ROI/ROI group.

Finally we statistically determined the threshold T2 values between the ICRS scores using the receiver operating characteristic (ROC) method with the help of the R-software package pROC. Any dependent T2 measurements per ROI attributable to repeated evaluations were eliminated by averaging. Assuming that potential thresholds were independent of ROIs, all available ICRS-T2 value pairs were investigated with varying dichotomizations of the T2 threshold values and discriminating groups of ICRS scores (e.g., ICRS score 0 vs ICRS score 1, 2, 3, 4) in order to analyze the resulting predictive models. In the ROC analysis, we evaluated the area under curve (AUC) to determine the resultant sensitivity and specificity of our predictive models. It was possible to determine an optimal threshold T2 value between the different classes of ICRS scores from the ROC curve. In this case, the optimal threshold was defined as the T2 value corresponding to the point on the ROC curve at which sensitivity was equal to 1 minus specificity. The 95% confidence intervals for AUC, specificity and sensitivity were estimated using bootstrapping methods.

We also assessed the reliability of the T2 measurement procedure on the basis of supplementary example measurements undertaken by the same observer and by a second independent one. The additional T2 data was collected by two independent investigators for all ROIs of the knee joints of five patients. This was used to quantify the intra- and interobserver reliability in terms of the intraclass correlation coefficient (ICC). P-values ≤ 0.05 were considered statistically significant.

Results

Quantitative T2 mapping for knee joint cartilage assessment was performed in 21 patients. In total, 882 ROIs (42 per joint, 21 participants) were analyzed. The mean size of these 882 ROIs was 1.08 ± 0.34 cm², ranging from 0.45 cm² to 2.17 cm². Out of 882 ROIs, 594 ROIs were classified as ICRS score 0 (67.3%); 222 as 1 (25.2%), 57 as 2 (6.5%), 6 as 3 (0.7%), and 3 as 4 (0.3%). The ROI scores for ICRS
score 3 and 4 were merged for statistical evaluation because of their small total number; i.e., only 9 ROIs had ICRS score 3/4 (1.0%). The distribution of the ICRS scores among the six anatomically defined regions is shown in Table II. One patient did not have any cartilage damage and was therefore assigned an ICRS score of 0 for all 42 ROIs (Fig. 1).

Mean T2 relaxation times significantly increased with increasing morphological cartilage defect grade, ranging from \(38.97 \pm 6.78\) ms in regions with ICRS score 0 to 97.16 ± 14.88 ms in regions with modified ICRS score 3 lesions. Mean T2 values for the corresponding ICRS scores are shown in Table III. The increase in T2 values relative to the grade of cartilage degeneration is illustrated by a box plot representing the values T2 minimum, lower quartile, T2 median, upper quartile, T2 maximum, and outliers [see Fig. 5(D)]. A marked statistically significant positive correlation was observed between T2 values and cartilage ICRS scores. The highest level of correlation was identified for the central medial femoral condyle region (\(r = 0.940\); \(P < 0.0001\)). The medial aspect of the patella was the only region where no significant correlation was observed (\(r = 0.295\); \(P = 0.195\)). In Fig. 2, Spearman’s correlation coefficients calculated per ROI including associated \(P\)-values are shown in accordance with anatomical positions of the ROIs. The close correlation between T2 values and arthroscopically determined ICRS scores for different grades of cartilage damage can be seen in Figs. 3 and 4. The diagnostic potential of T2 mapping in the medial patella, despite the weak correlation, is shown in Fig. 4(B).

Selected results of the ROC analysis are shown in Fig. 5. One of the main findings is that ROC curve indicates a clear differentiation for continuous ICRS scores with the risks of false-positive or true-negative decisions (i.e., when trying to conclude from measured T2 values the supposed cartilage lesions characterized by ICRS scores) as reflected by the postulated T2 thresholds described above.

ICR analysis showed a high level of intraobserver (ICC, 0.906; \(P < 0.05\)) and interobserver (ICC, 0.886; \(P < 0.05\)) reproducibility with regard to the T2 measurement procedure.

### Discussion

After suffering traumatic knee joint injury, most patients develop associated cartilage damage\(^2\). In this study, nearly one third (31.7%) of the evaluated cartilage surfaces showed low grade cartilage lesions (ICRS scores 1 and 2); overall, 32.7% of all examined ROIs (\(n = 882\)) were affected (ICRS grade \(> 0\)). There

### Table II

Distribution of ICRS scores in the six defined anatomical regions: central medial femoral condyle (CMFC), medial tibia plateau (MTP), central lateral femoral condyle (CLFC), lateral tibia plateau (LTP), patella, and trochlea. The percentage of each anatomical region in which individual ICRS scores were recorded is shown in parentheses.

<table>
<thead>
<tr>
<th>ICRS score</th>
<th>Anatomical regions</th>
<th>n (%)</th>
<th>n (%)</th>
<th>n (%)</th>
<th>n (%)</th>
<th>n (%)</th>
<th>n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICRS 0</td>
<td></td>
<td>78 (13.1%)</td>
<td>75 (12.6%)</td>
<td>98 (16.5%)</td>
<td>72 (12.1%)</td>
<td>145 (24.4%)</td>
<td>126 (21.2%)</td>
</tr>
<tr>
<td>ICRS 1</td>
<td></td>
<td>35 (15.8%)</td>
<td>40 (18.0%)</td>
<td>26 (11.7%)</td>
<td>43 (19.4%)</td>
<td>30 (13.5%)</td>
<td>48 (21.6%)</td>
</tr>
<tr>
<td>ICRS 2</td>
<td></td>
<td>10 (17.5%)</td>
<td>10 (17.5%)</td>
<td>2 (3.5%)</td>
<td>11 (19.3%)</td>
<td>12 (21.1%)</td>
<td>12 (21.1%)</td>
</tr>
<tr>
<td>ICRS 3/4</td>
<td></td>
<td>3 (33.3%)</td>
<td>1 (11.1%)</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
<td>2 (22.2%)</td>
<td>3 (33.3%)</td>
</tr>
</tbody>
</table>

### Table III

Mean T2 values (ms) ± standard deviation corresponding to ICRS scores in the six defined anatomical regions. 95% confidence intervals are shown in parentheses (lower limit/upper limit). *P*-values show the significance of differences in T2 values depending on the grade of cartilage defect (according to Kruskal–Wallis non-parametric analysis of variance). n.a. = not available in the sample.

<table>
<thead>
<tr>
<th>ICRS score</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>3/4</th>
<th>P-value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mean T2 values (ms)</td>
<td>38.97 ± 6.78 (38.43/39.52)</td>
<td>55.21 ± 7.20 (54.26/56.17)</td>
<td>73.06 ± 11.55 (69.99/76.12)</td>
<td>97.16 ± 14.88 (69.99/85.72)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>CMFC</td>
<td>40.05 ± 5.45</td>
<td>55.96 ± 7.24</td>
<td>80.18 ± 10.89</td>
<td>112.50 ± 4.51</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>MTP</td>
<td>34.17 ± 5.09</td>
<td>59.10 ± 5.86</td>
<td>77.48 ± 7.28</td>
<td>103.70 ± 17.23</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>CLFC</td>
<td>40.34 ± 4.06</td>
<td>51.08 ± 6.08</td>
<td>51.15 ± 10.11</td>
<td>n.a.</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>LTP</td>
<td>36.37 ± 6.47</td>
<td>55.57 ± 8.37</td>
<td>72.85 ± 8.96</td>
<td>n.a.</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Patella</td>
<td>37.76 ± 8.17</td>
<td>54.33 ± 7.50</td>
<td>69.27 ± 11.99</td>
<td>89.10 ± 15.41</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Trochlea</td>
<td>42.99 ± 5.77</td>
<td>53.90 ± 6.07</td>
<td>71.07 ± 11.89</td>
<td>85.00 ± 9.23</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
</tbody>
</table>
was a significant increase in T2 values in parallel with increasing grades of cartilage damage. A statistically significant positive correlation between T2 values and ICRS scores for most of the examined knee joint ROIs (40/42) was demonstrated. We also converted these results into a T2 value threshold, enabling differentiation between healthy and various grades of damaged cartilage. Thus, with the advantages of lack of need of contrast media, high image resolution and ease of integration in clinical practice, we consider quantitative T2 mapping to be a powerful technique for assessing knee cartilage status, particularly in the context of routine clinical use.

The fact that T2 values increased with increasing levels of cartilage defect corresponds well with the results described in several previous studies. We consider quantitative T2 mapping to be a powerful technique for assessing knee cartilage status, particularly in the context of routine clinical use.
mapping with morphological MRI methods\textsuperscript{25--27}. However, morphological MRI can only detect subtle cartilage alterations occurring early in course of OA to a limited extent\textsuperscript{14}. Preferred methods of assessing cartilage status that allow reproducible evaluation even at early stages include histological grading and intraoperative clinical assessment\textsuperscript{28,29}. In order to determine the precision of T2 mapping, it appears appropriate to compare T2 values with histological and arthroscopic findings. However, only few histological studies are available\textsuperscript{18,30}, while even fewer studies are available that compare T2 mapping with intraoperative results\textsuperscript{27}. Previous studies have shown that collagen network breakdown is associated with subsequent decreased anisotropy of the collagen fibers so that higher water content is responsible for the increase in T2 values in OA\textsuperscript{31--33}. Kim et al.\textsuperscript{30} demonstrated correlation between quantitative T2 mapping and histological grades of degenerated human articular cartilage in the lateral tibia condyle. Taking histological samples from the patient’s cartilage for OA diagnosis is not feasible. Therefore, for clinical practice, studies...
comparing quantitative T2 mapping with intraoperative findings and clinical scores are important.

Apprich et al. examined 43 patients with knee pain and an ICRS cartilage defect score ≤ 2 in quantitative T2 mapping. Morphological cartilage grading was based on high-resolution MRI sequences and a small sample of patients (n = 11) was additionally assessed by arthroscopy. A significant increase in T2 values was associated with a rise in the grade of cartilage defect. In addition, ICRS scores showed a significant positive correlation in the global layer with T2 mapping. This was congruent with the results obtained in our study. However, the study by Apprich et al. was limited by its low number of evaluated ROIs (n = 43) and even lower number of ROIs verified by arthroscopy; this represents a major difference to our study in which there was intraoperative evaluation of 882 ROIs. Moreover, they focused on the zonal variation and the changes in T2 values with loading and unloading prior to the assessment of only a single localization. In contrast, our study focused on alterations in the global cartilage layer to reveal the potential of T2 mapping for the detection of early cartilage damage in all regions of the knee joint. We prioritized the direct comparison between the ROIs measured using MRI and the corresponding ROIs determined using arthroscopy to show the applicability to clinical routine of T2 mapping. In connection with the differentiation between various grades of cartilage damage we examined T2 thresholds using ROC curve analysis. The most relevant T2 threshold value of 47.6 ms differentiates with high sensitivity between healthy cartilage (ICRS score 0) and very early onset OA, when treatment should be initiated. Such a threshold may be helpful in clinical routine when it comes to the interpretation of the results of T2 mapping. Our results may also provide the basis for a MRI-guided cartilage screening tool, which could be an effective means of monitoring subsequent treatment options of early OA and for the follow-up of cartilage abnormalities. Using quantitative T2 mapping, it might also be possible to monitor the effects of pharmacological forms of treatment of early OA. Moreover, targeted evaluation of cartilage before and after corrective osteotomy may also be viable with T2 mapping. Further treatment alternatives are being explored that could delay or even avoid the need for knee arthroplasty in younger active patients. However, further evaluations are needed in order to determine ‘cut-off values’ for the reproducible assessment of cartilage status that could be used to define the appropriate time points for intervention and thus lead to improved treatment outcomes.

Fig. 5. ROC curve (black) and delineation of 95% confidence band of the ROC curve (blue). The bisecting line in the ROC graphs indicates accuracy of random prediction. Marked are the threshold T2 values. AUC – area under the curve, estimated median and 95% confidence interval. A, ROC curve for differentiating clearly between ICRS score 0 and higher ICRS scores. B, ROC curve for differentiating clearly between ICRS score 0/1 and ICRS scores 2, 3, and 4. C, ROC curve for differentiating between ICRS scores 0/1/2 and ICRS scores 3 and 4. No useful ROC curve is available due to the low number of ROIs with ICRS scores 3 and 4 (n = 9). D, Box plots for T2 values per ICRS scores over all patients and ROIs. Box plots show minimum, median, and maximum values. O – outlier.
Despite the promising results, some limitations of our study should be taken into account. The current study was based on a relatively low number of patients. Nonetheless, by evaluating a high number of ROIs per patient, the total number of 882 ROIs provided sufficient data for assessment of correlations in all parts of the joint. Additionally, more experience with T2 mapping protocols will help in the development of comparable settings for future studies. We did not differentiate between deep and superficial layers in cartilage assessment. In previous studies, zonal variation was used to differentiate between healthy and repair cartilage tissue [14, 38]. In our study, this differentiation did not appear relevant because the T2 grade is not exclusively due to the articular surface. Instead, the presence or size of focal defects [22, 38] affects the signal intensity obtained from quantitative T2 mapping in the knee joint. Keeping in mind that our group of patients was small, we decided to avoid further subcategorization. In future studies, we intend to define a region-specific threshold. In order to achieve this, larger patient cohorts are needed. It is hoped that individual normed thresholds for each of the six knee compartments will facilitate decisions for or against a certain treatment. In a larger cohort, potential patient-specific influence parameters such as BMI, age, and gender could also be analyzed. Keeping in mind that our group of patients was small, we decided to avoid further subcategorization. In future studies we intend to deal with additional aspects in order to obtain an even more detailed picture of T2 values. The manually drawn T2 mapping analysis of a knee joint is time-consuming. In addition to broader evaluation of threshold values, it is also desirable to develop automated evaluation tools. In view of this, we will plan future studies in cooperation with pattern recognition engineers.

Despite the significant positive correlations obtained overall, the proximal and distal margins of the medial patella represent the only regions where we obtained non-significant and weak correlation (Fig. 2). Gomoll et al. [40] reported that the preoperative measurement of cartilage defects by MRI underestimates the extent of the final defect area that results following debridement. The discrepancy for the cartilage lesions can be explained by the small area of full-thickness damage seen in MRI; these areas are surrounded by a large zone of fissured cartilage that is also debrided during surgery, thereby vastly increasing the defect size [40]. Despite our low correlation coefficient for the distal medial patella, T2 mapping correlates well with intraoperative findings [Fig. 4(B)].

The aim of our study was to demonstrate the applicability of T2 mapping in clinical routine. Our objective was to prove that this method of human knee joint cartilage assessment is viable by means of intraoperative validation.

In conclusion, our study showed that quantitative T2 mapping is sensitive even to minor cartilage changes and is able to detect the onset of early stage OA in human knee joints. As T2 relaxation times increase with increasing cartilage defect grade, this MRI technique makes it possible to differentiate between healthy and damaged cartilage and to classify the cartilage damage using ICRS scores. So that this method can be established in clinical practice, our results need to be confirmed by prospective studies with larger patient cohorts and intraoperative validation of T2 values.

We postulate that quantitative T2 mapping may provide a useful diagnostic tool for assessing knee joint cartilage damage. Being a sensitive non-invasive method, it may facilitate the initial diagnosis of OA in clinical routine and the monitoring of therapeutic interventions, the consequences of which will be improved prognoses.

**Author contributions**

Study conception and design: SS, AG, GHW, MP.

Acquisition of data: SS, DM, AG, GHW, MP.

Analysis and interpretation of data: SS, AG, GHW, MP.

Drafting of article: SS, GHW, MP.

Critical revision of the article: SS, AG, GHW, MP.

Final approval of the article: SS, DM, AG, GHW, MP.

**Declaration of competing interests**

The authors herewith confirm that they have no competing interests to disclose.

**Role of the funding sources**

Sources of funding had no role in study design, collection, analysis and interpretation of data, in the writing of the article and in the decision to submit the article for publication.

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**References**


