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FULL PAPER

The immediate effect of long-distance running on T_2 and T_2^* relaxation times of articular cartilage of the knee in young healthy adults at 3.0 T MR imaging

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Objective: To quantitatively assess the immediate effect of long-distance running on T_2 and T_2^* relaxation times of the articular cartilage of the knee at 3.0 T in young healthy adults.

Methods: 30 healthy male adults (18–31 years) who perform sports at an amateur level underwent an initial MRI at 3.0 T with T_2 weighted [16 echo times (TEs): 9.7–154.6 ms] and T_2^* weighted (24 TEs: 4.6–53.6 ms) relaxation measurements. Thereafter, all participants performed a 45-min run. After the run, all individuals were immediately re-examined. Data sets were post-processed using dedicated software (ImageJ; National Institute of Health, Bethesda, MD). 22 regions of interest were manually drawn in segmented areas of the femoral, tibial and patellar cartilage. For statistical evaluation, Pearson product-moment correlation coefficients and confidence intervals were computed.

Results: Mean initial values were 35.7 ms for T_2 and 25.1 ms for T_2^* . After the run, a significant decrease in the mean T_2 and T_2^* relaxation times was observed for all segments in all participants. A mean decrease of relaxation time was observed for T_2 with 4.6 ms (± 3.6 ms) and for T_2^* with 3.6 ms (± 5.1 ms) after running.

Conclusion: A significant decrease could be observed in all cartilage segments for both biomarkers. Both quantitative techniques, T_2 and T_2^* , seem to be valuable parameters in the evaluation of immediate changes in the cartilage ultrastructure after running.

Advances in knowledge: This is the first direct comparison of immediate changes in T_2 and T_2^* relaxation times after running in healthy adults.

INTRODUCTION

As the onset and progression of osteoarthritis (OA) is strongly influenced by cartilage lesions,^{1,2} the impact of an early diagnosis of cartilage defects is of great importance.

The number of people suffering from OA is constantly rising. In 2008, 27 million people in the USA showed signs of OA and approximately 15 billion dollars were spent for treatment.³ With the main risk factors of OA being old age, obesity and joint injuries, OA will become an even more relevant topic in the ageing society in the near future. It is expected that about 86% of the US population will be considered overweight in 2030.⁴

Apart from the above-mentioned public health developments, the number of people performing sports at an amateur level has continually grown in the past decades.

In 2012, a new record of finishers in the official runs (of at least 5 km) was counted in the USA, with 15.7 million finishers compared with 4.8 million finishers in 1990.⁵ Especially young adults perform long-distance runs as their regular workout, accounting for >50% of the participants in the 2012 finishers. The effect of running on degenerative diseases of the knee is controversially discussed.^{6,7} Some studies support the thesis that running and a high physical activity can lead to early onset of OA.^{8,9} However, other studies revealed divergent results with no effect or even describe a protective effect on the onset of OA in physically active people.^{10,11}

In recent years, MRI techniques ($T_1\rho$, dGEMRIC, T_2 and T_2^*) have led to a high interest in quantitative biochemical evaluation of the articular cartilage.¹² These quantitative measurements are able to analyze the relaxation times of the articular cartilage and detect the initial stages of cartilage degeneration.¹³

Especially T_2 relaxation time has been acknowledged as a robust imaging biomarker in the evaluation of knee cartilage and early stages of OA even before morphological changes are visible.^{14,15} Cartilage degeneration and changes of internal organization of collagen fibres can lead to an increase of T_2 relaxation times in early stages of OA owing to a higher amount of water molecules in the articular cartilage.^{13,16}

In a few recently published studies, T_2^* has also proven its ability of reliably analyzing the articular cartilage as well as repairing the tissue after cartilage surgery with a significant correlation to T_2 .^{17,18}

$T_1\rho$ and T_2 have also proven to be reliable in the detection of acute effects on the articular cartilage of the knee after physical loading.^{19,20}

To the best of our knowledge, no comparison of the immediate effects on T_2 and T_2^* relaxation times after running has been published. Hence, the purpose of the presented feasibility study was to analyze the acute effects of long-distance running on T_2 and T_2^* relaxation times in young, active adults and to investigate the correlation between these two biomarkers.

METHODS AND MATERIALS

The local ethics committee approved this study and written informed consent was obtained from all volunteers. 30 young male adults between 18 and 31 years (mean age of 27.9 years; median, 28 years) with an average body mass index of 22.52 kg m^{-2} (minimum 19.1, maximum 26.1 kg m^{-2}) participated in the presented study. To minimize the risk of pre-existing early cartilage degeneration, no participants over the age of 35 years were included. All participants were recruited from a local university-based jogging society. All patients are physically active up to 6 h per week at an amateur level without

experiencing knee pain. No prior injuries (meniscal or ligament rupture, fracture, chondral lesion) of the knee were known and no surgery had been performed prior to the study.

Before the initiation of the pre-run MRI, all individuals rested for 30 min in supine position to exclude any effects of prior physical activity on cartilage relaxation times.¹

All participants were examined on 3.0-T MRI (Ingenia; Philips, Best, Netherlands). As the signal receiver, a dedicated eight-channel knee coil (Philips, Best, Netherlands) was placed around the knee with a maximum knee flexion of 10° .

Study protocol

First, the pre-run MRI scan was performed. The imaging protocol of pre-run MRI is summarized in Table 1, including a T_2 weighted turbo spin-echo sequence and a T_2^* weighted gradient-echo sequence. Acquisition time for the pre- and post-run MRI was approximately 30 min.

After the pre-run MRI, the acquired images were analyzed by a senior radiologist with 12 years' experience in musculoskeletal imaging using a commercially available post-processing workstation (Extended Brilliance Workspace, v. 2.0; Philips Healthcare, Best, Netherlands). No relevant cartilage lesions or serious injuries of the knee (meniscal tears, fractures, ligament ruptures) were diagnosed.

Immediately after the pre-run MRI, all participants performed a 45-min run on a commercially available treadmill (Quasar athletics; h/p/cosmos sports & medical, Germany) simulating a long-distance run. All participants ran at a pre-set speed of 6.0 mph.

The second MR examination was started with a mean delay of 4 min (range 2–6 min) after the run with identical positioning of

Table 1. MRI sequence parameters for the assessment of the articular cartilage of the knee at 3.0 T

Sequence parameters	Localizer	3D-PDw	T_1	T_2	T_2^*
TR (ms)	1217.8	1300	818.1	417.6	150
TE (ms)	30	37	10.8	9.7, 19.3, 29, 38.6, 48.6, 58, 67.6, 77.3, 86.9, 96.9, 106.3, 115.9, 125.6, 135.2, 144.9, 154.6	4.6, 6.9, 9.3, 11.6, 13.9, 16.3, 18.6, 20.9, 23.3, 25.6, 28, 30.3, 32.6, 35, 37.3, 39.6, 42, 44.3, 46.6, 49, 52.3, 53.6
Flip angle ($^\circ$)	90	90	90	90	25
Slice thickness (mm)	3.5	3	2	3	2
Slices	15	30	40	30	45
Orientation	Axial, coronal and sagittal	Axial, coronal and sagittal	Coronal	Sagittal	Sagittal
Gap (mm)	11.5	6	2.2	3	2
Matrix (mm)	288×288	320×320	672×672	320×320	320×320
FOV (mm)	300×300	185×185	180×180	160×160	160×160
Scan time (min)	3	8	4	10	7

3D, three-dimensional; FOV, field of view; PDw, proton density weighted; TE, echo time; TR, repetition time.

the participants. The two quantitative sequences for T_2 and T_2^* assessment were applied at the beginning of the post-run MRI in order to keep the time interval between running and quantitative MRI as short as possible. For data analysis, the knee was divided into a medial and a lateral compartment. The vertical ledge of the posterior surface of the patella served as the border between the medial and lateral compartments of the patella. Furthermore, in each compartment, 11 cartilage segments were defined: the patella was divided into 2 segments (base and apex), the femoral cartilage was divided into 6 segments (retropatellar, anterior, central and posterior condyle) and the tibial cartilage was divided into 3 segments (Figure 1).

In concordance to tibial cartilage segments, the central femoral condyle was divided into three subgroups. Here, the anterior and posterior ends of the meniscus represented the boundaries of the subsegments. Centrally, the inner margins of the meniscus horns defined the limits of the central femoral condyle as well as the central tibial cartilage segment.²¹

Two independent readers performed quantitative analysis in a blinded fashion. A polygonal region of interest (ROI) was manually drawn in every segment covering the whole articular cartilage, reading the quantitative maps at the same slice position (Figure 2). To minimize partial volume effects, special attention was paid to including the articular cartilage only and to excluding the cortical bone and meniscal tissue. In contrast to previously published studies, we did not perform a separate investigation of the superficial and deep cartilage layers in each cartilage segment.^{19,22} In some areas, e.g. the lateral anterior condyle, the cartilage appeared

to be too thin (1–3 mm) to safely and reproducibly integrate a sufficient amount of pixels in a single ROI and hence to generate robust results. We have therefore placed a single ROI per cartilage segment to ensure the generation of robust data.

Therefore, in each runner, 88 ROIs including the pre- and post-run measurements for T_2 and T_2^* were assessed, subsequently leading to a total of 2640 ROIs. The collected data were analyzed with a dedicated ImageJ-based software tool (qMapIt).

Statistical analysis

For every ROI in each cartilage segment, the mean relaxation times and confidence intervals in the pre- and post-run scans for T_2 and T_2^* were determined. To correlate the changes in T_2 and T_2^* relaxation times from pre- to post-run scans, the Pearson product-moment correlation coefficient was used independently for all 22 segments. The intraclass correlation coefficient (ICC) was determined to analyze the interobserver agreement.

The analysis and plots were carried out by the statistical software R¹ v. 3.1.2 (R Core Team, Vienna, Austria).

RESULTS

A detailed illustration of the relaxation times for each medial and lateral compartment of pre- and post-run MRI is displayed in Figures 3 and 4.

ICC was calculated for all segments between the two raters. An ICC of 0.92 indicated a very high interrater agreement. Therefore, the following data are presented as average relaxation times determined by both readers.

Figure 1. Predefinition of 11 segments in the lateral compartment of the articular cartilage of the patella, tibia and femur in one participant. Segments 1–11: 1—patella base, 2—patella apex, 3—femoropatellar region of the femur, 4—anterior femoral condyle, 5—anterior central femoral condyle, 6—central femoral condyle, 7—posterior central femoral condyle, 8—dorsal femoral condyle, 9—anterior tibia, 10—central tibia and 11—posterior tibia.

Figure 2. One exemplarily placed region of interest in the lateral posterior central femoral condyle (Segment 7), covering the whole articular cartilage of the T_2 weighted sagittal sequence.

Figure 3. T_2 and T_2^* relaxation times in the pre- and post-run scans in milliseconds (ms) for all 11 segments. Segments 1–11: 1—patella base, 2—patella apex, 3—femoropatellar region of the femur, 4—anterior femoral condyle, 5—anterior central femoral condyle, 6—central femoral condyle, 7—posterior central femoral condyle, 8—dorsal femoral condyle, 9—anterior tibia, 10—central tibia and 11—posterior tibia. l, lateral compartment; m, medial compartment.

Pre-run MRI

T_2

The overall T_2 relaxation times ranged from 26.6 to 42.8 ms.

For the lateral compartment, the mean relaxation time was 35.3 ms (± 26.6 –41.4 ms) and for the medial compartment, it was 36.1 ms (± 29.5 –42.8 ms).

The segment with the lowest T_2 relaxation time in the pre-run scan was the medial patella base (Segment 1; 28.7 ms). The

highest initial relaxation time was found in the lateral posterior central femoral condyle (Segment 7; 41.4 ms).

T_2^*

The overall T_2^* relaxation times ranged from 20.2 to 29.6 ms. The mean T_2^* relaxation time in the pre-run scan was 25.3 ms (21.2–29.6 ms) for the medial compartment and 25.2 ms (20.2–29.2 ms) for the lateral compartment (Figure 3). The lowest T_2^* relaxation times were found in the lateral anterior central femoral condyle (Segment 5; 21.6 ms), whereas the

Figure 4. Differences in milliseconds (ms) for T_2 and T_2^* relaxation times from pre- to post-run scans. In all segments for T_2 and T_2^* , confidence intervals are distinctly beneath the initial values implying significant decreases ($p < 0.05$). Segments 1–11: 1—patella base, 2—patella apex, 3—femoropatellar region of the femur, 4—anterior femoral condyle, 5—anterior central femoral condyle, 6—central femoral condyle, 7—posterior central femoral condyle, 8—dorsal femoral condyle, 9—anterior tibia, 10—central tibia and 11—posterior tibia. l, lateral compartment; m, medial compartment.

highest relaxation times were found in the medial posterior central femoral condyle (Segment 7; 28.1 ms) (Figure 4).

Post-run MRI

T_2

Compared with initial values of the pre-run scan, a significant decrease in relaxation times was assessed for all segments ($p < 0.05$) (Figure 4). The total T_2 values after the run ranged between 23.1 and 37.3 ms. The maximum decrease of 4.9 ms (3.5–6.6 ms) was found for the main weight-bearing area of the femoral condyle (Segments 5–6). In contrast, the slightest decrease in the T_2 relaxation time was noted in the patellar cartilage segments 1–2 with 4.0 ms (2.8–5.7 ms).

No significant difference from pre- to post-run measurements was noted on comparing the medial and lateral compartments ($p > 0.05$).

T_2^*

In all segments, a significant decrease of T_2^* relaxation times was noted after running ($p < 0.05$).

The total T_2^* relaxation times after the run ranged between 16.9 and 26.6 ms. The highest reduction of T_2^* relaxation times was noted in the Segments 5–6 with a mean decrease of 4.0 ms (2.6–5.2 ms). In concordance to T_2 , the slightest decrease was noted for T_2^* in Segments 1 and 2 averaging 2.4 ms (1.2–3.7 ms) (Figure 4).

No significant difference from pre- to post-run measurements was noted on comparing the medial and lateral compartments ($p > 0.05$).

The Pearson correlation coefficient for the differences from pre- to post-run scans in all 22 segments in T_2 was calculated with a mean value of 0.89 (0.63–0.98; standard deviation ± 0.16) and for T_2^* , it was calculated with a mean value of 0.84 (0.4–0.97; standard deviation ± 0.3).

DISCUSSION

In this study, we analyzed the immediate effects of a 45-min run on T_2 and T_2^* relaxation times of the articular cartilage of the knee at 3.0-T MRI in young, healthy adults.

The knee was divided into a medial and lateral compartment. In each compartment, 11 cartilage segments were defined (patella, femur and tibia).

A significant decrease of T_2 and T_2^* relaxation times in the post-run scans was observed in all predefined cartilage segments (Figure 4). A Pearson correlation coefficient of 0.89 for T_2 and 0.84 for T_2^* relaxometry revealed a highly robust correlation of the differences of the pre- to post-run scans for both techniques in all 11 segments. This underlines that the acute changes in the cartilage composition have an almost equivalent effect on T_2 and T_2^* . Moreover, a κ -value of 0.92 underlines a high interrater agreement and, hence, the reproducibility of the results.

The results of our pre-run scan are in concordance to previously reported studies. A recently published analysis of T_2 of the

hyaline cartilage in a healthy study population revealed mean values of 20–30 ms in the deep layer and 40–50 ms in the superficial layer of the femoral condyle with an arthroscopically normal articular cartilage.¹⁴ In comparison with our results, Subburaj et al¹⁹ found similar T_2 values with a mean T_2 relaxation time of 31.7 ms (± 3.9 ms) in 20 young healthy volunteers (age 28.7 years; 22–35 years).

In a baseline study on T_2^* relaxation of the knee, Bittersohl et al²³ published data similar to our results. They reported T_2^* relaxation times of at least 22.2 ms (± 3.2 ms) in the deep layer of the medial tibial plateau and a maximum of 36.6 ms (± 3.1 ms) in the superficial layer of the trochlea.

After mechanical knee loading, varying results have been reported for the analysis of T_2 relaxation time. Liess et al¹ observed a slight increase in T_2 relaxation times by 2.6% after performing 60 knee bends. Souza et al²⁴ observed a significant decrease in T_2 relaxation times in the medial compartment during knee loading.

In our study, the maximum T_2 and T_2^* relaxation times as well as differences from pre- to post-run scans were found in the central femoral condyle cartilage, where the lowest initial values and slightest decrease were found for both markers within the patellar cartilage segments. These findings are in concordance to previously published studies focusing on topographical differences in the cartilage relaxation times of weight-bearing and non-weight-bearing cartilage segments.^{25,26}

The purpose of our study was comparison of T_2 and T_2^* in the assessment of immediate effects of long-distance running on relaxation times. For the assessment of the immediate influence of athletic loading on cartilage relaxation times, only T1rho and T_2 have been applied and investigated so far.^{19,20,27} One previous investigation of Subburaj et al¹⁹ evaluated the acute effect of a 30-min run on T_2 relaxation times in 20 volunteers, analyzing the cartilage and meniscus. The authors reported a significant decrease in relaxation times in all regions of the articular cartilage apart from the lateral tibia. This finding is consistent with our results.

One recent publication by Cha et al²⁰ revealed partially divergent results. In their analysis of 20 amateur athletes, T_2 relaxation times before, immediately after and 2 h following a 30-min run were compared.

The authors observed a slight increase of relaxation times immediately after the run, but they returned to approximately pre-run values after 2 h. As an explanation, the authors argue that they analyzed actual running in an *in vivo* study design instead of passive knee bending. These findings are contrary to our results and to the above-mentioned publications, although the study designs are comparable.

Furthermore, we used two independent quantitative techniques (T_2 and T_2^*), which demonstrated analogue results of decreasing relaxation times immediately after running. Therefore, we support the idea of Mosher et al²⁷ and Subburaj et al¹⁹ of water

Figure 5. One example demonstrating the changes in T_2 and T_2^* from the pre- to post-run scans: a difference of 5.2 ms was noted from the pre-run scan (37.9 ms) (a) in the medial anterior central compartment to 32.7 ms in the post-run scan (b) for T_2 . For T_2^* , the pre-run scan (c) revealed a relaxation time of 23.1 ms in the same cartilage segment, decreasing to 21.0 ms in the post-run scan (d).

extrusion due to cartilage loading, with a subsequent decrease in relaxation times.

To the best of our knowledge, the presented study is the first to quantitatively assess the acute effect of long-distance running on T_2^* relaxation times of the articular cartilage of the knee and to intraindividually relate these results to T_2 measurement.

Longitudinal studies with measurements at several time points are needed to evaluate whether quantitative techniques such as T_2^* can monitor changes in the composition of the articular cartilage of the knee in runners. With this study design, it might be possible to answer whether physical activity can lead to early onset of OA or even protect cartilage degeneration.

Our findings support the thesis that acute loading of the articular cartilage results in decreased relaxation times (Figure 5). It can be assumed that the force on the articular cartilage related to long-distance running leads to a reduction of free water molecules in the extracellular matrix. Consequently, in the presented data, the relaxation times of T_2 and T_2^* have significantly decreased in all segments.

Moreover, if both techniques would be of equivalent value in the assessment of stress-related extrusion of water from the articular cartilage, T_2^* measurement might serve as a complementary quantitative parameter. Furthermore, if applied on the basis of a gradient-echo sequence, it could allow for multiecho imaging with a high image resolution at a rather short acquisition time.^{17,28} In theory, T_2^* imaging is prone to signal loss owing to susceptibility-induced artefacts. Therefore, recent publications raised the evidence that using an ultrashort echo time sequence, T_2^* measurement might allow for the detection of early signs of

degeneration, such as cartilage microcalcification in close proximity to the bone–cartilage interface.^{29,30}

Several limitations of our study have to be addressed. First, we did not perform subsequent scans to identify the time point when cartilage relaxation times return to the pre-run level. This is of potential interest and might be evaluated in future investigation.

Second, no separate investigation of the superficial and deep layers was performed. As previously mentioned, we aimed to assess robust data, allowing us to determine the concordance of two diverse techniques on the basis of reproducible results. We therefore decided to analyze a single ROI in each segment encompassing the whole articular cartilage with a sufficient amount of pixels.

Moreover, a comparable study design with patients suffering from early onset of OA or after anterior cruciate ligament reconstruction would be of interest to compare T_2 and T_2^* relaxation times in these specific cohorts.

In conclusion, this feasibility study investigated the relaxation times of T_2 and T_2^* in young healthy adults focusing on the acute effect of a 45-min long-distance run on the articular cartilage. A significant decrease could be observed in every cartilage segment for both imaging biomarkers. It could be successfully demonstrated that T_2 as well as T_2^* relaxation measurements both seem to be valuable quantitative parameters to analyze immediate changes in the cartilage ultrastructure after running without the application of a contrast agent. On the basis of the presented study, further investigation on the potential significance of T_2^* measurement as a complementary tool for the assessment of articular cartilage is warranted.

REFERENCES

1. Liess C, Lüsse S, Karger N, Heller M, Glüer CC. Detection of changes in cartilage water content using MRI T2-mapping *in vivo*. *Osteoarthritis Cartilage* 2002; **10**: 907–13. doi: <http://dx.doi.org/10.1053/joca.2002.0847>
2. Jackson DW, Simon TM, Aberman HM. Symptomatic articular cartilage degeneration: the impact in the new millennium. *Clin Orthop Relat Res* 2001; (Suppl. 391): S14–25. doi: <http://dx.doi.org/10.1097/00003086-200110001-00003>
3. Lawrence RC, Felson DT, Helmick CG, Arnold LM, Choi H, Deyo RA, et al. Estimates of the prevalence of arthritis and other rheumatic conditions in the United States. Part II. *Arthritis Rheum* 2008; **58**:

- 26–35. doi: <http://dx.doi.org/10.1002/art.23176>
4. Wang Y, Beydoun MA. The obesity epidemic in the United States—gender, age, socioeconomic, racial/ethnic, and geographic characteristics: a systematic review and meta-regression analysis. *Epidemiol Rev* 2007; **29**: 6–28. doi: <http://dx.doi.org/10.1093/epirev/mxm007>
5. Schütttrumpf JP, Behzadi C, Balcerek P, Walde TA, Frosch S, Wachowski MM, et al. Radiologically hyperdense zones of the patella seem to be partial osteonecroses subsequent to fracture treatment. *J Knee Surg* 2013; **26**: 319–26. doi: <http://dx.doi.org/10.1055/s-0032-1332805>
6. Cymet TC, Sinkov V. Does long-distance running cause osteoarthritis? *J Am Osteopath Assoc* 2006; **106**: 342–5.
7. Urquhart DM, Tobing JF, Hanna FS, Berry P, Wluka AE, Ding C, et al. What is the effect of physical activity on the knee joint? A systematic review. *Med Sci Sports Exerc* 2011; **43**: 432–42. doi: <http://dx.doi.org/10.1249/MSS.0b013e3181ef5b8>
8. Kujala UM, Kettunen J, Paananen H, Aalto T, Battié MC, Impivaara O, et al. Knee osteoarthritis in former runners, soccer players, weight lifters, and shooters. *Arthritis Rheum* 1995; **38**: 539–46. doi: <http://dx.doi.org/10.1002/art.1780380413>
9. McAlindon TE, Wilson PW, Aliabadi P, Weissman B, Felson DT. Level of physical activity and the risk of radiographic and symptomatic knee osteoarthritis in the elderly: the Framingham study. *Am J Med* 1999; **106**: 151–7. doi: [http://dx.doi.org/10.1016/S0002-9343\(98\)00413-6](http://dx.doi.org/10.1016/S0002-9343(98)00413-6)
10. Rogers LG, Macera CA, Hootman JM, Ainsworth BE, Blair SN. The association between joint stress from physical activity and self-reported osteoarthritis: an analysis of the Cooper clinic data. *Osteoarthritis Cartilage* 2002; **10**: 617–22. doi: <http://dx.doi.org/10.1053/joca.2002.0802>
11. Fries JF, Singh G, Morfeld D, Hubert HB, Lane NE, Brown BW Jr. Running and the development of disability with age. *Ann Intern Med* 1994; **121**: 502–9. doi: <http://dx.doi.org/10.7326/0003-4819-121-7-199410010-00005>
12. Matzat SJ, van Tiel J, Gold GE, Oei EH. Quantitative MRI techniques of cartilage composition. *Quant Imaging Med Surg* 2013; **3**: 162–74. doi: <http://dx.doi.org/10.3978/j.issn.2223-4292.2013.06.04>
13. Regatte RR, Akella SV, Lonner JH, Kneeland JB, Reddy R. T1rho relaxation mapping in human osteoarthritis (OA) cartilage: comparison of T1rho with T2. *J Magn Reson Imaging* 2006; **23**: 547–53. doi: <http://dx.doi.org/10.1002/jmri.20536>
14. Kijowski R, Blankenbaker DG, Munoz del Rio A, Baer GS, Graf BK. Evaluation of the articular cartilage of the knee joint: value of adding a T2 mapping sequence to a routine MR imaging protocol. *Radiology* 2013; **267**: 503–13. doi: <http://dx.doi.org/10.1148/radiol.12121413>
15. Balamoody S, Williams TG, Wolstenholme C, Waterton JC, Bowes M, Hodgson R, et al. Magnetic resonance transverse relaxation time T2 of knee cartilage in osteoarthritis at 3-T: a cross-sectional multicentre, multi-vendor reproducibility study. *Skeletal Radiol* 2013; **42**: 511–20. doi: <http://dx.doi.org/10.1007/s00256-012-1511-5>
16. Mosher TJ, Dardzinski BJ, Smith MB. Human articular cartilage: influence of aging and early symptomatic degeneration on the spatial variation of T2—preliminary findings at 3 T. *Radiology* 2000; **214**: 259–66. doi: <http://dx.doi.org/10.1148/radiology.214.1.r00ja15259>
17. Marik W, Apprich S, Welsch GH, Mamisch TC, Trattnig S. Biochemical evaluation of articular cartilage in patients with osteochondrosis dissecans by means of quantitative T2- and T2-mapping at 3T MRI: a feasibility study. *Eur J Radiol* 2012; **81**: 923–7. doi: <http://dx.doi.org/10.1016/j.ejrad.2011.01.124>
18. Stelzeneder D, Shetty AA, Kim SJ, Trattnig S, Domayer SE, Shetty V, et al. Repair tissue quality after arthroscopic autologous collagen-induced chondrogenesis (ACIC) assessed via T2* mapping. *Skeletal Radiol* 2013; **42**: 1657–64. doi: <http://dx.doi.org/10.1007/s00256-013-1708-2>
19. Subburaj K, Kumar D, Souza RB, Alizai H, Li X, Link TM, et al. The acute effect of running on knee articular cartilage and meniscus magnetic resonance relaxation times in young healthy adults. *Am J Sports Med* 2012; **40**: 2134–41. doi: <http://dx.doi.org/10.1177/0363546512449816>
20. Cha JG, Lee JC, Kim HJ, Han JK, Lee EH, Kim YD, et al. Comparison of MRI T2 relaxation changes of knee articular cartilage before and after running between young and old amateur athletes. *Korean J Radiol* 2012; **13**: 594–601. doi: <http://dx.doi.org/10.3348/kjr.2012.13.5.594>
21. Mosher TJ, Liu Y, Torok CM. Functional cartilage MRI T2 mapping: evaluating the effect of age and training on knee cartilage response to running. *Osteoarthritis Cartilage* 2010; **18**: 358–64. doi: <http://dx.doi.org/10.1016/j.joca.2009.11.011>
22. Apprich S, Mamisch TC, Welsch GH, Stelzeneder D, Albers C, Totzke U, et al. Quantitative T2 mapping of the patella at 3.0T is sensitive to early cartilage degeneration, but also to loading of the knee. *Eur J Radiol* 2012; **81**: e438–43. doi: <http://dx.doi.org/10.1016/j.ejrad.2011.03.069>
23. Bittersohl B, Hosalkar HS, Sondern M, Miese FR, Antoch G, Krauspe R, et al. Spectrum of T2* values in knee joint cartilage at 3 T: a cross-sectional analysis in asymptomatic young adult volunteers. *Skeletal Radiol* 2014; **43**: 443–52. doi: <http://dx.doi.org/10.1007/s00256-013-1806-1>
24. Souza RB, Stehling C, Wyman BT, Hellio Le Graverand MP, Li X, Link TM, et al. The effects of acute loading on T1rho and T2 relaxation times of tibiofemoral articular cartilage. *Osteoarthritis Cartilage* 2010; **18**: 1557–63. doi: <http://dx.doi.org/10.1016/j.joca.2010.10.001>
25. Xia Y. Heterogeneity of cartilage laminae in MR imaging. *J Magn Reson Imaging* 2000; **11**: 686–93. doi: [http://dx.doi.org/10.1002/1522-2586\(200006\)11](http://dx.doi.org/10.1002/1522-2586(200006)11)
26. Kurkijärvi JE, Nissi MJ, Kiviranta I, Jurvelin JS, Nieminen MT. Delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) and T2 characteristics of human knee articular cartilage: topographical variation and relationships to mechanical properties. *Magn Reson Med* 2004; **52**: 41–6. doi: <http://dx.doi.org/10.1002/mrm.20104>
27. Mosher TJ, Smith HE, Collins C, Liu Y, Hancy J, Dardzinski BJ, et al. Change in knee cartilage T2 at MR imaging after running: a feasibility study. *Radiology* 2005; **234**: 245–9. doi: <http://dx.doi.org/10.1148/radiol.2341040041>
28. Pauli C, Bae WC, Lee M, Lotz M, Bydder GM, D'Lima DL, et al. Ultrashort-echo time MR imaging of the patella with bicomponent analysis: correlation with histopathologic and polarized light microscopic findings. *Radiology* 2012; **264**: 484–93. doi: <http://dx.doi.org/10.1148/radiol.12111883>
29. Bae WC, Dwek JR, Znamirovski R, Statum SM, Hermida JC, D'Lima DD, et al. Ultrashort echo time MR imaging of osteochondral junction of the knee at 3 T: identification of anatomic structures contributing to signal intensity. *Radiology* 2010; **254**: 837–45. doi: <http://dx.doi.org/10.1148/radiol.09081743>
30. Chu CR, Williams AA, West RV, Qian Y, Fu FH, Do BH, et al. Quantitative magnetic resonance imaging UTE-T2* mapping of cartilage and meniscus healing after anatomic anterior cruciate ligament reconstruction. *Am J Sports Med* 2014; **42**: 1847–56. doi: <http://dx.doi.org/10.1177/0363546514532227>