Magnetic resonance mapping of the rim of articular cartilage defects of the patella

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Abstract

Purpose Elevated T2-values of articular cartilage are associated with an increase in cartilage water that results from a damaged collagen matrix, and provide a marker for cartilage damage. We used T2 mapping to analyse the rim of cartilage defects that appeared to be intact on the morphological sequences, to determine whether there are early biochemical changes already present.

Method We calculated T2 values for the rim of cartilage defects in 25 patients and compared these values to another area of control cartilage in these patients.

Results A highly significant increase in T2 values of the deep, superficial, and global layer of the rim versus the control cartilage was measured. ANOVA showed a significant correlation of the defect levels with the T2 values of the deep and global zone of the adjacent cartilage tissue, but not with the superficial zone.

Conclusion Although cartilage appears to be intact on morphological sequences, T2 mapping can show a loss of

structural anisotropy of collagen and the associated increase in cartilage water that indicates the destruction of the adjacent cartilage. Preoperative information about the degree of damage of the collagen matrix will support decision making for cartilage repair.

Keyword MRI · T2 mapping · Cartilage defect · Patella · Chondromalacia patella

Introduction

The treatment of focal cartilage defects of the patella is a major challenge in the field of cartilage repair. Various studies have reported a frequency of cartilage defects between 11 % and 36 % located on the patella, with a mean size of 2.1 cm² [1–3]. These defects can result from macrotrauma and repetitive microtrauma, are often associated with abnormal patellofemoral stress due to dysplastic morphology of the trochlea groove, and impairment of the soft tissue static stabilisers [4]. Cartilage defects can also occur in combination with varus and valgus malalignment of the tibiofemoral axis and rotational differences in femoral version [5]. Elevated strain on the cartilage next to the defect site has been shown to induce cell death and matrix damage [6]. Leaving those defects untreated will lead to more severe joint damage and, ultimately, to osteoarthritis [7].

Cartilage defects can be treated by mosaicplasty, marrow stimulation techniques, anteromedialisation of the tibial tubercle, allograft transplantation, or autologous chondrocyte implantation (ACI) and matrix-induced autologous chondrocyte transplantation/implantation (MACT/MACI) [8–14]. The advantage of ACI and MACT/MACI is that these techniques are intended to encourage the formation of hyaline-like repair tissue. The MACT/MACI that is supported by a type I/III collagen membrane shows clinical outcomes similar to those with the ACI technique, but with fewer complications than the

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ACI technique [15]. Nevertheless, the success rate for the treatment of cartilage defects on the patella cannot be compared with those of the femur. While a success rate of 80–90 % good to excellent results has been reported for defects of the femoral condyle, only a 60–70 % rate has been reported for defects of the patella [16].

The transverse relaxation time (T2) has been shown to be a sensitive parameter with which to show the interaction between the extracellular matrix and water molecules of the cartilage. Changes in water content and collagen concentration can be detected in accordance with the zonal variation of the cartilage tissue, and is visible in an increase of T2 values from the deep to the superficial zone. It has been shown that increased T2 values indicate damage in the collagen structure that is also characterised by increased water mobility [17–20].

The aim of this study was to evaluate the rim of cartilage defects with T2 mapping to obtain more information on the condition of the cartilage adjacent to the defect. We postulate that information about the extent of cartilage destruction could better determine the resection margins required to create a healthy edge area, which may allow better integration of the graft in the defect.

Materials and methods

Patient population

In this study, we retrospectively examined 112 patients, between the year 2009 and 2010, who were referred for an MRI examination of the knee joint for a suspected cartilage defect of the patella. We included all patients 18 years and above of age, who had a cartilage defect with a maximal extension of one centimetre in the transverse plane in three consecutive MRI layers on standard axial T2-weighted FSE sequences. Based on the medical history, patients with previous surgery and patella fracture were excluded. In total, 25 patients (13 female and 12 male) with a mean age of 33.04 years (range, 16–54) were included. All patients had given written, informed consent to use their anonymised data for scientific purposes prior to the MRI examination. The Ethics Committee of the Medical University of Vienna approved the protocol.

Magnetic resonance imaging

MRI was performed on a 3.0 T whole-body Magnetom TimTrio scanner (Siemens Medical Solutions, Erlangen, Germany), using a gradient strength of 40 mT/m and an eight-channel knee array coil (IN vivo, Gainesville, FL, USA). Patients were positioned in the supine position with the extended knee tightly fixed and the joint space in the middle of the coil.

The MRI protocol consisted of an axial multi-echo spin-echo (MESE) T2 sequence for T2 mapping, as previously described: repetition time (TR) 1200 ms; echo time (TE) 13.8, 27.6, 41.4, 55.2, 69, and 82.8 ms; field of view (FoV) 160×160 mm; pixel matrix 384×384; voxel size 0.4×0.4×3 mm; bandwidth 228 Hz/pixel; 12 slices; scan time 4:09 min [21].

For the morphological evaluation, the MRI protocol consisted of an isotropic three-dimensional (3D) true fast imaging with steady-state precession (TrueFISP) sequence: TR 7.69 ms; TE 3.85 ms; flip angle 30°; FoV 192×192 mm; pixel matrix 384×384; voxel size 0.5×0.5×0.5 mm; scan time 6:21 min [22].

The TrueFISP-sequence was obtained for the whole knee in the coronal plane and reformatted in the axial and sagittal planes through multiplanar reconstruction (MPR). In addition, a high-resolution, proton-density (PD) turbo-spin-echo (TSE) sequence was obtained for the patella in the axial plane: TR 2400 ms; TE: 36 ms; FoV 120×120 mm; matrix size 512×512; voxel size 0.2×0.2×2 mm; 24 slices; interslice gap 10%; flip angle 160°; bandwidth 244 Hz/pixel; scan time 6:11 min. The pixel size of 200 µm for the morphological PD TSE sequence remained below the level that is deemed required to reliably show superficial alterations of articular cartilage [23].

Morphological and T2 mapping sequences were planned on the same set of localisers. Acquired images were oriented perpendicular to the patella surface in the axial plane (Fig. 1).

Any additional sequences performed during the scans were not used for this analysis.

Image and data analysis

The cartilage surface of the patella was morphologically graded based on a modified ICRS classification system (grade 0: normal cartilage without notable defects; grade 1: cartilage without tissue loss, but with fibrillation and superficial fissures at the superficial surface; grade 2: defects that extend to less than 50 % in depth; grade 3: lesions that extend to more than 50 % of the cartilage thickness; and grade 4: full-thickness injuries of cartilage [24]).

T2 relaxation times were derived from on-line reconstructed T2 maps using a pixel-wise, mono-exponential, non-negative least squares (NNLS) fit analysis (MapIt, Siemens Medical Solutions, Erlangen, Germany). To verify the localisation and size of cartilage defects, we used the 3D spatial presentation from the high-resolution TrueFISP images. With the help of header information and anatomical landmarks, the defects were reproduced on the T2 maps using the first echo images (TE=13.8 ms), as these have the best SNR. T2 values from the subchondral bone to the cartilage surface (global T2) were assessed on manually drawn regions of interest (ROI) on one to three consecutive slices of the T2 map, depending on defect size. In addition, a reference area

Fig. 1 Axial PD TSE MR image (*left*) shows the cartilage defect in the transition from the vertical ridge to the medial facet of the patella. On the right side, the corresponding colour-coded T2 map

with a morphologically normal appearance on TrueFISP and PD TSE images, i.e., with preserved cartilage thickness, intact surface, and without intrachondral signal alterations, was identified in the same patient, either on the contralateral facet of the patella or at least two slices away from the defect in the cranio-caudal direction, taking into account the magic angle effect. Corresponding ROIs for the assessment of the T2 values were manually drawn on one to three slices similar in size to the ROI and these served as a reference (Fig. 2).

Subsequently, to evaluate the impact of cartilage degeneration on the zonal variation of T2, ROIs were divided into two layers of equal thickness, a deep and a superficial one, and zonal variation was calculated as the difference between the T2 values.

Morphological and ROI analyses were performed by an experienced senior musculoskeletal radiologist (S.T., 23 years of experience), in consensus with an orthopedic surgeon who had five years of experience in musculoskeletal MRI.

Statistics

The data were examined using graphic representation in a box plot for normal distribution. A paired t-test was used to compare the T2 mean value of the deep, superficial, and global zones of the reference cartilage and the T2 mean value of the deep, superficial, and global zones of the adjacent tissue. A one-way analysis of variance (ANOVA), along with a post hoc Duncan test, was used to investigate the influence of the ICRS grade on the T2 value from the superficial and the deep zone of the adjacent cartilage. The correlation between T2 values and cartilage defect grade was investigated using Spearman's rank correlation analysis. The statistical analysis was performed using the computer program SPSS for Apple

(20.0, SPSS, Chicago, IL, USA, IBM). P-values less than or equal to 0.05 were considered statistically significant.

Results

Compared to the morphologically healthy reference cartilage (mean ROI size for global layer: 308 pixels), a highly significant increase in the T2 values could be detected in the deep zone ($p=0.007$), as well as in the superficial zone ($p=0.002$), and thus, in the global zone ($p=0.002$) of the adjacent cartilage region (mean ROI size for global layer: 258 pixels) (Table 1). On the high-resolution morphological MR sequences, the adjacent tissue of all patients appeared to be healthy and was judged to be intact. Ten patients had an ICRS grade 2 (40 %), eight patients an ICRS grade 3 (32 %), and seven patients an ICRS grade 4 (28 %). The ANOVA analysis showed the significant effect of the defect levels to the deep zone ($p=0.004$) and the global T2 values ($p=0.049$) of the adjacent cartilage tissue. Surprisingly, there was no significant increase in the T2 values for the superficial layer of the adjacent cartilage ($p=0.248$), despite increasing T2 values with increasing degree of defect. The T2 relaxation time of the superficial, deep, and the global zones in relation to the ICRS defect levels are shown in Table 2. The additionally calculated Duncan post hoc test showed a significant difference ($p<0.05$) in the deep and superficial zone for the T2 values in patients with ICRS grade 2 and grade 4. The Spearman's rank correlation showed that the T2 values of the deep, superficial, and global layers and the ICRS cartilage defect grades showed a strong association between the deep layer values ($R_s=0.642$, $p=0.001$) and a median correlation between the global T2 values ($R_s=0.456$, $p=0.022$).

Fig. 2 The morphological sequence (PD-TSE MRI) on the left shows the traumatic defect. On the right side, the corresponding T2 map shows the T2 relaxation time measurements of the deep and superficial layers of the adjacent tissue and the control cartilage

Discussion

Focal cartilage defects on the patella surface can be a cause of anterior knee pain. The treatment of these defects tends to reduce pain, but also tends to postpone the cartilage degeneration that is associated with cartilage defects. Left untreated the defect enlarges, loses cartilage volume, and the cartilage next to the defects can show histopathological signs of degeneration [6]. As already mentioned, the success rate for ACI for the treatment of the patella is between 60 and 70 % [16].

Due to the fact that the transverse relaxation time (T2) reflects the interaction of the extracellular matrix and the water molecules, healthy cartilage is characterised by increasing T2 from the deep to the superficial zone of the cartilage [25]. T2 mapping of the cartilage next to the defect could provide information on possible additionally damaged cartilage tissues and the extent of such damage, and thus, help improve clinical outcomes of surgical interventions.

In this study, we investigated the defect margins of cartilage defects located on the patellar surface using T2 mapping. The T2 values of the deep, superficial, and global layers were correlated with the T2 values of the deep, superficial and global layers of the reference cartilage, as well as with the evaluated ICRS grade. We showed a highly significant in-

crease in the T2 values adjacent to the cartilage defect in the deep (T2 mean 35.78 ± 9.68 , $p=0.007$), superficial (T2 mean 51.41 ± 12.78 , $p=0.002$), and global (T2 mean 43.73 ± 2.08 , $p=0.002$) layers with regard to the healthy reference cartilage (T2 mean: deep 29.21 ± 6.47 ; superficial 41.23 ± 9.16 ; global 35.29 ± 7.48). Based on the correlation between the T2 values of the tissue adjacent to the defect and the defect grade, there was a significant influence of the defect grade on the T2 values of the deep ($p=0.004$) and the global ($p=0.049$) layers. Although we had increasing T2 values in the superficial layer, these did not reach significance ($p=0.248$).

We are aware of the limited level of evidence associated with a consecutive case series for intraoperative evaluation and the lack of a control group. There is a wide variation of T2 in healthy cartilage, therefore we aimed to evaluate the differences of the various cartilage regions within individuals [26]. Nevertheless, these data demonstrate a significant difference between the properties of the cartilage adjacent to the defect and the normal controls which is not apparent in morphological MRI.

Wong et al. evaluated the influence of patella-femoral articulation on cartilage defects [6]. He exposed the cartilage adjacent to the defect to shear, axial, and lateral strain, and found that, at 20 % of the total depth of the cartilage, the strain reaches the highest values. He confirmed existing opinions that those strains mechanically induce cell death, tissue loss, reduce cell count, and represent the beginning of osteoarthritic changes in the knee joint. We found a significant increase in T2 values in the deep layer that was associated with the deterioration of collagen integrity and the increase of water content [19]. In the biomechanical in vitro study by Wong et al. the defects were created by sharp incisions, so that vertical cartilage walls surrounded the defects and all the strains were aimed directly onto the cartilage wound edges. Our defects were caused by trauma, where we assume that the defects would have been formed by the increased shear forces

Table 1 Mean T2 values (ms) ($\pm$ = standard deviation) for the global, deep, and superficial cartilage layers of the healthy control cartilage, and T2 values of the tissue adjacent to the defect. Differences between control cartilage and adjacent tissue were tested for significance using a paired *t*-test (***P*-value) with a confidence interval of 95 %

Layer	T2 (ms) control cartilage	T2 (ms) adjacent tissue	<i>p</i>
Superficial layer	41.23 ± 9.16	51.41 ± 12.78	0.002
Deep layer	29.21 ± 6.47	35.78 ± 9.69	0.007
Global layer	35.29 ± 7.48	43.73 ± 2.08	0.002

Table 2 Mean T2 values (ms) for the global, deep, and superficial layers of the adjacent tissue and the control cartilage, categorised according to the ICRS grade and the mean T2 values for the deep ($p=0.004$), superficial ($p=0.248$), and global ($p=0.049$) layers of all 25 patients

Layer	ICRS grade			Mean
	2 ($n=10$)	3 ($n=8$)	4 ($n=7$)	
Superficial layer	46.21±9.26	53.94±13.13	55.96±15.68	51.41±12.78
Deep layer	29.46±7.51	36.48±7.97	44.00±8.39	35.78±9.69
Global layer	38.07±7.98	45.28±9.27	50.05±11.51	43.73±10.39
Control cartilage				
Superficial layer	43.22±9.89	43.14±9.22	44.10±7.68	43.44±8.74
Deep layer	29.48±6.26	29.69±6.22	33.98±5.21	30.81±6.07
Global layer	36.22±7.66	36.39±7.66	39.20±6.16	37.11±6.85

acting on the collagen fibres that are oriented in a perpendicular direction to the bone, which occurs in the deep zone [27]. In addition, during the movement of the knee joint, the articular cartilage of the trochlea of the femur and the patella are in contact with each other, a process characterised by shear and compression forces. Under loading conditions, with 1.5 times the body weight, the patellofemoral joint demonstrates a compression of the cartilage up to 10 % of the thickness of the cartilage [28]. Therefore, we assume that the acting force during trauma is so high that the collagen fibres in the deep zone will crack. This is the place where the degeneration of cartilage begins. This injury pattern is supported by the highly significant increase in T2 values in the deep layer in our study. In addition, the finding in our study that the T2 values in the deep layer increase significantly in correlation with the defect grade supports this theory, whereas the T2 values of the superficial layer increase with increasing defect grade, but not in a significant way. In healthy articular cartilage, T2 values increase from the deep to the superficial zone. Dardzinski et al. reported an increase in T2 values from 30 to 70 ms within the cartilage of the patella of asymptomatic volunteers [18]. In the deep/radial zone, these investigators found values of $32\text{ ms}\pm 1$, and, in the outer transitional zone, $67\text{ ms}\pm 2$ ($p=0.001$). A focal increase in T2 values was also observed in the radial/deep zone of symptomatic volunteers examined by Mosher et al. and are in accordance with the findings of McCauley et al. who determined that patients with chondromalacia patellae had focal elevated T2 values in the deep zone, but showed an absence of these pathological findings during arthroscopy, which does not allow evaluation of the deep cartilage zones [29, 30]. Our study clearly showed a highly significant increase in T2 in the deep zone ($35.8\text{ ms}\pm 9$, $p=0.007$) of the rim of the cartilage defect, compared to the healthy control, and also supports the theory that injuries of the cartilage initially damage the deep layer and may finally lead to Chondromalacia of the patella. Using the ANOVA analysis, a significant effect of the defect grade (ICRS) could be detected for the deep layer ($p=0.004$), but not for the superficial layer ($p=0.248$). These results prompted us to assume that the cartilage of the adjacent tissue, although

appearing morphologically healthy at the superficial layer, already shows early destruction in the deep layer that is not visible on morphological MR imaging. This healthy-appearing cartilage during arthroscopy could partly explain the poor results of the ACI/MACI technique because less cartilage is resected to create a stable and healthy rim. A very important issue for the outcome of cartilage repair procedures is a better graft integration into the defect site. Poor integration is associated with more cartilage wear, and may result in delamination of the graft from the adjacent cartilage tissue [31]. Marlovits et al. reported complete integration of the graft with the surrounding cartilage in 82 % of patients [32]. No detailed information concerning the integration on the patella site was reported. Although these authors had no graft hypertrophy in patients with a defect located on the patella, they observed adhesions in two of seven patella grafts. Ebert et al. reported their MACT results, with a follow-up of five years, and showed, in 89 % of their cases, good to excellent filling of the chondral defects [33]. No results were provided concerning the results of the defects located on the patella.

In conclusion, our study supports the existing opinion that T2 mapping is an appropriate tool for the accurate staging of cartilage. While morphological imaging, even when performed with a high-resolution protocol, shows intact cartilage adjacent to a cartilage defect, T2 mapping shows signs of cartilage degeneration in the deep zone. This additional pre-operative information helps to form a better idea of the extent of the cartilage defect that seems to be intact in the superficial zone but not in the deep zone. Thus, this information can help to prepare vertical walls with healthy cartilage at the periphery of the lesion during surgery. This may help to improve the clinical outcome of cartilage repair surgeries on the patella.

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Conflict of interest The authors declare that they have no conflict of interest.

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