Eur Radiol (2009) 19: 1246–1252
DOI 10.1007/s00330-008-1242-0

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Kinematic biomechanical assessment of human articular cartilage transplants in the knee using 3-T MRI: an in vivo reproducibility study

Received: 8 July 2008
Accepted: 18 October 2008
Published online: 5 December 2008
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Abstract The aims of this study were to examine the clinical feasibility and reproducibility of kinematic MR imaging with respect to changes in T_2 in the femoral condyle articular cartilage. We used a flexible knee coil, which allows acquisition of data in different positions from 40° flexion to full extension during MR examinations. The reproducibility of T_2 measurements was evaluated for inter-rater and inter-individual variability and determined as a coefficient of variation (CV) for each volunteer and rater. Three different volunteers were measured twice and regions of interest (ROIs) were selected by three raters at different time points. To prove the clinical feasibility of this method, 20 subjects (10 patients and 10 age- and sex-matched volunteers) were enrolled in the study. Inter-rater variability ranged from 2 to 9 and from 2 to 10% in the deep and superficial zones, respectively. Mean inter-individual variability was 7% for both zones. Different T_2 values were observed in the superficial cartilage zone of patients compared with volunteers. Since repair tissue showed a different behavior in the contact zone compared with healthy cartilage, a possible marker for improved evaluation of repair tissue quality after matrix-associated autologous chondrocyte transplantation (MACT) may be available and may allow biomechanical assessment of cartilage transplants.

Keywords MR imaging/diagnosis · MR imaging/kinematics · Transplantation · Chondrocytes · Autologous

Introduction

The articular cartilage supports weight-bearing mechanics through its highly organized collagen architecture and osmotic pressure via water flux [1]. After injury or in diseased cartilage, normal function may be impaired. Articular cartilage itself has limited capability for repair; however, several surgical procedures have been developed to treat cartilage defects [2]. The idea of using a patient's own chondrocytes for treatment of cartilage defects was developed by Brittberg et al. in 1994 [3]. Autologous chondrocyte implantation (ACI) has been recommended for defects from 2 to 12 cm^2. Briefly, the procedure involves harvesting a specimen of articular cartilage from a relatively low load-bearing area of the patient's own joint during an initial arthroscopy. The cells are then cultivated

for several weeks to expand the chondrocyte population in order to develop a suitable graft for implantation; subsequently, the graft is inserted into the defect during a second operation via a miniarthrotomy. Due to technical difficulties associated with ACI, such as periosteal hypertrophy, delamination, and alteration of chondrocyte phenotypes that lead to decreased ability to produce proteoglycans and collagen type II, matrix-associated autologous chondrocyte transplantation (MACT, Verigen Transplantation Service, Copenhagen, Denmark) has been developed [4]. MACT uses a carrier on which cells are seeded and this carrier is trimmed into the cartilage defect, which simplifies the second stage of classical ACI, since a periosteal flap is no longer necessary. ACI and MACT lead to a maturation of cartilage matrix over time, with the development of an organized collagen architecture. Thus, depending on the postoperative interval, variations in the degree of collagen organization and water content in cartilage repair tissue are seen, which result in altered biomechanical properties compared with healthy native cartilage.

Valuable information can be provided by clinical scoring. Furthermore, histological evaluation from arthroscopic biopsies offers a gold standard for the assessment of cartilage repair tissue. However, this process is invasive, associated with potential morbidity, and has come to be considered an ethically unacceptable way of following up patients after cartilage repair surgery. On the other hand, MRI is a noninvasive technique that can be used for the morphological and biochemical assessment of articular cartilage [5–7]. MRI studies have shown the significant potential of dGEMRIC, T_2 mapping, and diffusion-weighted imaging for the quantitative assessment of cartilage repair tissue [8–14]. dGEMRIC has been proven to be a suitable method for the assessment of proteoglycan (PG) content in healthy and repair cartilages and is widely used in clinical practice [14–17]. T_2 mapping has been extensively studied under loading conditions, either through the use of special compression devices ex vacuo [18–21] or by exposing subjects to exercise and performing consecutive in vivo measurements [22–24]. In general, T_2 relaxation time mapping is indicative of the integrity and arrangement of the collagen network [25, 26], and MRI has been proven to be a sufficiently sensitive modality for evaluating the status of the collagen network [2, 27–29]. Since T_2 was shown in previous studies to be sensitive to loading [30, 31], and T_2 assessment was proved to be a suitable marker for cartilage transplant evaluation in clinical applications [32–34], quantitative T_2 assessment was chosen for our method.

Additional information on the compositional and functional integrity of cartilage may be provided by evaluating the diffusivity within the tissue [35]. Diffusion coefficients have been previously investigated by MRI and have been indicated as a possible marker of early degeneration in articular cartilage [9, 35, 36].

During routine MRI examination of the knee joint, patients are supine with a nearly fully extended knee. In this position, there are only minimal joint reaction forces across the knee as a result of resting muscle tone and so only a fixed area of cartilage is exposed to a small amount of load. If load is applied, as occurs with standing or changing knee flexion, cartilage loading and contact area change, and, as a consequence, water is ‘squeezed’ out of the cartilage tissue to redistribute the load. Evaluation of this behavior is vital to understanding the response of the knee joint and cartilage repair tissue to load.

In our unit, we have a flexible knee coil that allows acquisition of data throughout a continuous range of movement from 0° to 40° within a conventional, closed 3-T MRI scanner. This potentially allows us to assess articular cartilage response to a range of knee movement, which is clinically relevant to the normal gait cycle.

The aims of this study were: first, to examine the clinical feasibility and reproducibility of kinematic MR imaging, with respect to changes in T_2 in the femoral articular cartilage; and second, to assess variations in articular cartilage properties in joint contact areas and nonjoint contact areas in patients after MACT of the femoral condyle, compared with healthy volunteers, as a possible clinical marker for the overall status of transplant maturation.

Materials and methods

MR measurements with a flexible knee coil

MR examinations were performed on a 3-T MR unit (Magnetom Tim Trio, Siemens Erlangen, Germany) with a gradient strength of 40 mT/m using a flexible eight-channel (phased array) knee coil (Fig. 1), consisting of two separate components with four channels on each side (Noras, Germany). The MR examination was performed twice: once with the knee joint in 40° flexion (the maximum possible in a 60-cm magnet bore) and once with the knee joint in full extension (0°). The T_2 relaxation times were obtained from T_2 maps that were reconstructed using a multi-echo, spin-echo technique with a repetition time (TR) of 1650 ms. Six echo times (TE) were collected (12.9 ms, 25.8 ms, 38.7 ms, 51.6 ms, 65.5 ms, and 77.4 ms). Knees were imaged in the sagittal plane and 10 slices in each sequence were used. A 20.0 cm×20.0 cm FOV, 320×320 pixel matrix, a slice thickness of 1 mm, and an in-plane resolution of 0.6 mm×0.6 mm were used. From the acquired data, a pixel-by-pixel basis fitting of signal intensities was performed according to the function $S(TE) = S(0) \times e^{-TE/T_2}$, which describes transversal relaxation. Total scan time for both knee positions was 11 min 50 s. Maps were reconstructed using software incorporated in the clinical scanner (Syngo, Siemens, Erlangen, Germany).

Reproducibility of MR assessment

To evaluate the reproducibility of T_2 measurements, the patellofemoral joints of three different volunteers were imaged in two positions (flexed and extended) twice at different time points. Subsequently, the ROI selection was performed separately within the same slices, at maximal zoom, by three observers experienced in musculoskeletal imaging (Fig. 2). Two sets of ROI were selected in each volunteer: the first in the place where the contact area was observed in extremity extension, and the second in the place where the femoral and tibial cartilage are close to each other during flexion but with no interaction. Analysis was performed on a multimodal workstation (Leonardo, Siemens Medical Solutions, Erlangen, Germany). Reproducibilities, with regard to inter-rater and inter-individual variability, were determined as a coefficient of variation (CV, %) for each volunteer and rater, respectively, and averaged as a root mean square (RMSA, %). Statistical evaluation of reproducibility was performed using analysis of variance (ANOVA) in SPSS version 15 (SPSS Institute, Chicago, IL, USA) for Windows (Microsoft, Redmont, WA, USA).

Volunteer and patient studies

Twenty subjects, 10 patients and 10 age- and sex-matched volunteers, were enrolled in the study. The mean ages of the patients and volunteers were 28.0±6.5 and 28.4±3.6, respectively. There were six males and four females in each group. The MACT graft (mean size of 4 cm^2) was on the medial femoral condyle in six patients and on the lateral femoral condyle in four patients. All patients and volunteers provided written, informed consent to participate in the study, and ethical approval for the study was granted by the Medical University of Vienna Ethics Commission.

In patients, two regions of interest (ROIs) were defined and localized by an experienced musculoskeletal radiologist on two consecutive slices, comprising the MACT graft region. Each ROI was also separated into two equal zones covering the superficial (first half of cartilage from the surface down to deep tissue) and deep (second half) portion of the cartilage layer. In the flexed position, the femoral condyle MACT graft and tibial condyle showed no contact area; however, with the knee in the extended position, a broad contact area for the corresponding femoral and tibial cartilage layers could be seen. In volunteers, identical ROIs were positioned over the femoral cartilage layer in regions corresponding to the ROIs of the age- and sex-matched controls with MACT grafts in both the flexed and extended positions. To allow for the different measurements within each patient, an analysis of variance, using a three-way ANOVA with random factors, was performed using SPSS version 15 (SPSS Inc., Chicago, USA). Values were considered to be statistically significantly different at $p<0.05$.

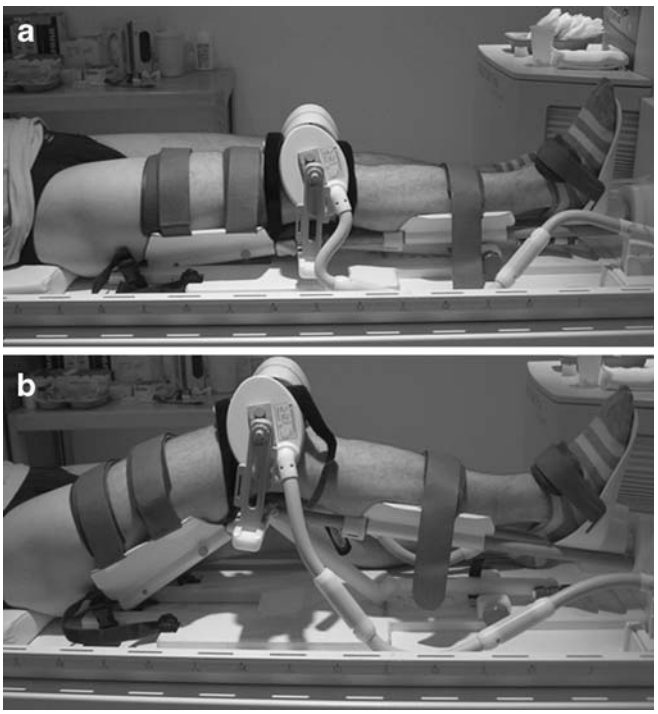

Fig. 1 Flexible eight-channel knee coil used for knee imaging in different flexion positions: **a** complete extension (0°); **b** maximal flexion allowed in scanner bore (40°) 181×195 mm (300×300 DPI)

Results

Reproducibility of quantitative T_2 assessment

With regard to qualitative T_2 measurements, the coefficient of variance (CV %) in volunteers ranged from 3 to 15 and 2 to 13 in the deep and superficial zones, respectively; RMSA was 7% for both zones. The CV (%) of inter-rater variability ranged from 2 to 9 and 2 to 10 in the deep and superficial zones, respectively; RMSA was 7% in the deep zone and 6% in superficial zone.

Volunteer study

Zonal ROI differentiation in the volunteer group's cartilage showed features characteristic of healthy cartilage, i.e., an increasing trend of T_2 values from the deep to the superficial cartilage zone [11, 12]. In the noncontact regions (flexed positions of the knee joint), T_2 values increased significantly ($p<0.05$) from the deep zone (T_2= 41.88±13.07 ms) to superficial zone (T_2=55.17± 19.95 ms). Within contact areas (extended knee position), the T_2 values also increased from the deep zone (T_2=44.25± 10.94 ms) to the superficial zone (T_2=55.91±11.05 ms). This

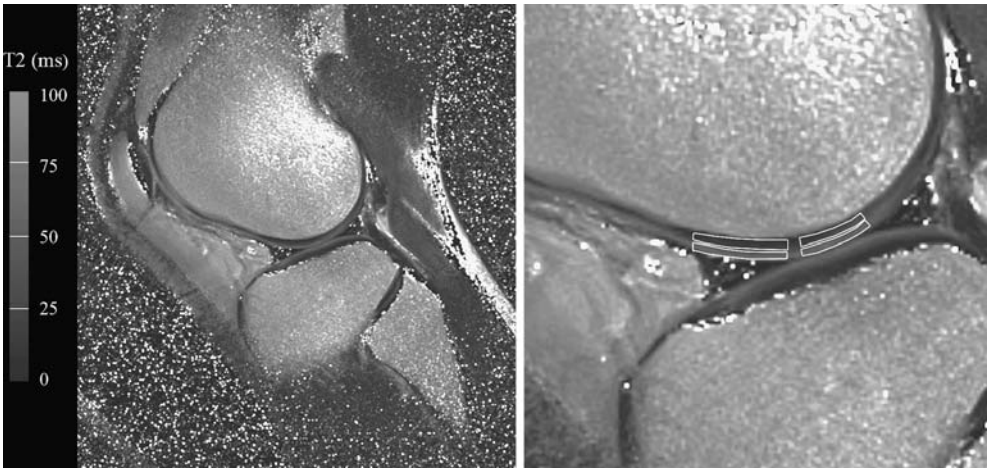

Fig. 2 T_2 map of volunteer in 40° flexion. Multi-echo spin-echo sequence; TR 1650 ms; matrix size 320×320 pixels; FOV 20.0 cm×20.0 cm; TE 12.9 ms, 25.8 ms, 38.7 ms, 51.6 ms, 65.5 ms, and 77.4 ms. Original T_2 map is on the *left*; maximal zoom used for ROI selection is on the *right*. 186×87 mm (300×300 DPI)

difference was also statistically significant ($p<0.05$). The difference in mean T_2 values between contact (50.03±10.84 ms) and noncontact (48.53±16.29 ms) areas was 1.56 ms and was not significant ($p>0.05$).

Patient study

When considering patients with MACT grafts, the T_2 values in noncontact areas were significantly higher in the superficial zone, 56.67±12.45 ms, compared with the deep zone, 48.61±16.63 ms, $p<0.05$. In the contact areas a slight, but nonsignificant, decrease in T_2 was observed from the superficial to deep zones, 48.41±9.2 ms and 46.29±12.44 ms, respectively. The comparison of the deep zone in contact and noncontact areas showed no significant difference, but, in the superficial zone, T_2 values were significantly higher in the noncontact regions compared with the contact regions, 56.67±12.44 ms and 48.41±9.32 ms, respectively. When considering the entire thickness of articular cartilage, mean T_2 values were 52.64±14.03 ms in noncontact areas, but were 47.32±10.40 ms in contact areas; however, this increase was not statistically significant ($p=0.061$). An example of T_2 maps of a patient in different flexion positions is depicted in Fig. 3.

Discussion

The biomechanical properties of repair tissue are different from native articular cartilage due to variations in collagen organization and type, glycosaminoglycan content, and distribution and water content. MRI plays an important role, not only in the diagnosis of chondral lesions, but also in planning the appropriate surgical procedure and in the evaluation of such treatment [37, 38]. MRI has significant potential for the objective evaluation of the morphological properties of transplants, such as filling of the defect, integration into adjacent normal cartilage and bone, as well as the surface, structure, and signal intensity of repair tissue [7, 39–41]. Another advantage is the ability to noninvasively monitor the maturation of transplant tissue in terms of biochemical and ultrastructural development [42–44].

We found that T_2 values vary in both native cartilage and cartilage repair tissue due to joint reactive forces that occur

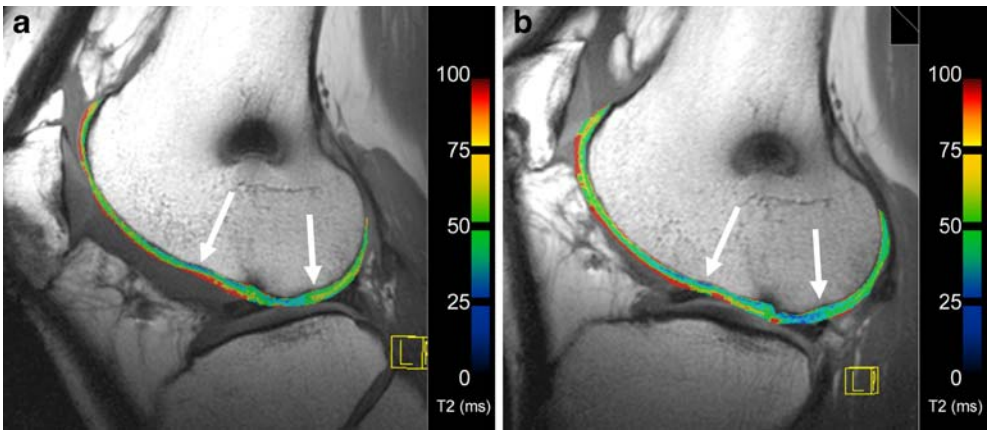

Fig. 3 Color-coded T_2 maps of patient with MACT are depicted; multi-echo spin-echo; TE 12.9 ms, 25.8 ms, 38.7 ms, 51.6 ms, 65.5 ms, and 77.4 ms sequence; TR 1650 ms; matrix size 320×320 pixels; FOV 20.0 cm×20.0 cm. **a** 40° knee joint flexion, **b** full extension; *arrows* indicate the borders of MACT site. 279×121 mm (300×300 DPI)

in contact areas when the knee is examined in flexion and extension, even without weight bearing on the joint. Comparison of contact and noncontact area T_2 values showed statistically significant decreases in T_2 from superficial noncontact areas to superficial contact areas.

One of the significant advances achieved in this study was the implementation of a flexible knee coil combined with our custom-made, MR-compatible joint positioning device. This allowed us to perform scans with the knee in a variety of positions. Most importantly, the degree of flexion could be accurately set and, if required, the device could be positioned at any angle throughout its full range of motion. Measurements were reproducible, with inter-rater variance <7% and inter-individual variance of 7%.

Niitsu et al. highlighted the importance of being able to examine the knee in a flexed position, albeit for evaluation of the anterior cruciate as opposed to articular cartilage. However, these authors were limited by the achievable joint position using a standard knee coil. The joint position was approximately 30°, but this was not accurately and reproducibly measured [45]. The device used in our study allows the joint position to be smoothly set anywhere in the range from full extension to 45°, within a conventional closed MRI scanner. Beyond this degree of flexion, the limiting factor becomes the diameter of the scanner bore. In other studies where the aim was to image the knee in flexed position, only general-purpose surface coils have been used [46, 47].

In our study, the joint contact areas were exposed to joint reactive forces caused by resting muscle tone. While the level of loading is much lower than that which occurs in standing, walking, running, and jumping, etc., we feel that these results provide an initial insight into the articular cartilage response to varying load and joint positions and that the response to increased load is likely to follow a broadly similar pattern but with a greater magnitude.

The biochemical behavior of cartilage tissue during loading has been widely tested in many in vitro studies, in both animal [18, 48] and human [21, 49] models. In a number of these studies, specialized MR-compatible compression devices were used [21, 24, 50]; however, these devices were relatively primitive, difficult to use, unsuitable for in vivo use, or required an open MRI scanner. Subsequent in vivo studies verified the results from in vitro studies. Mosher et al. found a statistically significant decrease in T_2 of the superficial 40% of weight-bearing femoral cartilage after exercise [22]. This supports the hypothesis that cartilage compression results in greater anisotropy of superficial collagen fibers. When normal cartilage is compressed, cartilage water is the major weight-bearing pathway, carrying more than 90% of the load [51]. During compression, there is movement of water through the solid matrix and exudation of fluid from the cartilage surface [52]. Lusse and colleagues have demonstrated a linear relationship between inverse water content and transverse relaxation rates, supporting fast exchange between bound and unbound cartilage water [53]. MACT shows maturation of its matrix over time, with development of an organized collagen structure; thus, a different tissue response in native and transplant tissue to static loading occurs. Proteoglycan content could also be related to observed changes in transversal relaxation time. Reggate and coworkers found no significant change in cartilage T_2 after enzymatic degradation of cartilage proteoglycans in the uncompressed state; however, when proteoglycan-depleted cartilage was placed under compression, there was a statistically significant decrease in T_2 compared with normal cartilage [18]. Therefore, a T_2 decrease can potentially detect differences in transplant tissue, depending on the degree of maturation, compared with native cartilage.

One limitation of our study may be the restriction of maximal flexion, which is related to scanner bore diameter. Flexion in larger angles could provide additional information for patient assessment after MACT, but most commercially available scanners do not allow flexion of more than 40°.

The presented findings indicate the clinical feasibility and reproducibility of kinematic biochemical MR imaging, as the results show significant changes in T_2 in zones of cartilage contact areas. A decrease of T_2 values in the cartilage contact zones may reflect efflux of water content or change of collagen fiber orientation produced by the position-dependent contact of two cartilage layers alone. Since repair tissue shows a different behavior in the contact zone compared with healthy cartilage, a possible marker for improved evaluation of the repair tissue quality after MACT may be available and will allow biomechanical assessment of cartilage transplants.

Acknowledgement Funding for this study was provided by the Austrian Science Fund (FWF) FWF P-18110-B15 and FWF-TRP 494-B05.

References

1. Cohen NP, Foster RJ, Mow VC (1998) Composition and dynamics of articular cartilage: Structure, function, and maintaining healthy state. J Orthop Sport Phys 28:203–215
2. Recht MP, Goodwin DW, Winalski CS et al (2005) MRI of articular cartilage: revisiting current status and future directions. Am J Roentgenol 185:899–914
3. Brittberg M, Lindahl A, Nilsson A et al (1994) Treatment of deep cartilage defects in the knee with autologous chondrocyte transplantation. N Engl J Med 331:889–895
4. Behrens P, Ehlers E, Kochermann K et al (1999) New therapy procedure for localized cartilage defects: encouraging results with autologous chondrocyte implantation. MMW Fortschr Med 141:49–51
5. Marlovits S, Trattnig S (2006) Cartilage repair. Eur J Radiol 57:1–2

6. Chung CB, Frank LR, Resnick D (2001) Cartilage imaging techniques-Current clinical applications and state of the art imaging. Clin Orthop Relat Res S370–S378
7. Marcacci M, Berruto M, Brocchetta D et al (2005) Articular cartilage engineering with Hyalograft® C-3-year clinical results. Clin Orthop Relat Res 96–105
8. Mosher TJ, Dardzinski BJ, Smith MB (2000) Human articular cartilage: influence of aging and early symptomatic degeneration on the spatial variation of T2—preliminary findings at 3 T. Radiology 214:259–266
9. Mlynarik V, Sulzbacher I, Bittsansky M et al (2003) Investigation of apparent diffusion constant as an indicator of early degenerative disease in articular cartilage. J Magn Reson Imaging 17:440–444
10. Burstein D, Velyvis J, Scott KT et al (2001) Protocol issues for delayed Gd (DTPA)(2−)-enhanced MRI: (dGEMRIC) for clinical evaluation of articular cartilage. Magnet Reson Med 45:36–41
11. Welsch GH, Mamisch TC, Domayer SE et al (2008) Cartilage T2 assessment at 3-T MR imaging: in vivo differentiation of normal hyaline cartilage from reparative tissue after two cartilage repair procedures—initial experience. Radiology 247:154–161
12. White LM, Sussman MS, Hurtig M et al (2006) Cartilage T2 assessment: differentiation of normal hyaline cartilage and reparative tissue after arthroscopic cartilage repair in equine subjects. Radiology 241:407–414
13. Trattnig S, Mamisch TC, Welsch GH et al (2007) Quantitative T2 mapping of matrix-associated autologous chondrocyte transplantation at 3 tesla: an in vivo cross-sectional study. Invest Radiol 42:442–448
14. Trattnig S, Marlovits S, Gebetsroither S et al (2007) Three-dimensional delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) for in vivo evaluation of reparative cartilage after matrix-associated autologous chondrocyte transplantation at 3.0T: preliminary results. J Magn Reson Imaging 26:974–982
15. Tiderius CJ, Olsson LE, Leander P et al (2003) Delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) in early knee osteoarthritis. Magnet Reson Med 49:488–492
16. Williams A, Gillis A, McKenzie C et al (2004) Glycosaminoglycan distribution in cartilage as determined by delayed gadolinium-enhanced MRI of cartilage (dGEMRIC): potential clinical applications. Am J Roentgenol 182:167–172
17. Trattnig S, Mamisch TC, Pinker K et al (2008) Differentiating normal hyaline cartilage from post-surgical repair tissue using fast gradient echo imaging in delayed gadolinium-enhanced MRI (dGEMRIC) at 3 tesla. Eur Radiol 18:1251–1259
18. Regatte RR, Kaufman JH, Noyszewski EA et al (1999) Sodium and proton MR properties of cartilage during compression. J Magn Reson Imaging 10:961–967
19. Alhadlaq HA, Xia Y (2004) The structural adaptations in compressed articular cartilage by microscopic MRI (mu MRI) T-2 anisotropy. Osteoarthr Cartil 12:887–894
20. Kaufman JH, Regatte RR, Bolinger L et al (1999) A novel approach to observing articular cartilage deformation in vitro via magnetic resonance imaging. J Magn Reson Imaging 9:653–662
21. Herberhold C, Faber S, Stammberger T et al (1999) In situ measurement of articular cartilage deformation in intact femoropatellar joints under static loading. J Biomech 32:1287–1295
22. Mosher TJ, Smith HE, Collins C et al (2005) Change in knee cartilage T2 at MR imaging after running: a feasibility study. Radiology 234:245–249
23. Liess C, Lusse S, Karger N et al (2002) Detection of changes in cartilage water content using MRI T-2-mapping in vivo. Osteoarthr Cartil 10:907–913
24. Eckstein F, Hudelmaier M, Putz R (2006) The effects of exercise on human articular cartilage. J Anat 208:491–512
25. Kurkijarvi JE, Nissi MJ, Rieppo J et al (2007) The zonal architecture of human articular cartilage described by T(2) relaxation time in the presence of Gd-DTPA(2−). Magn Reson Imaging
26. David-Vaudey E, Ghosh S, Ries M et al (2004) T2 relaxation time measurements in osteoarthritis. Magn Reson Imaging 22:673–682
27. Nieminen MT, Rieppo J, Toyras J et al (2001) T-2 relaxation reveals spatial collagen architecture in articular cartilage: a comparative quantitative MRI and polarized light microscopic study. Magn Reson Med 46:487–493
28. Recht M, Bobic V, Burstein D et al (2001) Magnetic resonance imaging of articular cartilage. Clin Orthop Relat Res S379–S396
29. Smith HE, Mosher TJ, Dardzinski BJ et al (2001) Spatial variation in cartilage T2 of the knee. J Magn Reson Imaging 14:50–55
30. Mosher TJ, Smith HE, Collins C et al (2005) Change in knee cartilage T2 at MR imaging after running: a feasibility study. Radiology 234:245–249
31. Rubenstein JD, Kim JK, Henkelman RM (1996) Effects of compression and recovery on bovine articular cartilage: appearance on MR images. Radiology 201:843–850
32. Welsch GH, Mamisch TC, Domayer SE et al (2008) Cartilage T2 assessment at 3-T MR imaging: in vivo differentiation of normal hyaline cartilage from reparative tissue after two cartilage repair procedures—initial experience. Radiology 247:154–161
33. Trattnig S, Mamisch TC, Welsch GH et al (2007) Quantitative T-2 mapping of matrix-associated autologous chondrocyte transplantcation at 3 tesla—an in vivo cross-sectional study. Invest Radiol 42:442–448
34. Marlovits S, Mamisch TC, Vekszler G et al (2008) Magnetic resonance imaging for diagnosis and assessment of cartilage defect repairs. Injury 39:S13–S25
35. Burstein D, Gray ML, Hartman AL et al (1993) Diffusion of small solutes in cartilage as measured by nuclear magnetic resonance (NMR) spectroscopy and imaging. J Orthop Res 11:465–478
36. Mamisch TC, Menzel MI, Welsch GH et al (2008) Steady-state diffusion imaging for MR in-vivo evaluation of reparative cartilage after matrix-associated autologous chondrocyte transplantation at 3 tesla—preliminary results. Eur J Radiol 65:72–79
37. Nieminen MT, Toyras J, Rieppo J et al (2000) Quantitative MR microscopy of enzymatically degraded articular cartilage. Magn Reson Med 43:676–681
38. Henderson I, Francisco R, Oakes B et al (2005) Autologous chondrocyte implantation for treatment of focal chondral defects of the knee-a clinical, arthroscopic, MRI and histologic evaluation at 2 years. Knee 12:209–216
39. Minas T (2001) Autologous chondrocyte implantation for focal chondral defects of the knee. Clin Orthop Relat Res S349–S361
40. Marlovits S, Zeller P, Singer P et al (2006) Cartilage repair: generations of autologous chondrocyte transplantation. Eur J Radiol 57:24–31
41. Trattnig S, Ba-Ssalamah A, Pinker K et al (2005) Matrix-based autologous chondrocyte implantation for cartilage repair: noninvasive monitoring by high-resolution magnetic resonance imaging. Magn Reson Imaging 23:779–787
42. Winalski CS, Minas T (2000) Evaluation of chondral injuries by magnetic resonance imaging: repair assessments. Oper Tech Sports Med 8:108–119

43. Hunziker EB (2002) Articular cartilage repair: basic science and clinical progress. A review of the current status and prospects. Osteoarthr Cartil 10:432–463
44. Roberts S, McCall IW, Darby AJ et al (2003) Autologous chondrocyte implantation for cartilage repair: monitoring its success by magnetic resonance imaging and histology. Arthritis Res Ther 5:R60–R73
45. Niitsu M, Ikeda K, Itai Y (1998) Slightly flexed knee position within a standard knee coil: MR delineation of the anterior cruciate ligament. Eur Radiol 8:113–115
46. Krampla W, Mayrhofer R, Malcher J et al (2001) MR imaging of the knee in marathon runners before and after competition. Skeletal Radiol 30:72–76
47. Niitsu M, Endo H, Ikeda K et al (2000) MR imaging of the flexed knee: comparison to the extended knee in delineation of meniscal lesions. Eur Radiol 10:1824–1827
48. Kiviranta P, Rieppo J, Korhonen RK et al (2006) Collagen network primarily controls Poisson's ratio of bovine articular cartilage in compression. J Orthop Res 24:690–699
49. Armstrong CG, Bahrani AS, Gardner DL (1979) In vitro measurement of articular cartilage deformations in the intact human hip joint under load. J Bone Joint Surg Am 61:744–755
50. Kaufman JH, Regatte RR, Duvvuri U et al (2000) Cartilage T2 dynamics during compression. Proc Intl Sot Mag Reson Med 8:2116
51. Mow VC, Kuei SC, Lai WM et al (1980) Biphasic creep and stress relaxation of articular cartilage in compression? Theory and experiments. J Biomech Eng 102:73–84
52. Mow VC, Holmes MH, Lai WM (1984) Fluid transport and mechanical properties of articular cartilage: a review. J Biomech 17:377–394
53. Lusse S, Knauss R, Werner A et al (1995) Action of compression and cations on the proton and deuterium relaxation in cartilage. Magn Reson Med 33:483–489