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Differences of radiocarpal cartilage alterations in arthritis and osteoarthritis using morphological and biochemical magnetic resonance imaging without gadolinium-based contrast agent administration

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Abstract

Objectives To identify differences of radiocarpal cartilage alterations in osteoarthritis and arthritis using multiparametrical magnetic resonance imaging (MRI) comprising morphological and biochemical sequences without gadolinium-based contrast agent administration.

Methods In this prospective study, multiparametrical MRI of the radiocarpal cartilage was performed in 47 participants (mean age, 46.6 ± 17.6 years; min., 20 years; max., 79 years) on a 3 Tesla MRI. The cohort consisted of 11 patients suffering from arthritis, 10 patients with osteoarthritis, 14 patients after distal radius fracture, and 12 healthy volunteers. The radiocarpal cartilage was assessed using morphological (DESS, TrueFISP) and biochemical (T2*) MRI sequences without the application of intravenous contrast agent. The modified Outerbridge classification system for morphological and region-of-interest analyses for biochemical analysis was applied to assess the degree of cartilage damage in each patient before data were statistically tested for significant difference between the groups using a post hoc Tukey test.

Results In morphological imaging, cartilage damage was significantly more frequent in arthritis and osteoarthritis than in healthy volunteers (DESS: $p = 0.01$, $p = 0.0004$; TrueFISP: $p = 0.02$, $p = 0.0001$). In T2* imaging, patients with osteoarthritis showed higher cartilage damage compared to patients with arthritis ($p = 0.01$).

Conclusion With multiparametrical MRI, it is possible to identify differences of radiocarpal cartilage alterations of patients with arthritis and osteoarthritis using the combination of morphological and biochemical MR imaging of the radiocarpal cartilage without the application of contrast agent. Multiparametrical MRI without the usage of contrast agent may be a potential tool helping to distinguish both entities.

Key Points

- *Multiparametrical MRI with morphological and biochemical sequences allows the differentiation of patients with arthritis and osteoarthritis.*
- *High-resolution MRI of radiocarpal cartilage is possible without administration of contrast agent.*

Keywords Morphological and cartilage MR imaging · Without gadolinium-based contrast agent · Arthritis · Osteoarthritis · Radiocarpal cartilage

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Abbreviations

ANOVA	Analysis of variance
CI	Confidence interval
DESS	Double echo steady state
DGEMRIC	Delayed gadolinium-enhanced MRI of cartilage
DRF	Distal radius fracture
DWI	Diffusion-weighted imaging
EMA	European Medicines Agency
GagCEST	Glycosaminoglycan chemical exchange saturation transfer
ICC	Intraclass correlation coefficient
LC	Central lunate
LP	Peripheral lunate
MRI	Magnetic resonance imaging
OA	Osteoarthritis
PD	Proton density
RA	Rheumatoid arthritis
ROI	Region-of-interest
SC	Central scaphoid
SP	Peripheral scaphoid
STARD	Standards for reporting of diagnostic accuracy studies
TNF-α	Tumor necrosis factor α
TRUFI	True fast imaging with steady state precession

Introduction

The radiocarpal cartilage of the wrist is one of the most challenging joints for magnetic resonance imaging (MRI) due to its thin hyaline cartilage layers and multiple surfaces [1]. Wrist pain is a common clinical problem of varying etiology [2]. In many cases, articular cartilage injury or loss is suspected if other obvious clinical syndromes are excluded [3]. To guide therapy, it is essential to detect cartilage damage. Cartilage injury may result either from direct trauma or as a common end point of inflammatory or degenerative diseases [4]. In clinical practice, the differentiation of arthritis and osteoarthritis (OA) may cause diagnostic problems because of the chronic progressive nature of both entities [5, 6]. However, different treatment strategies are tracked in both diseases, which asks for better diagnostic tools to detect early stages, especially in the case of rheumatoid arthritis where an early therapy start is considered to be a decisive prognostic factor [7].

Conventional radiographs are limited in showing cartilage damage until the disease has processed to joint space narrowing [2]. For wrist imaging, MRI is the technique of choice [8]. Particularly, MRI is able to depict both focal and diffuse cartilage defects [9]. Several MR sequences are available for morphological cartilage imaging of the wrist. Among them, the TRUFI (true fast imaging with steady state precession) sequence is the most accurate method according to a current study [10]. The DESS (double echo steady state) sequence is another morphological MR sequence that has been proven useful for cartilage assessment [11, 12]. Biochemical cartilage imaging has been proposed to assess extracellular matrix components of hyaline cartilage with delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) technique as the gold standard [13]. For dGEMRIC, the application of intravenous contrast agent is obligatory. However, recent studies brought potential adverse effects of gadolinium to international attention [14, 15]. Due to potential gadolinium depositions in the brain, the European Medicines Agency (EMA) banned several linear gadolinium-based contrast agents, even though macrocyclic contrast agents have not been suspended their use should be limited to those examinations where there is no alternative [16]. Hence, future research should focus on gadolinium-free molecular MR imaging of cartilage such as glycosaminoglycan chemical exchange saturation transfer (gagCEST), sodium MRI and T1 rho mapping to visualize the GAG content, T2/T2* mapping to evaluate the water content, and collagen network integrity or diffusion-weighted imaging (DWI) [17–19]. In this study, we applied T2* mapping for molecular cartilage imaging. T2* mapping is advantageous in many ways. Next to no needed application of contrast media, it allows a three-dimensional (3D), high-resolution, isotropic cartilage evaluation with a short acquisition time [20].

The purpose of this study was to identify differences in osteoarthritis and arthritis with multiparametrical MRI using morphological (DESS, TRUFI) and biochemical (T2*) sequences of radiocarpal cartilage without the usage of intravenous contrast agent.

Materials and methods

Study design

The study was approved by the local ethics committee. Written informed consent was obtained from all volunteers prior to inclusion for this prospective study.

Study population

Forty-seven participants (27 male, 20 female; mean age, 46.6 ± 17.6 years; min., 20 years; max., 79 years) who underwent 3T wrist MRI during the period from October 2016 to March 2017 were prospectively enrolled in this study. The cohort consisted of 11 patients suffering from arthritis (disease duration, 2.9 ± 1.7 years; min., 1 year; max., 7 years; 5 male; 6 female; mean age, 47.3 ± 15.7 years; min., 27 years; max., 76 years), 10 patients with osteoarthritis (disease duration, 7.6 ± 4.7 years; min., 2 years; max., 19 years; 6 male; 4 female; mean age, 63.3 ± 9.6 years; min., 50 years; max., 79 years), 14 patients with a condition following distal radius fracture (trauma 4.1 ± 2.7 years ago; min., 1 year; max., 11 years; 8 male, 6 female; mean age,

Table 1 Detailed sequence parameters

		T2* map 3D	DESS 3D	TrueFISP 3D
T_R/T_E	ms/ms	33.0/4.95	11.86/4.54	10.06/4.16
Field of view	mm^2	100 × 61	94 × 61	100 × 61
Slice thickness	mm	0.42	0.42	0.42
Flip angle	°	25	25	57
Averages		1	2	2
Basic resolution		256	128	256
Number of slices		144	144	144
Acquisition duration	min:sec	5:47	5:41	5:13

45.5 ± 16.3 years; min., 23 years; max., 70 years) and 12 healthy controls (8 male; 4 female; mean age, 33.5 ± 13 years; min., 20 years; max., 65 years) without any wrist pain or trauma in their clinical history. The patients with condition following distal radius fracture could be divided into six patients with intraarticular fracture and eight patients without joint involvement. The group of arthritis consisted of five (three seropositive) patients with rheumatoid arthritis (RA). Among them, two patients were treated with methotrexate (one in combination with prednisolone), one patient received TNF-α inhibitors in combination with prednisolone, one patient prednisolone only, and another patient received no therapy. The other six arthritis patients were suffering from psoriatic arthritis (treated with apremilast in combination with prednisolone), spondyloarthritis (treated with TNF-α inhibitors), Stills disease (treated with prednisolone), sarcoidosis (treated with prednisolone), and systemic juvenile idiopathic arthritis (treated with methotrexate). All patients with arthritis showed signs of wrist synovitis in a clinical examination. The patients suffering from osteoarthritis received conservative therapy, such as pain medication or physical therapy. All patients with a condition following distal radial fracture had terminated disease-specific therapy and osteosynthesis equipment had been removed prior to the study. All patients were diagnosed by clinically experienced rheumatologists and trauma surgeons. Exclusion criteria were general contraindications to MR imaging, metal implants at the wrist, and undefined wrist disease.

MR imaging protocol

All MR examinations were performed at a 3T MRI scanner (Magnetom Skyra, Siemens Healthineers) using a dedicated, 16 channel, high-resolution wrist coil. Two patients were measured with a four-channel flex coil, because they did not fit into the dedicated wrist coil due to plaster casts. All participants were examined in prone position with the arm over the head, the so-called superman position. Our sequence protocol included the morphological sequences DESS and TRUFI as well as the biochemical imaging sequence T2*, each acquired in coronal orientation. For T2* mapping, nine consecutive echoes were obtained (TE: 16.1 ms, 32.2 ms, 48.3 ms, 64.4 ms, 80.5 ms, 96.6 ms, 113.0 ms, 129.0 ms, 145.0 ms). To complete the sequence protocol, T1- and PD (proton density)-weighted images in coronal orientation were supplemented for the evaluation of bone and joint fluid in a clinical setting. These five sequences resulted in an examination duration of about 22 min. No intravenous contrast application was applied. The MR protocol details were given in Table 1.

Data analysis

All data sets were evaluated by a board certified radiologist with 6 years of experience in musculoskeletal imaging and a medical student, trained in cartilage segmentation. Both readers were blinded to clinical diagnosis and to the other morphological analyses, respectively. The molecular image analysis was performed in consensus [21]. Analysis of the two morphological sequences and the biochemical sequence were performed separately and with 2 weeks apart to avoid recognition bias. Due to the scapholunate ligament, the radiocarpal cartilage was divided into different zones: peripheral lunate (LP), central lunate (LC), peripheral scaphoid (SP),

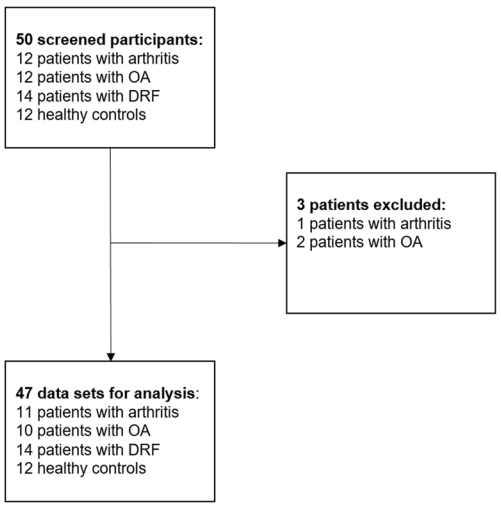

Fig. 1 Screening flow chart of the study participants according to STARD. Three patients (one with arthritis and two with osteoarthritis) prematurely terminated the MR examination and hat to be excluded

Table 2 Morphological and biochemical assessment of radiocarpal cartilage in healthy participants, patients with arthritis, osteoarthritis, and with a condition following distal radius fracture

	Mean	Std	Median	Min	Max	CI (lower limit)	CI (upper limit)
Control DESS	0.521	0.511	0.375	0	3	0.355	0.81
Control TrueFISP	0.25	0.433	0	0	3	0.005	0.495
Control T2* map [ms]	21.398	3.45	21.525	12.7	26.9	19.44	23.35
Arthritis DESS	1.625	1.31	1.125	0	4	0.813	2.437
Arthritis TrueFISP	1.475	1.48	0.875	0	4	0.557	2.393
Arthritis T2* map [ms]	19.08	3.579	19.325	10.2	27	16.964	21.195
Osteoarthritis DESS	2.639	1.263	3	0	4	1.814	3.464
Osteoarthritis TrueFISP	2.472	1.192	2.75	0	4	1.694	3.251
Osteoarthritis T2* map [ms]	14.698	4.478	14.64	5.8	23.5	11.922	17.468
Trauma DESS	1.696	1.035	1.5	0	4	1.154	2.239
Trauma TrueFISP	1.607	1.174	1.375	0	4	0.992	2.222
Trauma T2* map [ms]	18.366	2.913	17.938	11.3	28.8	16.84	19.766

and central scaphoid (SC). For morphological cartilage assessment, the modified Outerbridge classification [22] was used: grade 0, normal; grade 1, cartilage softening; grade 2, cartilage abrasion; grade 3, cartilage loss; grade 4, no evaluation of cartilage possible. The data sets of the molecular sequence were converted to the Leonardo® Workstation (Siemens Healthineers) and a region-of-interest (ROI) analysis was performed for each cartilage zone. T2* images with a TE time of 16.1 ms were used as an anatomic reference for cartilage identification. The ROIs were transferred to the co-registered T2* map. TE times in milliseconds of the different cartilage zones were calculated. The degree of cartilage damage correlates with decreasing TE times in the T2* map [23].

Statistical analysis

Statistical analysis was performed using MATLAB (MathWorks). The mean, standard deviations, median, minimum, maximum, and 95% confidence interval (CI) were calculated for morphological and biochemical assessment of radiocarpal cartilage. Kolmogorow-Smirnow-Lilliefors tests were used to assess normal distribution. Univariate analysis of variance (ANOVA) and post hoc Tukey test were performed to assess statistical differences of the means of the morphological and biochemical cartilage evaluation of the different groups and subgroups. After Bonferroni correction, $p < 0.0167$ was assumed statistically significant. Intra- and interreader reliability were tested with intraclass correlation coefficient (ICC) for morphological cartilage evaluation.

Results

The cartilage assessment of 47 participants could be used for statistical analysis. Three patients (one with arthritis and two with osteoarthritis) had prematurely terminated the MR examination (Fig. 1). The descriptive statistics were summarized in Table 2 (mean ± standard deviation; median; minimum/maximum; 95% CI [lower limit; upper limit]). Interreader (ICC = 0.91) and intrareader reliability (ICC = 0.91) were excellent.

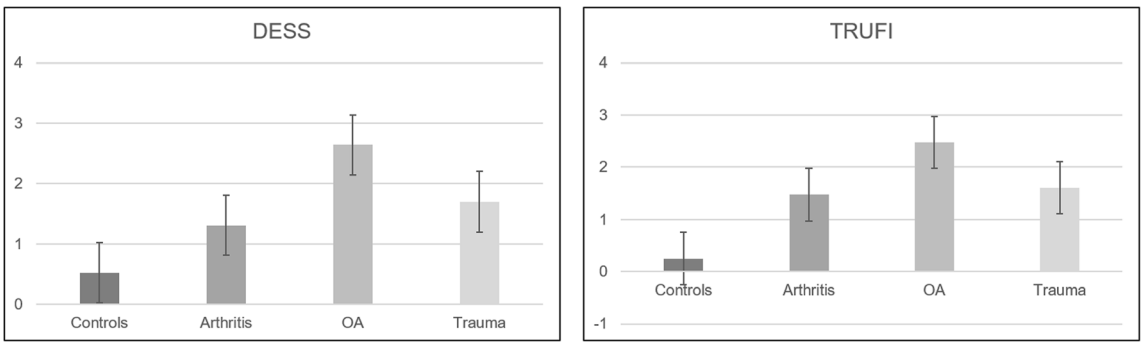

Fig. 2 Bar chart of the morphological radiocarpal cartilage assessment according to modified Outerbridge classification for healthy controls, patients with arthritis, osteoarthritis (OA), or with a condition following distal radius fracture (trauma). Significantly higher cartilage damage was found in patients with arthritis, OA, or trauma compared to healthy controls with morphological cartilage imaging (DESS, TRUFI)

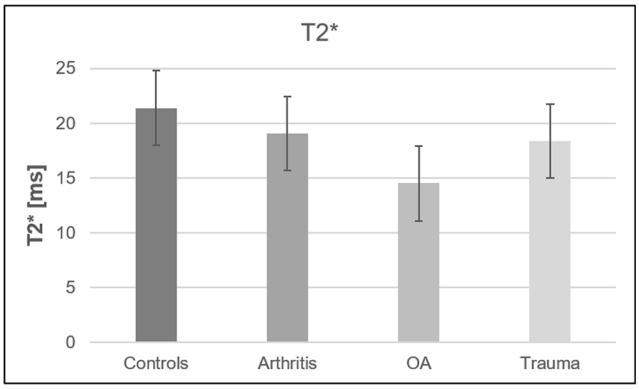

Fig. 3 Bar chart of the biochemical radiocarpal cartilage assessment according to T2* mapping in milliseconds (ms) for healthy controls, patients with arthritis, osteoarthritis (OA), or with a condition following distal radius fracture (trauma). Significantly higher cartilage damage with lower T2* values was found in patients with OA compared to patients suffering from arthritis, patients with condition after distal radius fracture, and healthy controls

Analysis of morphological cartilage assessment

DESS sequence showed significantly higher cartilage damage in patients with arthritis ($p = 0.018$) and osteoarthritis ($p < 0.0001$) and patients with condition after distal radius fracture ($p = 0.005$) compared with healthy controls. TRUFI revealed significantly higher cartilage degradation in patients suffering from arthritis ($p = 0.0162$), patients with osteoarthritis ($p < 0.0001$), and patients with condition after distal radius fracture ($p = 0.003$) compared with healthy controls. For both, DESS and TRUFI, patients with arthritis illustrated significantly lower cartilage damage in central zones (LC and SC) compared to osteoarthritis (DESS: $p = 0.003$; TRUFI: $p = 0.011$). For peripheral zones (LP and SP), no significant difference could be found ($p > 0.05$). In patients with arthritis, as well as in patients suffering from osteoarthritis, significantly higher cartilage loss was found in central zones (LC and SC) compared to peripheral zones (LP and SP) (arthritis: $p = 0.04$; osteoarthritis: $p = 0.02$). No significant difference between intraarticular fracture and no intraarticular fracture line could be depicted in patients with condition after distal radius fracture for DESS and TRUFI ($p > 0.05$) (Fig. 2).

Analysis of molecular cartilage assessment

T2* sequence showed significantly higher cartilage damage in patients with osteoarthritis compared to patients with arthritis ($p = 0.005$), patients with condition after distal radius fracture

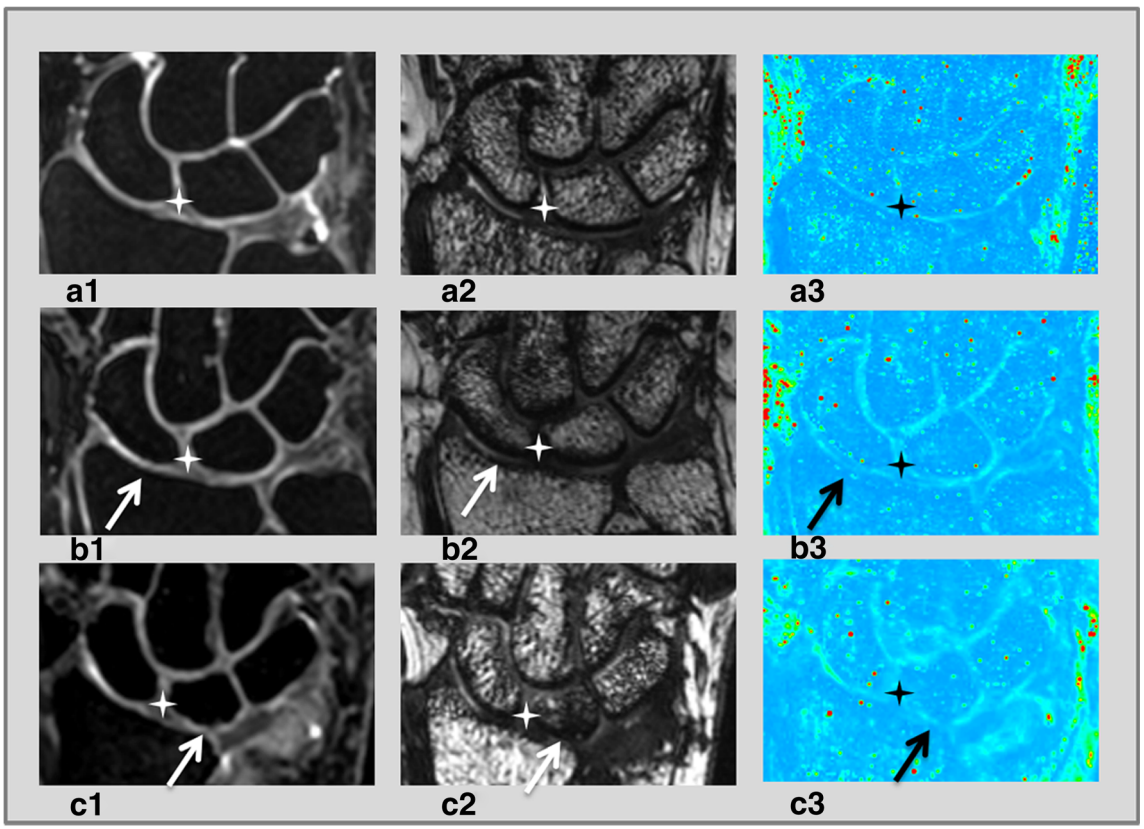

Fig. 4 Image synopsis of a healthy participant (**a**), a patient with arthritis (**b**), and a patient suffering from osteoarthritis (**c**). For each case, the three main sequences DESS (1), TrueFISP (2), and T2* map (3) were presented. The arrows in figures **b**1–**b**3 emphasize a low-grade cartilage damage of central zone under the scaphoid of a patient with arthritis. Images **c**1–**c**3 of a patient suffering from osteoarthritis show a high-grade cartilage damage of the articular cartilage of the lunate

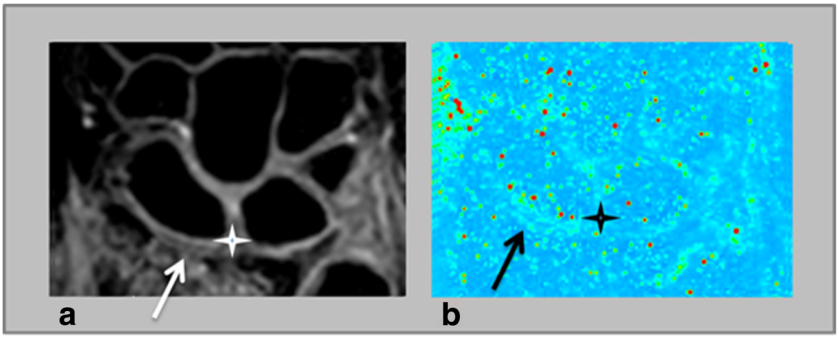

Fig. 5 Delamination of radial articular cartilage after intraarticular distal radius fracture 19 months ago. The damage can be shown in DESS (**a**) and is also recognizable in the corresponding T2* map (**b**). A bone marrow edema in the distal radius can be illustrated in the DESS sequence (**a**)

($p = 0.014$), and healthy controls ($p < 0.0001$). For T2*, patients with arthritis illustrated significantly lower cartilage damage in central zones (LC and SC; $p = 0.005$) and peripheral zones (LP and SP; $p = 0.0002$) compared to osteoarthritis. Patients with arthritis illustrated significantly higher cartilage damage in central zones (LC and SC) compared to peripheral zones (LP and SP) ($p = 0.0004$). No significant difference between intraarticular fracture and no intraarticular fracture line could be depicted in patients with condition after distal radius fracture for T2* ($p > 0.05$) (Figs. 3, 4, 5 and 6).

Discussion

Our data showed that multiparametrical MRI of the radiocarpal cartilage with the combination of high-resolution, morphological DESS and TRUFI sequences and biochemical T2* mapping has the potential to identify differences of cartilage alterations in patients with arthritis compared with patients with osteoarthritis. This is all the more important because it can clinically be difficult to distinguish both diseases, especially in the condition of erosive osteoarthritis [24]. Additionally, our data revealed that multiparametrical MRI of assessing radiocarpal cartilage is able to differentiate healthy participants from patients suffering from arthritis, osteoarthritis, or distal radius fracture. In many cases, articular cartilage injury or loss is suspected for wrist pain [3]. Haims et al could not demonstrate significant cartilage alterations in patients with wrist pain using indirect MR arthrograms and unenhanced MRI [2]. Our MR protocol comprised 3D, high-resolution sequences that allow the detailed illustration of the thin hyaline cartilage layers of radiocarpal cartilage [1]. For the triangular fibro-cartilaginous complex (TFCC), high-resolution MRI has shown good sensitivity in correlation with arthroscopy [25, 26]. Our multiparametrical MRI demonstrated higher cartilage degradation in central compared to peripheral zones in arthritis and osteoarthritis. In addition, significantly higher cartilage damage in central zones of radiocarpal cartilage was found in patients with osteoarthritis compared with patients suffering from arthritis. This may be explainable by force distribution over the wrist that relatively show a stronger impact on the central zones of radiocarpal cartilage in patients with osteoarthritis compared with arthritis [27]. In patients with a condition after distal radial fracture, no significant difference of cartilage alterations could be found between intraarticular fracture and no intraarticular fracture line. Both entities could lead to severe posttraumatic cartilage damage and secondary osteoarthritis [28]. The advantage of our MR protocol is that no contrast media is necessary for cartilage evaluation. With regard to the recently discovered gadolinium deposits in the brain resulting from intravenous MR contrast agent application, gadolinium-free imaging of articular cartilage is becoming a focus both for research and clinical imaging [16].

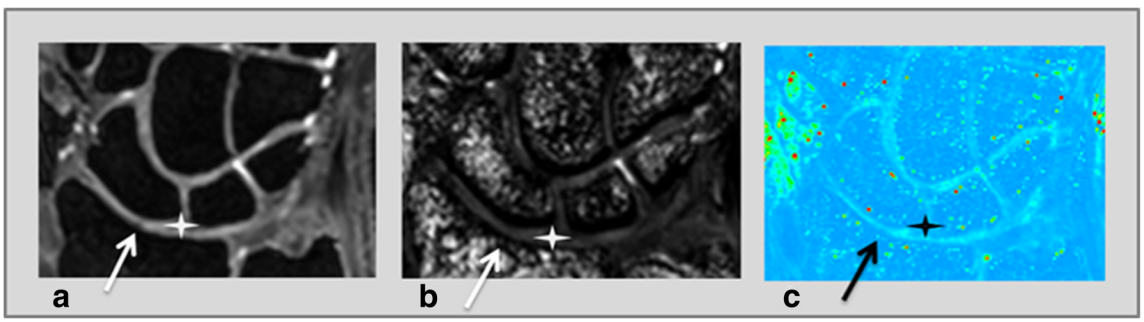

Fig. 6 Intraarticular fracture of distal radius that was treated osteosynthesis. The current picture represents severe local cartilage damage corresponding to the former fracture line. The trauma happened 5 years ago

Our study has limitations. In spite of 47 examined participants, the main limitation is the small sample size. It should be noted that the study was performed without an arthroscopic or histological correlation. This was not possible due to ethical reasons. For patients suffering from osteoarthritis, no classification system could be specified. Conventional radiographs were not performed in this prospective study. Another limitation is the missing inter- and intrareader reliability for biochemical imaging. In our opinion, this is a minor limitation, as T2* mapping has already been proven to provide high inter- and intrareader reliability in former studies [29]. No age-matched groups between patients suffering from arthritis and patients with osteoarthritis could be applied. This is because of the different onset of the two diseases.

In conclusion, multiparametrical MRI of the radiocarpal cartilage with a combination of high-resolution morphological and biochemical sequences on a clinical 3T MRI system may be a powerful, non-invasive tool to investigate and diagnose patients with wrist pain. Our MR imaging protocol allows to identify differences in cartilage evaluation of patients with arthritis and osteoarthritis, healthy subjects could be distinguished from patients suffering from arthritis, osteoarthritis, or trauma, and zonal distribution of cartilage damage could be worked out. Moreover, we found that this is possible without the use of gadolinium-based contrast agent, that is expected to be a growing focus in future MR imaging trials of articular cartilage.

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Compliance with ethical standards

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Conflict of interest The authors of this manuscript declare no relationships with any companies, whose products or services may be related to the subject matter of the article.

Statistics and biometry No complex statistical methods were necessary for this paper.

Informed consent Written informed consent was obtained from all patients in this study.

Ethical approval Institutional Review Board approval was obtained.

Methodology
- prospective
- diagnostic study
- performed at one institution

References

1. Rehnitz C, Kuni B, Wuennemann F et al (2017) Delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) and T2 mapping of talar osteochondral lesions: indicators of clinical outcomes. J Magn Reson Imaging 46:1601–1610
2. Haims AH, Moore AE, Schweitzer ME et al (2004) MRI in the diagnosis of cartilage injury in the wrist. AJR Am J Roentgenol 182:1267–1270
3. Strickland CD, Kijowski R (2011) Morphologic imaging of articular cartilage. Magn Reson Imaging Clin N Am 19:229–248
4. Hayter CL, Gold SL, Potter HG (2013) Magnetic resonance imaging of the wrist: bone and cartilage injury. J Magn Reson Imaging 37:1005–1019
5. Kouri T, Saario R, Merilahti-Palo R, Söderström KO (1987) Simplified distinction of rheumatoid synovial histopathology from that of degenerative joint diseases. Clin Rheumatol 6:98–100
6. Ehrlich GE (2001) Erosive osteoarthritis: presentation, clinical pearls, and therapy. Curr Rheumatol Rep 3:484–488
7. Schneider M, Lelgemann M, Abholz H-H et al (2011) DGRh-Leitlinie: management der frühen rheumatoiden arthritis. Springer Verlag, Berlin, Heidelberg
8. Chhabra A, Soldatos T, Thawait GK et al (2012) Current perspectives on the advantages of 3-T MR imaging of the wrist. Radiographics 32:879–896
9. Oneson SR, Scales LM, Erickson SJ, Timins ME (1996) MR imaging of the painful wrist. Radiographics 16:997–1008
10. Rehnitz C, Klaan B, von Stillfried F et al (2016) Comparison of modern 3D and 2D MR imaging sequences of the wrist at 3 Tesla. Rofo 188:753–762
11. Abraham CL, Bangerter NK, McGavin LS et al (2015) Accuracy of 3D dual echo steady state (DESS) MR arthrography to quantify acetabular cartilage thickness. J Magn Reson Imaging 42:1329–1338
12. Schleich C, Hesper T, Hosalkar HS et al (2017) 3D double-echo steady-state sequence assessment of hip joint cartilage and labrum at 3 Tesla: comparative analysis of magnetic resonance imaging and intraoperative data. Eur Radiol 27:4360–4371
13. Miese FR, Ostendorf B, Wittsack HJ et al (2010) Metacarpophalangeal joints in rheumatoid arthritis: delayed gadolinium-enhanced MR imaging of cartilage–a feasibility study. Radiology 257:441–447
14. Stojanov D, Aracki-Trenkic A, Benedeto-Stojanov D (2016) Gadolinium deposition within the dentate nucleus and globus pallidus after repeated administrations of gadolinium-based contrast agents-current status. Neuroradiology 58:433–441
15. Fingerhut S, Sperling M, Holling M et al (2018) Gadolinium-based contrast agents induce gadolinium deposits in cerebral vessel walls, while the neuropil is not affected: an autopsy study. Acta Neuropathol. https://doi.org/10.1007/s00401-018-1857-4
16. Gulani V, Calamante F, Shellock FG, Kanal E, Reeder SB (2017) Gadolinium deposition in the brain: summary of evidence and recommendations. Lancet Neurol 16:564–570
17. Rehnitz C, Kupfer J, Streich NA et al (2014) Comparison of biochemical cartilage imaging techniques at 3 T MRI. Osteoarthritis Cartilage 22:1732–1742
18. Welsch GH, Trattnig S, Paternostro-Sluga T et al (2011) Parametric T2 and T2* mapping techniques to visualize intervertebral disc degeneration in patients with low back pain: initial results on the clinical use of 3.0 Tesla MRI. Skeletal Radiol 40:543–551
19. Schleich C, Müller-Lutz A, Blum K et al (2016) Facet tropism and facet joint orientation: risk factors for the development of early biochemical alterations of lumbar intervertebral discs. Osteoarthritis Cartilage 24:1761–1768

20. Hesper T, Hosalkar HS, Bittersohl D et al (2014) T2* mapping for articular cartilage assessment: principles, current applications, and future prospects. Skeletal Radiol 43:1429–1445
21. Hesper T, Neugroda C, Schleich C et al (2017) T2*-mapping of acetabular cartilage in patients with femoroacetabular impingement at 3 Tesla: comparative analysis with arthroscopic findings. Cartilage. https://doi.org/10.1177/1947603517741168: 1947603517741168
22. Holstein A, Zilkens C, Bittersohl B et al (2011) Delayed gadolinium-enhanced MRI of cartilage (dGEMRIC) and morphologic MRI of cartilage in the long-term follow-up after Legg-Calve-Perthes disease (LCPD). J Med Imaging Radiat Oncol 55:259–265
23. Bittersohl B, Miese FR, Hosalkar HS et al (2012) T2* mapping of hip joint cartilage in various histological grades of degeneration. Osteoarthritis Cartilage 20:653–660
24. Ehrlich GE (2003) Osteoarthritis beginning with inflammation. Definitions and correlations. Bull World Health Organ 81:691–693
25. Ochman S, Wieskötter B, Langer M, Vieth V, Raschke MJ, Stehling C (2017) High-resolution MRI (3T-MRI) in diagnosis of wrist pain: is diagnostic arthroscopy still necessary? Arch Orthop Trauma Surg 137:1443–1450
26. Chang AL, Yu HJ, von Borstel D et al (2017) Advanced imaging techniques of the wrist. AJR Am J Roentgenol 209:497–510
27. Hara T, Horii E, An KN, Cooney WP, Linscheid RL, Chao EY (1992) Force distribution across wrist joint: application of pressure-sensitive conductive rubber. J Hand Surg Am 17:339–347
28. Medved F, Gonser P, Lotter O, Albrecht D, Amr A, Schaller HE (2013) Severe posttraumatic radiocarpal cartilage damage: first report of autologous chondrocyte implantation. Arch Orthop Trauma Surg 133:1469–1475
29. Bittersohl B, Hosalkar HS, Hughes T et al (2009) Feasibility of T2* mapping for the evaluation of hip joint cartilage at 1.5T using a three-dimensional (3D), gradient-echo (GRE) sequence: a prospective study. Magn Reson Med 62:896–901