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Early postoperative cartilage evaluation by magnetic resonance imaging using T_2 mapping after arthroscopic partial medial meniscectomy

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Purpose: This study was performed to quantitatively evaluate postoperative changes in cartilage by T2 mapping after arthroscopic partial medial meniscectomy.
Material and Methods: The study enrolled 17 patients with 20 knees that underwent arthroscopic partial medial meniscectomy. MRI was performed preoperatively and at six months postoperatively, with subjects evaluated by T_2 mapping of the central part of the medial condyle of the femur in the sagittal plane. Regions of interest (ROIs) were set at 10 points between the point of intersection of the anatomical axis of the femur and the articular surface of the medial condyle and posterior area approximately 90 degrees to the anatomical axis. Pre- and postoperative T_2 values at each ROI were evaluated.
Results: Postoperative T_2 values were significantly longer than preoperative values at approximately 20, 30, 40, and 50 degrees to the anatomical axis of the femur. The maximum change between pre- and postoperative T_2 values was +6.65% at 30 degrees to the anatomical axis.
Conclusions: Mechanical stress at positions approximately 20, 30, 40, and 50 degrees relative to the anatomical axis of the femur increased soon after arthroscopic medial meniscectomy. These findings indicate the start of degeneration, via disorganization of collagen arrays, of the articular cartilage and increased water content.

1. Introduction

The meniscus distributes the load on the knee joint and acts as a shock absorber, as well as contributing to knee joint stability. Removal of the entire meniscus has been shown to lead to the long-term development of osteoarthritis (OA) in a high proportion of knees [1]. Advances in arthroscopic surgery have enabled minimization of the amount of damaged meniscus removed by partial meniscectomy, or even preservation of the damaged meniscus by meniscal repair [2]. However, partial meniscectomy weakens the load-dampening mechanism in the knee resulting in the development of OA in the long term [3].

The effect of partial meniscectomy on the articular cartilage during the early postoperative period has not been determined. High magnetic field (3T) magnetic resonance imaging (MRI) has enabled the qualitative, minimally invasive evaluation of the articular cartilage [4]. T_2 mapping with high magnetic field MRI can quantitatively analyze changes in collagen arrays and the water content of articular cartilage [5–18]. To assess the effects of partial meniscectomy on articular cartilage during the early postoperative period, this study utilized T_2 mapping with high magnetic field MRI to quantitatively evaluate qualitative changes to articular cartilage from before to six months after arthroscopic partial medial meniscectomy.

2. Material and methods

All procedures were in accordance with the ethical standards of the Kyoto Prefectural University of Medicine review board and the Helsinki Declaration of 1975, as revised in 2000.

2.1. Subjects

This study enrolled 17 patients with 20 knees that underwent arthroscopic partial medial meniscectomy between November 2010 and September 2013 to treat injuries to the white zone of the medial

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meniscus. All patients provided written informed consent. Patients with ligament injury or other complications were excluded.

The study included 17 knees of 14 men and three knees of three women. The mean age of the study subjects was 52.4 years (range, 33–76 years) and their mean body mass index was 24.7 kg/m^2 (range, 18.3–37.2 kg/m^2). Plain radiographs showed that Kellgren-Lawrence classification was grade 0 in all knees, with none having indications of OA of the knee. In all knees, the McMurray test was positive preoperatively and negative six months postoperatively, with pain and clicking having disappeared.

2.2. T_2 mapping

MRI scans before and at six months after arthroscopic partial medial meniscectomy were performed using a 3T MRI (Achieva 3.0T X-series, Philips Healthcare, Netherlands) and 8-channel knee coil, with the following imaging conditions: T_2 value measurement method, turbo spin echo (TSE) multi-echo time (TE); repetition time (TR), 2000 ms; TE, 15/30/45/60/75/90 (ms); scan time, 5 min 22 sec; sensitivity encoding reduction factor, 2; phase encoding direction, AP; bandwidth, 292.1 Hz (1.48 pixels); field of view (FOV), 160 × 160 (mm); slice thickness, 2.5 mm; and a 384 × 313 matrix. T_2 mapping images were evaluated on sagittal views. One slice of the central part of the femoral medial condyle was used for evaluation (Fig. 1), with 10 points set at 10 degree intervals along the articular surface between the point of intersection of the anatomical axis of the femur and the articular surface of the medial condyle and the posterior area at approximately 90 degrees relative to the anatomical axis. Regions of interest (ROIs) were set with their centers at these points and extending 5 degrees in an anterior-posterior direction. The depth of the ROIs in the articular cartilage was set to encompass the superficial and intermediate zones, and changes between preoperative and postoperative T_2 values at each ROI were evaluated (Fig. 2). To avoid partial volume effects, ROIs were set without a few pixels from the surface of the articular cartilage. The ROIs were measured by two orthopedic surgeons, including one author, board-certified by the Japanese Orthopedic Association. Mean T_2 values and changes from preoperative to postoperative T_2 values were calculated using Philips MR console software.

3. Statistical analysis

Results are reported as mean ± standard error (SE) and compared by paired t-tests. A p value <0.05 was defined as statistically significant.

4. Results

Both preoperatively and six months postoperatively, the T_2 values lengthened as the angle with respect to the anatomical axis of the femur increased from 0 to 50 degrees, with the longest at 50 degrees. From 70 to 90 degrees with respect to the anatomical axis, the T_2 values as the angle increased; however, this difference was not statistically significant. T_2 values were longer six months postoperatively than preoperatively at seven ROIs, located 0 to 60 degrees relative to the anatomical axis of the femur. The postoperative means were significantly longer than the preoperative means at 20 (51.0 ± 0.88 ms [range, 40.2–61.5 ms] vs. 48.4 ± 0.96 ms [range, 32.7–59.7 ms]; $p < 0.001$); 30 (53.6 ± 0.95 ms [range, 40.8–64.1 ms] vs. 50.4 ± 0.89 ms [range, 36.6–59.6 ms]; $p < 0.001$); 40 (56.3 ± 0.89 ms [range, 43.0–67.5 ms] vs. 53.1 ± 0.85 ms [range, 40.1–62.6 ms]; $p < 0.001$); and 50 (57.4 ± 0.82 ms [range, 48.7–66.0 ms] vs. 55.3 ± 0.78 ms [range, 45.5–67.8 ms]; $p < 0.001$) degrees (Fig. 3). At 60–90 degrees the preoperative and postoperative T_2 values were similar, with no significant differences. The maximum change between preoperative and postoperative T_2 values was +6.65 ± 1.09% at 30 degrees to the anatomical axis (Fig. 4).

4.1. Representative patient

MR images of a 39-year-old man showed a horizontal oblique tear extending to the articular surface in the posterior segment of the medial meniscus (Grade 3 signal intensity) [19] (Fig. 5). This patient subsequently underwent arthroscopic partial medial meniscectomy. Preoperative T_2 mapping images revealed that the articular cartilage

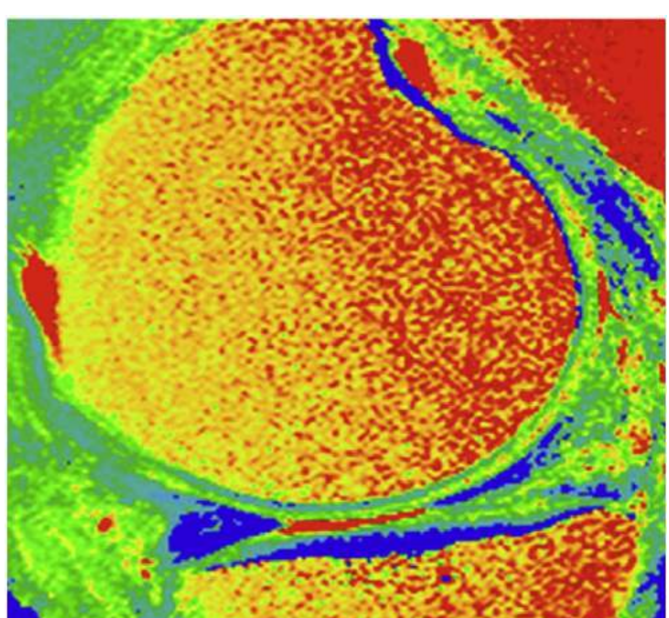

Fig. 1. Sagittal cross-section by magnetic resonance imaging (MRI) T_2 mapping of the central part of the medial condyle of the femur. Two layers were visible, the superficial/intermediate layer and the deep layer.

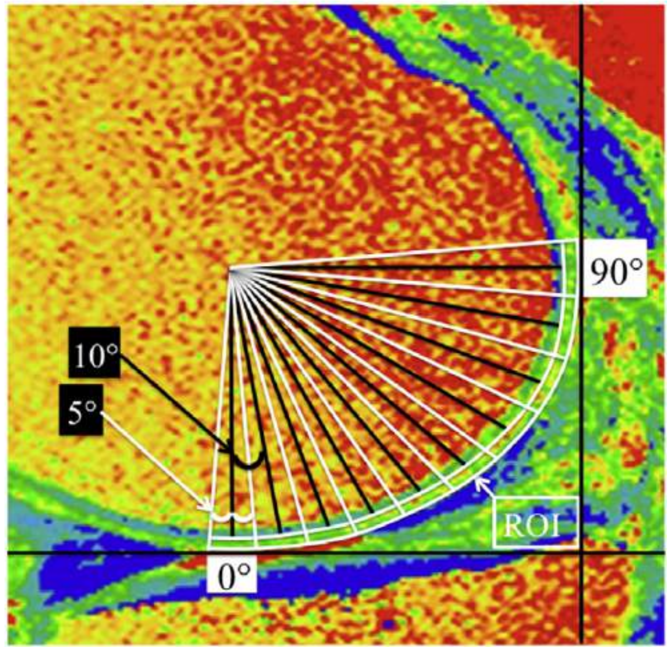

Fig. 2. Evaluation points. Ten points were set at 10 degree intervals along the articular surface between the point of intersection of the anatomical axis of the femur and the articular surface of the medial condyle and the posterior area at approximately 90 degrees relative to the anatomical axis. Regions of interest (ROIs) were set with their centers at these points. The depth of the ROIs in the articular cartilage was set to encompass the superficial and intermediate layers.

was divided into two layers, a superficial/intermediate layer and a deep layer, with longer T_2 values (red areas) evident in some areas of the superficial/intermediate layer (Fig. 6). Postoperative T_2 mapping images showed an increase in areas with longer T_2 values (Fig. 7). T_2 values six months after surgery were longest at 20, 30, 40, and 60 degrees to the anatomical axis of the femur (Fig. 8).

5. Discussion

The articular cartilage is composed of 70% water, 20% collagen, and 10% proteoglycans. Collagen is arrayed in a regular formation, which maintains the shape of the cartilage and limits the motility of water molecules. Proteoglycans are glycoproteins consisting of glycosaminoglycans (GAGs) bound to a core protein. These proteins bind to water molecules, maintaining the expansion pressure of the cartilage and enabling it to function as a shock absorber. The MRI evaluation of articular cartilage has gone beyond morphological analysis [20,21] to include the analysis of collagen arrays, GAG concentration, and water content. MRI methods used to qualitatively evaluate articular cartilage include T_{1rho} mapping [8,9,11,12,21-23], delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) [24], and T_2 mapping [7,8]. Relatively few MRI devices can be used for T_{1rho} mapping, and imaging requires a comparatively longer time; therefore, this technique is mainly used for research purposes. dGEMRIC requires the intravenous administration of 2 to 3 times the normal dose of the contrast agent gadopentetate dimeglumine (Gd-$DTPA^{2-}$) and includes waiting times after its administration; thus, imaging takes several hours to complete. These evaluation methods can be used to analyze GAG concentrations and water contents of articular cartilage. As GAGs are metabolized comparatively quickly in

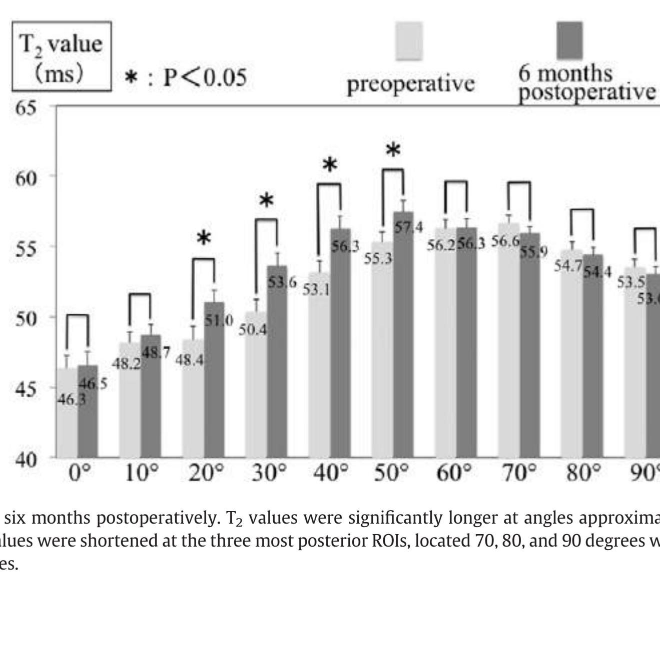

Fig. 3. T_2 values of ROIs preoperatively and six months postoperatively. T_2 values were significantly longer at angles approximately 20, 30, 40, and 50 degrees relative to the anatomical axis of the femur ($p < 0.05$). T_2 values were shortened at the three most posterior ROIs, located 70, 80, and 90 degrees with respect to the anatomical axis of the femur. Error bars indicate standard error (SE) values.

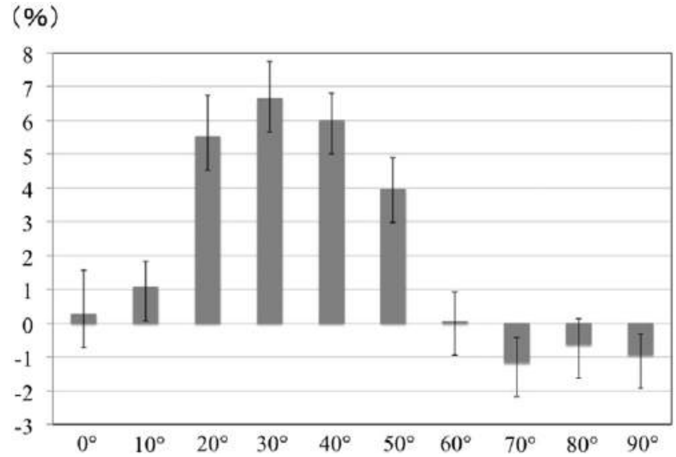

Fig. 4. Difference between preoperative and postoperative T_2 values at each ROI. The difference was greatest at an angle approximately 30 degrees relative to the anatomical axis.

articular cartilage, these methods may enable the assessment of reversible changes in the joint. T_2 mapping is widely used in everyday clinical practice; as it evaluates collagen, which is metabolized more slowly than GAGs, it can be used to assess irreversible degenerations in articular cartilage. Thus, this technique was used for the qualitative analysis of articular cartilage in the early postoperative period after partial medial meniscectomy.

Collagen density and arrays of articular cartilage vary depending on location and layers, with T_2 values differing in layers, even in healthy cartilage. Collagen arrays are comparatively dense in the deep layer of articular cartilage, resulting in shorter T_2 values, but these values tend to be longer from the intermediate to the superficial layer [27]. T_2 values are longest when collagen arrays are oriented 54.7 degrees to the static magnetic field, the so-called "magic angle effect," resulting in healthy cartilage being interpreted as degenerated [25]. In this study, both the pre- and postoperative T_2 values lengthened as the angle increased from 0 to 50 degrees relative to the anatomical axis, but shortened as the angle increased from 70 to 90 degrees. This magic angle effect was also illustrated by the changes in T_2 values at different angles with respect to the anatomical axis, being longest at 50 degrees. The effect of articular cartilage location and layer on T_2 values at the same location in the same patient is reduced, as is the magic angle effect. Moreover, changes in T_2 values at the same point are more strongly affected by

Fig. 5. Representative results in a male patient, aged 39 years, with damage to the medial meniscus of the right knee. Preoperative MRI showed a horizontal oblique tear extending to the articular surface in the posterior segment of the medial meniscus.

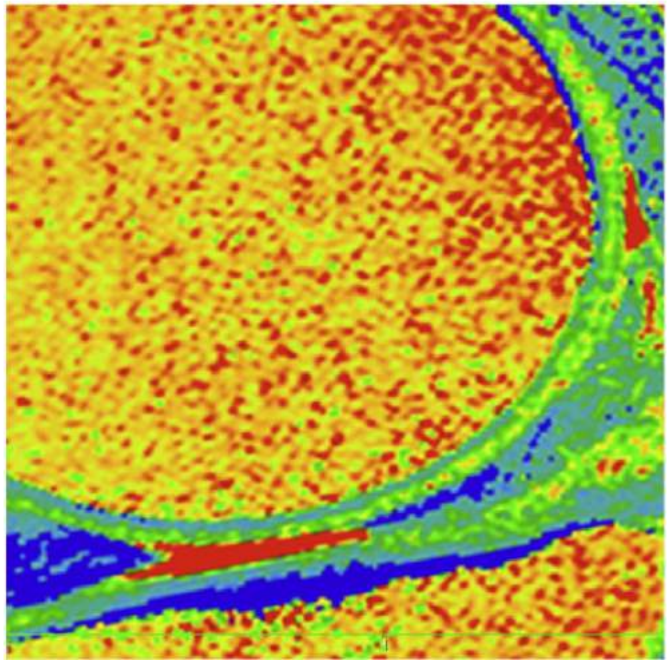

Fig. 6. Preoperative T_2 mapping image from the representative patient. Areas with longer T_2 values were evident in the femoral articular cartilage.

factors other than location and layer [10]. The changes in T_2 values observed in this study may have mainly reflected the effects of partial medial meniscectomy on articular cartilage.

Chemical shift artifacts are caused by fat/water shifts in the interface between bone and cartilage. Since fat/water shifts appear in the phase encoding direction, these shifts have effects on vertical zones, in which the angle between the articular surface and phase encoding direction is 90 degrees. Fat/water shifts affect cortical bone and the deep zone of cartilage because its bandwidth was 292.1 Hz (1.48 pixels), but may have little effect on the superficial and intermediate zones of articular cartilage.

The meniscus is involved in load distribution, joint congruence, shock absorbance and knee joint stability. Removal of the meniscus is removed results in clinical symptoms in approximately 44% of patients over the long term, with arthritic changes evident on plain radiographs in around 66% of the latter [32]. Use of MRI in finite-element analysis of changes in stress after medial meniscectomy, using a 3-dimensional model of the knee, showed that normal stress, shear, and deformation stress on the articular cartilage of the femur increased [29], and the point of concentration of stress had shifted posteriorly [15]. Medial meniscectomy reduced the contact surface area of the femoral condyle by 50–70% and increased contact

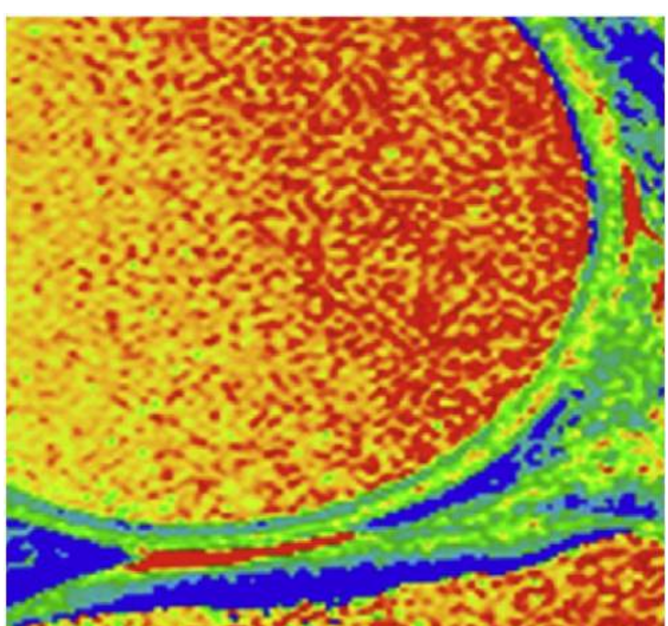

Fig. 7. Six-month postoperative T_2 mapping image from the representative patient. The number of areas with longer T_2 values had increased compared with the preoperative image.

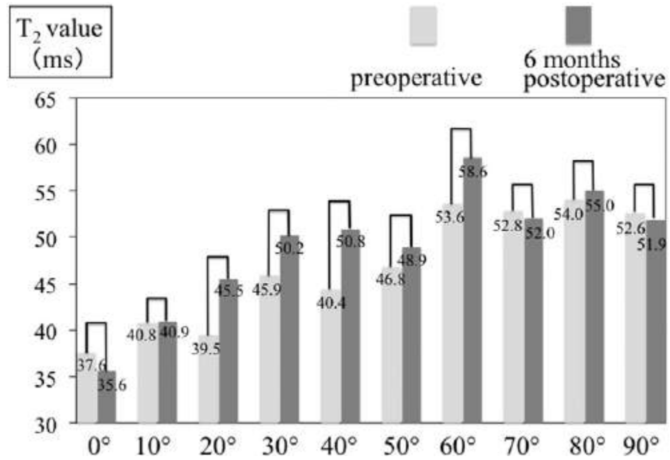

Fig. 8. Preoperative and 6-month postoperative T_2 values at each ROI in the representative patient. Lengthening of T_2 values was observed approximately 20, 30, 40, and 50 degrees relative to the anatomical axis.

pressure by 100% [30,31]; however, changes that occur *in vivo* remain unknown. This study found that T_2 values at points approximately 20, 30, 40, and 50 degrees relative to the anatomical axis of the femur lengthened significantly, with the maximum rate difference between pre- and postoperative T_2 values observed at 30 degrees. These results showed that stresses increased at angles approximately 20, 30, 40, and 50 degrees relative to the anatomical axis of the femur during the early postoperative period after arthroscopic medial meniscectomy, with the greatest stress at approximately 30 degrees. These findings suggested that disorganization of the collagen arrays or increased water content in the articular cartilage may have developed. However, abrasion of the femoral articular cartilage in OA knees was found to occur at positions located approximately 30–60 degrees with respect to the anatomical axis [26], with the maximum point of abrasion of the medial condyle of the femur located at approximately 20 degrees [28]. Therefore, degeneration of the articular cartilage begins at the site of initial onset of OA of the knee after partial medial meniscectomy.

This study had several limitations, including the small number of patients and the lack of a control group and control areas. Moreover, it is unknown whether arthroscopy without meniscectomy influences the signal intensity of cartilage.

6. Conclusions

T_2 mapping was utilized to evaluate qualitative changes in the articular cartilage during the early postoperative period after partial medial meniscectomy. T_2 values in the femoral articular cartilage were significantly longer at points located approximately 20, 30, 40, and 50 degrees with respect to the anatomical axis. The location at which degeneration of the articular cartilage begins is the same as the site of initial onset of OA of the knee after partial medial meniscectomy.

Contributions

All authors have participated sufficiently in drafting the article critically for important intellectual content, and the authors approved the content of the manuscript.

Study conception and design: Kammei Kato, Yuji Arai, Kazuya Ikoma, Shuji Nakagawa, Hiroyoshi Fujiwara, Toshikazu Kubo.

Acquisition of data: Kammei Kato, Yuji Arai, Kazuya Ikoma, Hiroaki Inoue, Hiroyuki Kan, Tomohiro Matsuki.

Analysis and interpretation of data: Kammei Kato, Yuji Arai, Kazuya Ikoma, Shuji Nakagawa, Hiroaki Inoue, Hiroyuki Kan, Tomohiro Matsuki.

Role of the funding source

The authors have no study sponsor.

Competing interests

The authors have no competing interest.

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