Knee Surg Sports Traumatol Arthrosc (2015) 23:2406–2412
DOI 10.1007/s00167-014-2913-9

ANKLE

T2-mapping at 3 T after microfracture in the treatment of osteochondral defects of the talus at an average follow-up of 8 years

Christoph Becher · David Zühlke · Christian Plaas · Marc Ewig · Tilman Calliess · Christina Stukenborg-Colsman · Hajo Thermann

Received: 2 July 2013 / Accepted: 9 February 2014 / Published online: 23 February 2014

Abstract
Purpose To compare repaired cartilage with native cartilage, and inter-observer reliability, using T2 mapping at 3 T for assessing cartilage repair in osteochondral defects of the talus after the microfracture technique.
Methods We enrolled eight females and seven males undergoing arthroscopic microfracture for osteochondral defects of the talus at an average follow-up of 7.9 ± 2.2 years (range 5–13 years). Cartilage tissue was assessed using a 3-T magnetic resonance imaging unit with an 8-channel phased array foot and ankle coil (gradient strength, 50 mT/m; slew rate, 200 T/m/s). T2 maps were then calculated. Three independent boarded specialists evaluated the images, and magnetic resonance observation of cartilage repair tissue scores was used to assess the cartilage and joint status. Clinical results were assessed using the Hannover Scoring System (HSS) for the ankle and the American Orthopaedic Foot and Ankle Society (AOFAS) hind-foot score.
Results No significant mean differences were found between the T2 properties of the repair tissue and those of the native reference cartilage (T2 = 38.6 ± 5.3 ms, range 30.2–55.8 ms vs. 40.3 ± 8.5 ms, range 31.4–59.8 ms, respectively; intra-class correlation coefficient = 0.94; confidence interval 0.84–0.99, $P \leq 0.001$). Despite ≥50 % defect filling in all patients, subchondral bone changes were considerable. The HSS at the follow-up revealed a mean score of 87 ± 12 (range 51–97), and the AOFAS-Score was 90 ± 13 (range 59–100).
Conclusions 3 T T2 maps were similar in repaired and native cartilage with good inter-observer reliability.
Level of evidence IV.

Keywords Ankle · Microfracture technique · Osteochondral defect · T2 mapping

Introduction

Arthroscopic debridement and bone marrow stimulation using the microfracture technique are an established, simple, and cost-effective operative treatment for osteochondral defects (OCD) of the talus, with low morbidity [6, 7, 16, 17, 28].

In recent years, magnetic resonance imaging has become increasingly useful for the evaluation of cartilage repair. Newly developed biochemical MR methods such as T2 mapping, delayed gadolinium-enhanced MRI of cartilage, and diffusion-weighted imaging (DWI) provide information on the morphological appearance of the repair tissue, as well as the cartilage structure and molecular composition [1, 26]. T2 mapping was recently used to evaluate cartilage repair in the ankle at different field strengths and using operative techniques such as microfracture, matrix-associated autologous chondrocyte transplantation (MACT), and bone marrow-derived cell transplantation [4, 5, 12–14, 25]. T2 values were shown to be related to both the water and collagen content of

C. Becher (✉) · D. Zühlke · C. Plaas · T. Calliess · C. Stukenborg-Colsman
Department of Orthopedic Surgery, Hannover Medical School, Anna-von-Borries-Str. 1-7, 30625 Hannover, Germany
e-mail: becher.chris@web.de

M. Ewig
Radiologie am Raschplatz, Hannover, Germany

H. Thermann
Center for Hip, Knee and Foot Surgery, ATOS-Clinic Center, Heidelberg, Germany

cartilage but especially to the collagen network structure [26]. Because microfracture suggests fibrocartilage healing of the defect, disorganization of the fibre network may result in different T2 properties compared with healthy hyaline cartilage. These differences might explain deterioration of clinical results over time as found after the application of microfracture for treating knee cartilage defects. However, although the microfracture technique in the knee suggested significant differences between the repair tissue after microfracture and the native cartilage [30], similar T2 properties were demonstrated in the ankle joint [12] showing that no deterioration of results was found after microfracture for treating chondral and osteochondral defects of the talus [6].

The aim of this study was to evaluate patients with a mid- to long-term follow-up after microfracture treatment for an osteochondral defect of the talus using T2 mapping at 3 T and common clinical scores. The hypothesis was that the T2 properties of the repair tissue after microfracture are not different to those of the adjacent native cartilage, and evaluation by T2 mapping at 3T MRI demonstrates a high inter-observer reliability. Furthermore, it was evaluated whether acquired T2 properties show correlations to the magnetic resonance observation of cartilage repair tissue (MOCART) score, age, follow-up time, and clinical scores of the patients.

Materials and methods

Patients from our database who underwent arthroscopic microfracture for isolated osteochondral defects of the talus with a minimum follow-up of 5 years were invited for clinical and MRI evaluation. Patients with rheumatologic diseases, degenerative defects or kissing lesions, severe arthritis of the hind foot, metabolic diseases, and structural malalignment or clinical instability requiring operative correction were excluded. Fifteen patients (eight female and seven male) with an average age of 37 ± 17 years (range 16–61 years) at the time of surgery participated in the study. All patients gave informed consent. The average follow-up was 7.9 ± 2.2 years (range 5–13 years). Defects were located in 13 cases at the medial side and two cases at the lateral side, and two patients had undergone prior operative treatment (ligament reconstruction).

Surgical technique and post-operative protocol

The surgical technique consisted of arthroscopic microfracture as previously described [6–8]. Briefly, the patients were operated in the supine position. Noninvasive distraction of the ankle was performed, and in some cases, in addition to the standard anteromedial and anterolateral ports, a superomedial port located 1 cm above the joint, medial to the tibialis anterior tendon, was used. A 2.5- or 2.7-mm arthroscope was used in all procedures. After debridement of all necrotic and sclerotic bone from the defect, the microfractures were placed with arthroscopic awls of different angles approximately 3–4 mm apart and 2–4 mm deep until fat droplets were evident.

A standard protocol for rehabilitation was used as described earlier [6]. Briefly, continuous passive motion (Artromot, DJO Global, Freiburg, Germany) was started as early as tolerated by pain and swelling, and continued for 6–8 h daily for 4–6 weeks. Patients were advised to limit weight bearing to no more than 15 kg for the first 4 weeks. If the ankle was pain-free, weight bearing was increased as tolerated.

MRI assessment

Cartilage repair tissue MRI assessment was performed using a 3 T MR unit (Discovery MR750, GE Healthcare, Milwaukee, WI, USA) with a maximum gradient strength of 50 mT/m and 200 T/m/s slew rate using an 8-channel (phased array) foot and ankle coil. The patients were placed in the supine position with the foot at a 90° angle relative to the lower leg. The following sequences were obtained: (1) sagittal isotropic 3-dimensional (3D) gradient echo fast imaging employing steady-state acquisition (FIESTA) with a 160-mm field of view (FOV) and 512 matrix resulting in 0.3 × 0.3 × 0.4-mm isotropic resolution; (2) sagittal proton density fat-suppressed fast-spin echo (PD-FSE) with an in-plane resolution of 0.3 × 0.3 mm with a slice thickness of 3 mm, repetition time/echo time (TR/TE) of 2,000/31 ms, a flip angle of 90°, and a bandwidth of 195 Hz/pixel; and (3) coronal and sagittal multiecho spin echo (T2 map) to obtain the T2 relaxation times for T2 mapping. A 160 × 160-mm FOV and 512 × 512-pixel matrix resulted in an in-plane resolution of 0.3 × 0.3 mm with a slice thickness of 2 mm; TR was 1,300 s, and eight different echo times were used. The bandwidth was 244 Hz/pixel. T2 maps were calculated with a pixel-wise, monoexponential nonnegative least-squares-fit analysis (CartiGram, GE Healthcare).

Images were evaluated by three independent examiners (two board-certified orthopaedic surgeons and a board-certified radiologist) blinded to the clinical outcome. Prior to the beginning of the study, the protocol was discussed among the examiners for agreement on the measurement methodology by evaluating an excluded patient with an osteochondral defect of the talus. The morphological 3D-true fast imaging with steady-state precession and the PD-weighted fast-spin turbo spin echo images determined the defect site. Region-of-interest (ROI) analysis with the measurement of the defect size and T2 values (Figs. 1, 2a)

was done at the repair tissue (RT) and at the native adjacent healthy cartilage (RC) as an internal reference using two consecutive representative coronal and sagittal images following earlier published protocols [26]. The ROIs were drawn manually, carefully excluding the subchondral bone and synovial fluid. The data of all measurements were then analysed to calculate mean RT T2 and RC T2.

The classification system for cartilage repair by Marlovits et al. (MOCART) [20] was used to assess the cartilage repair and joint status comprising the following variables: (1) degree of defect repair and filling; (2) integration to border zone; (3) surface of the repair tissue; (4) structure of the repair tissue; (5) subchondral bone alterations; (6) signal intensity of the repair tissue; and (7) effusion. Discrepancies in interpretation were settled by consensus.

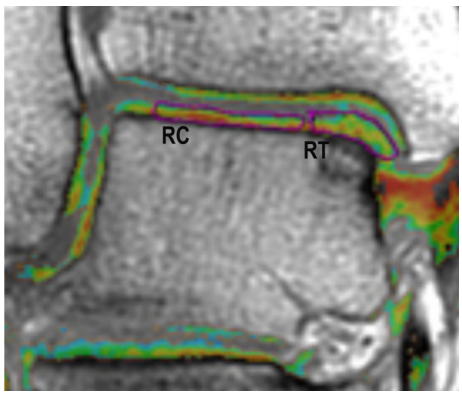

Fig. 1 Coronal T1-weighted spin echo image with T2 map and an illustration of the region-of-interest (ROI) analysis of a 28-year-old female 5.4 years post-operatively. The RT (repair tissue) was 40.3 ms, and the RC (healthy cartilage) was 38.8 ms. The defect is completely covered with repair tissue that appears slightly hypertrophic

Score outcome measures

Data collection was performed at the follow-up examination and according to the patient records. Rating of the results was performed with the Hannover Scoring System (HSS) for the ankle [7, 24] and the American Orthopaedic Foot and Ankle Society (AOFAS) hind-foot score [18]. The HSS was modified because of the lack of access to standard preoperative and post-operative plain film radiographs. The maximum score was therefore adjusted to 100 %, and the scores were reported as a percentage of the maximum [6, 8]. Satisfaction was evaluated by a questionnaire that rated the general satisfaction with the treatment outcomes (1 = excellent, 2 = very good, 3 = good, 4 = fair, and 5 = poor), also asking patients if they would undergo the procedure again and if they would recommend this procedure. Institutional review board approval (ID 5791) was obtained from the ethical committee of Hannover Medical School prior to the study.

Statistical analysis

Descriptive statistics were calculated (mean, range, and standard deviation values). To determine differences between the T2 values, a two-sided independent Student's *t* test was used after confirming normality of the variances of the T2 values by the Kolmogorov–Smirnov test. The nonparametric Mann–Whitney test was used to confirm the *t* test result. Correlations between the T2 values, MOCART score, and associations between the clinical scores as well as defect size, age, and the follow-up time were assessed using the Pearson coefficient of correlation. Inter-observer reliability was evaluated using the intra-class correlation coefficient (ICC). SPSS 18.0 (SPSS Inc., Chicago, IL, USA) was used for all analyses. A P value ≤ 0.05 was considered significant.

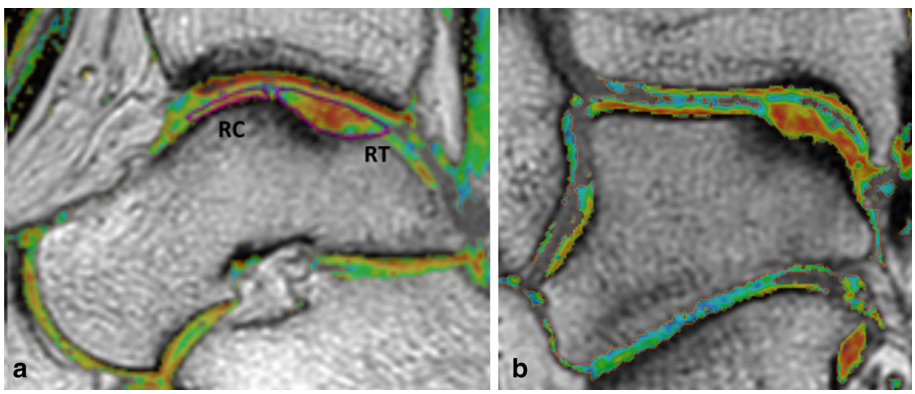

Fig. 2 Sagittal and coronal T1-weighted spin echo image with T2 map and an illustration of the ROI analysis **a** of a 23-year-old female 6.5 years post-operatively. The RT was 41.8 ms, and the RC was 43.3 ms. The defect is completely covered with repair tissue that appears slightly hypertrophic. **b** The T2 value of the majority of the repair tissue appears comparable to that of the adjacent native cartilage. However, although integration appears complete, the integration zone displays higher T2 properties

Results

No intra- or post-operative complications were observed, and none of the patients underwent further operative treatment of the affected ankle. One of the patients underwent arthroscopic microfracture for contralateral OCD of the talus 8 months prior to the follow-up examination.

The mean defect size was 87 ± 30 mm^2 (range 37–189 mm^2). The ICC for measuring the defect size was 0.94 (CI 0.84–0.99, $P \leq 0.001$). No significant mean differences were found between the T2 properties of the repair tissue and the native adjacent reference cartilage. RC T2 was 40.3 ± 8.5 ms (range 31.4–59.8 ms), and RT T2 was 38.6 ± 5.3 ms (range 30.2–55.8 ms) (n.s.). The ICC for evaluating the T2 properties was 0.80 (CI 0.43–0.94, $P \leq 0.001$).

MRI showed regeneration of tissue in the microfractured area in all patients, and the mean MOCART score was 64 ± 14 points (Table 1). The structure of the repair tissue was inhomogeneous, and the surface was damaged in 13/15 of patients. Integration of the repair tissue to the border zone was complete in 10/15 of the patients with 5/15 ankles having a small demarcating border. The signal intensity of the repair tissue appeared normal with both 3-D FIESTA and PD-FSE in 5/15 patients. Although coverage with repair tissue occurred, with no patient having <50 % filling of the defect compared with the level of the adjacent cartilage, considerable changes were observed in the subchondral bone. In 11/15 ankles, the subchondral bone appeared not intact with oedema in 4/15 (Fig. 3), granulation tissue in 4/15 (Fig. 4), cyst formation in 6/15 (Figs. 3, 4), and sclerosis in 8/15 ankles (Fig. 5).

The modified HSS at the follow-up revealed a mean score of 87 ± 12 (range 51–97), and the AOFAS-Score was 90 ± 13 (range 59–100). Of the 15 patients, the result was rated excellent in 8/15, very good in 6/15, and in 1/15 as fair. All but one patient indicated that they would undergo the procedure again and would recommend it.

Statistically significant correlations were found between the HSS and AOFAS score ($r = 0.76$; $P \leq 0.001$) as well as the MOCART score and defect size ($r = 0.71$; $P = 0.008$) with better MOCART score results for patients with smaller defects. No other statistically significant correlations were observed.

Table 1 MRI findings of the repair tissue in 15 ankles by using the MOCART score [20]

Finding	No. of ankles *n* (%)
Degree of defect repair and filling of the defect	
(1) Complete (on level with the adjacent cartilage)	7 (47)
(2) Hypertrophy (over the level with the adjacent cartilage)	5 (33)
Incomplete (under the level with the adjacent cartilage)	
(3) Greater than 50 % of the adjacent cartilage	3 (20)
(4) Less 50 % of the adjacent cartilage	
(5) Subchondral bone exposed	
Integration to border zone	
(1) Complete (complete integration with adjacent cartilage)	10 (67)
Incomplete (incomplete integration with adjacent cartilage)	
(2) Demarcating boarder visible (split-like)	5 (33)
(3) Defect visible (less than or greater than 50 % of the length of the repair tissue)	
Surface of the repair tissue	
(1) Surface intact (congruent articular surface)	2 (13)
Surface damaged (fibrillations, fissures, and ulcerations)	
(2) Less than 50 % of repair tissue depth	13 (87)
(3) Greater than 50 % of repair tissue depth or total degeneration	
Structure of the repair tissue	
(1) Homogen (typical cartilage layers are formed over the entire repair tissue)	2 (13)
(2) Inhomogen or cleft formation (structural formation is lost)	13 (87)
Signal intensity of the repair tissue	
(1) Normal (identical to adjacent cartilage)	5 (33)
(2) Nearly normal (slight areas of signal alteration)	10 (67)
(3) Abnormal (large areas of signal alteration)	
Subchondral lamina	
(1) Intact	3 (20)
(2) Not intact	12 (80)
Subchondral bone	
(1) Intact	4 (27)
(2) Not intact	11 (73)
Adhesions	
(1) No	14 (93)
(2) Yes	1 (7)
Effusion	
(1) No	13 (87)
(2) Yes	2 (13)

Discussion

The most important finding of our study was that the T2 properties of the repair tissue after microfracture in the treatment of osteochondral defects did not differ when compared with those of the adjacent native cartilage. This is consistent with the findings of Domayer et al. who found no significant differences between the repair tissue after ankle microfracture and the adjacent native cartilage at a mean follow-up of 4.6 ± 2.3 years [12]. The mean RC T2 in our study was 40.3 ± 8.5 ms, and RT T2 was 38.6 ± 5.3 ms—well within the range of 35–45 ms

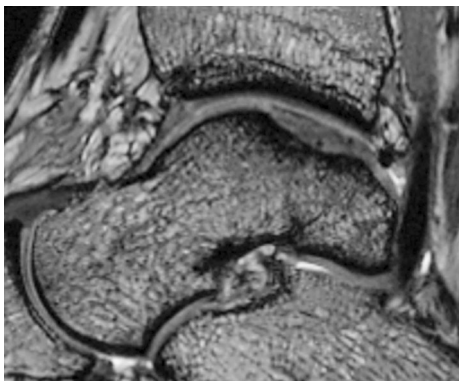

Fig. 3 Sagittal isotropic three-dimensional (3-D) gradient echo fast imaging employing steady-state acquisition (FIESTA) sequence of the same patient from Fig. 2. The repair tissue is moderately hyperintense compared with the adjacent cartilage. The subchondral bone appears sclerotic

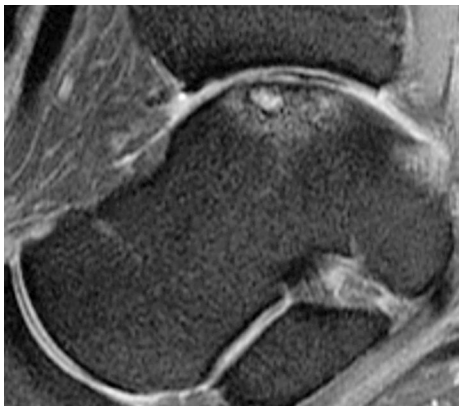

Fig. 4 Sagittal proton density fat-suppressed fast-spin echo (PD-FSE) of a 63-year-old male 7.3 years post-operatively. Marked subchondral alterations are observed with cyst formation and oedema. The American Orthopaedic Foot and Ankle Society (AOFAS) and Hannover Scoring System (HSS) scores were 94 and 87, respectively. The patient rated the result as very good

considered compatible with normal hyaline cartilage previously reported [4]. However, individual evaluation of the repair tissue as shown in the figures demonstrated variability of the T2 properties within the tissue with typical alterations such as abnormalities of the structure and surface consistent with the description of fibrocartilage [22, 23].

The mean MOCART score for the repair tissue in our series was 64 ± 14 points. Previous studies evaluating spongiosa grafting and autologous matrix-induced chondrogenesis (AMIC) or matrix-induced autologous chondrocyte transplantation (MACT) obtained similar results, but had shorter follow-up periods than that in our study [1, 2, 21, 27]. Therefore, considering the considerably

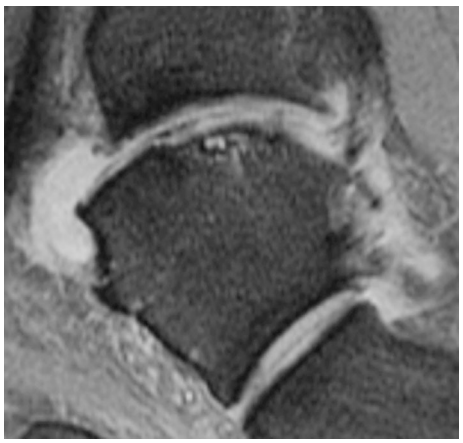

Fig. 5 Sagittal PD-FSE of a 26-year-old female 9 years post-operatively. The patient underwent lateral ligament reconstruction (Broström procedure) 1 year prior to the microfracture procedure for the osteochondral defect (OCD). The defect appears to be completely filled with repair tissue, and effusion is observed anteriorly. The subchondral bone shows a small cyst and slight oedema. The AOFAS and HSS scores were 100 and 95, respectively, and the patient rated the result as excellent

longer follow-up of our series, the repair tissue appears not to deteriorate in terms of morphological appearance. However, complete (or hypertrophic) fill or complete integration with the adjacent cartilage was found in only 80 and 67 % of the patients, respectively. In addition, the structure and surface of the repair tissue was damaged in the majority of patients (87 %). Although most authors described better results concerning the structure and especially the surface of the repair tissue than those in the present study [2, 12, 15, 21, 27], comparable findings were reported with respect to the defect fill and integration of the repair tissue using the MOCART score [2, 15, 21, 27]. Subchondral alterations such as oedema, granulation tissue cyst formation, and sclerosis were evident in 73 % of our patients. Other authors confirm these findings independent of the technique used with rates of 57 % after microfracture [12], 88 % after spongiosa grafting and an AMIC procedure [27], 65 % after ACT [5], and 92 % after MACT [21]. In contrast, however, one report stated that the subchondral bone was intact in all cases (100 %) after MACT [2].

Although a systematic review and meta-analysis showed that MRI findings after cartilage repair surgery in the knee correlate with clinical outcomes, no current MRI classification system, including the MOCART score, has been shown to correlate with clinical outcomes after all types of cartilage repair surgery [9]. We found no significant correlations of the T2 properties with the MOCART score, age, follow-up time, and clinical scores in our patients. This is consistent with findings in previous studies after ACT revealing neither significant correlations of clinical scores and T2 properties nor MOCART score parameters

[5]. However, the MOCART scores in our series correlated with defect size, suggesting better MOCART scores for patients with smaller defects, similar to reports of inferior clinical results for patients with defect sizes >1.5 cm^2 [10, 11]. However, it should be noted that the clinical scores were excellent with a high satisfaction in our patients, regardless of the defect size. We hypothesize that the comparable T2 properties and excellent clinical results at an average follow-up of 8 years are related to better metabolic, biochemical, and biomechanical properties of the ankle cartilage repair tissue as well as better joint congruity of the ankle allowing less shear forces on the repair tissue compared with the knee [3, 19, 29]. However, this remains to be proven.

The major strength of this series is the long average follow-up of 7.9 ± 2.2 years. The major limitation is the small number of patients ($n = 15$). However, other published series using T2 mapping after talar cartilage repair at 3 T also had small numbers [12]. Larger series using T2 mapping after bone marrow-derived cell transplantation or arthroscopic ACT used a 1.5-T MR scanner for evaluation, rather than a 3 T scanner [5, 15]. Another limitation of our cohort is the lack of a control group. RC T2 was measured at the adjacent cartilage in the same ankles without histological controls. An additional healthy control group might have improved the informative value and validity of the findings. However, previous studies used the adjacent cartilage as a reference [11–13], and because talar cartilage rarely undergoes primary degenerative changes, it can be assumed that the adjacent healthy-appearing cartilage in a high-resolution MRI provides satisfactory comparative value.

Conclusion

It was found that the T2 properties of the repair tissue after microfracture in the treatment of osteochondral defects of the talus were similar to those of the adjacent native cartilage and that evaluation by T2 mapping using 3T MRI demonstrated a high inter-observer reliability. The T2 values demonstrated no correlation with the MOCART score, age, follow-up time, and clinical scores of our patients. Although the T2 properties were comparable to the native adjacent cartilage, the appearance of the repair tissue and the MOCART scores suggest fibrocartilaginous repair tissue with persistent high rates of subchondral alterations in the defect area.

Acknowledgments The authors would like to thank Dr. Michael Burke (GE Medical Systems, Solingen, Germany) for his work in the preparation of the MRI set-up and help in the description of the MR assessment methodology.

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

References

1. Apprich S, Trattnig S, Welsch GH, Noebauer-Huhmann IM, Sokolowski M, Hirschfeld C, Stelzeneder D, Domayer S (2012) Assessment of articular cartilage repair tissue after matrix-associated autologous chondrocyte transplantation or the microfracture technique in the ankle joint using diffusion-weighted imaging at 3 Tesla. Osteoarthr Cartil 20:703–711
2. Aurich M, Bedi HS, Smith PJ, Rolauffs B, Muckley T, Clayton J, Blackney M (2011) Arthroscopic treatment of osteochondral lesions of the ankle with matrix-associated chondrocyte implantation: early clinical and magnetic resonance imaging results. Am J Sports Med 39:311–319
3. Aurich M, Squires GR, Reiner A, Mollenhauer JA, Kuettner KE, Poole AR, Cole AA (2005) Differential matrix degradation and turnover in early cartilage lesions of human knee and ankle joints. Arthritis Rheum 52:112–119
4. Battaglia M, Rimondi E, Monti C, Guaraldi F, Sant'andrea A, Buda R, Cavallo M, Giannini S, Vannini F (2010) Validity of T2 mapping in characterization of the regeneration tissue by bone marrow derived cell transplantation in osteochondral lesions of the ankle. Eur J Radiol 80(2):e132–e139
5. Battaglia M, Vannini F, Buda R, Cavallo M, Ruffilli A, Monti C, Galletti S, Giannini S (2011) Arthroscopic autologous chondrocyte implantation in osteochondral lesions of the talus: mid-term T2-mapping MRI evaluation. Knee Surg Sports Traumatol Arthrosc 19:1376–1384
6. Becher C, Driessen A, Hess T, Longo UG, Maffulli N, Thermann H (2010) Microfracture for chondral defects of the talus: maintenance of early results at midterm follow-up. Knee Surg Sports Traumatol Arthrosc 18:656–663
7. Becher C, Driessen A, Thermann H (2008) Microfracture technique for the treatment of articular cartilage lesions of the talus. Orthopade 37:196–203
8. Becher C, Thermann H (2005) Results of microfracture in the treatment of articular cartilage defects of the talus. Foot Ankle Int 26:583–589
9. Blackman AJ, Smith MV, Flanigan DC, Matava MJ, Wright RW, Brophy RH (2013) Correlation between magnetic resonance imaging and clinical outcomes after cartilage repair surgery in the knee. A systematic review and meta-analysis. Am J Sports Med 41(6):1426–1434
10. Choi WJ, Park KK, Kim BS, Lee JW (2009) Osteochondral lesion of the talus: is there a critical defect size for poor outcome? Am J Sports Med 37:1974–1980
11. Chuckpaiwong B, Berkson EM, Theodore GH (2008) Microfracture for osteochondral lesions of the ankle: outcome analysis and outcome predictors of 105 cases. Arthroscopy 24:106–112
12. Domayer SE, Welsch GH, Stelzeneder D, Hirschfeld C, Quirbach S, Dorotka R, Nehrer S, Mamisch TC, Trattnig S (2010) Microfracture in the Ankle: clinical Results and MRI with T2-mapping at 3.0 T after 1–8 years. Cartilage 2:73–80
13. Domayer SE, Apprich S, Stelzeneder D, Hirschfeld C, Sokolowski M, Kronnerwetter C, Chiari C, Windhager R, Trattnig S (2012) Cartilage repair of the ankle: first results of T2 mapping at 7.0 T after microfracture and matrix associated autologous cartilage transplantation. Osteoarthr Cartil 20:829–836
14. Domayer SE, Kutscha-Lissberg F, Welsch G, Dorotka R, Nehrer S, Gabler C, Mamisch TC, Trattnig S (2008) T2 mapping in the knee after microfracture at 3.0 T: correlation of global T2 values

and clinical outcome—preliminary results. Osteoarthr Cartil 16: 903–908
15. Giannini S, Buda R, Battaglia M, Cavallo M, Ruffilli A, Ramponi L, Pagliazzi G, Vannini F (2013) One-step repair in talar osteochondral lesions: 4-year clinical results and t2-mapping capability in outcome prediction. Am J Sports Med 41:511–518
16. Giannini S, Vannini F (2004) Operative treatment of osteochondral lesions of the talar dome: current concepts review. Foot Ankle Int 25:168–175
17. Jung HG, Carag JA, Park JY, Kim TH, Moon SG (2011) Role of arthroscopic microfracture for cystic type osteochondral lesions of the talus with radiographic enhanced MRI support. Knee Surg Sports Traumatol Arthrosc 19:858–862
18. Kitaoka HB, Alexander IJ, Adelaar RS, Nunley JA, Myerson MS, Sanders M (1994) Clinical rating systems for the ankle-hind foot, midfoot, hallux, and lesser toes. Foot Ankle Int 15:349–353
19. Kuettner KE, Cole AA (2005) Cartilage degeneration in different human joints. Osteoarthr Cartil 13:93–103
20. Marlovits S, Striessnig G, Resinger CT, Aldrian SM, Vecsei V, Imhof H, Trattnig S (2004) Definition of pertinent parameters for the evaluation of articular cartilage repair tissue with high-resolution magnetic resonance imaging. Eur J Radiol 52:310–319
21. Quirbach S, Trattnig S, Marlovits S, Zimmermann V, Domayer S, Dorotka R, Mamisch TC, Bohndorf K, Welsch GH (2009) Initial results of in vivo high-resolution morphological and biochemical cartilage imaging of patients after matrix-associated autologous chondrocyte transplantation (MACT) of the ankle. Skelet Radiol 38:751–760
22. Shapiro F, Koide S, Glimcher MJ (1993) Cell origin and differentiation in the repair of full-thickness defects of articular cartilage. J Bone Jt Surg Am 75:532–553
23. Steadman JR, Rodkey WG, Rodrigo JJ (2001) Microfracture: surgical technique and rehabilitation to treat chondral defects. Clin Orthop Relat Res 391(Suppl):S362–S369
24. Teshima R, Ono M, Yamashita Y, Hirakawa H, Nawata K, Morio Y (2004) Immunohistochemical collagen analysis of the most superficial layer in adult articular cartilage. J Orthop Sci 9:270–273
25. Trattnig S, Welsch G, Domayer S, Apprich S (2012) MR imaging of postoperative talar dome lesions. Semin Musculoskelet Radiol 16:177–184
26. Trattnig S, Winalski CS, Marlovits S, Jurvelin JS, Welsch GH, Potter HG (2010) Magnetic resonance imaging of cartilage repair: a review. Cartilage 2:5–26
27. Valderrabano V, Miska M, Leumann A, Wiewiorski M (2013) Reconstruction of osteochondral lesions of the talus with autologous spongiosa grafts and autologous matrix-induced chondrogenesis. Am J Sports Med 41:519–527
28. van Bergen CJ, de Leeuw PA, van Dijk CN (2008) Treatment of osteochondral defects of the talus. Rev Chir Orthop Reparatrice Appar Mot 94:398–408
29. van Dijk CN, Reilingh ML, Zengerink M, van Bergen CJ (2010) The natural history of osteochondral lesions in the ankle. Instr Course Lect 59:375–386
30. Welsch GH, Trattnig S, Domayer S, Marlovits S, White LM, Mamisch TC (2009) Multimodal approach in the use of clinical scoring, morphological MRI and biochemical T2-mapping and diffusion-weighted imaging in their ability to assess differences between cartilage repair tissue after microfracture therapy and matrix-associated autologous chondrocyte transplantation: a pilot study. Osteoarthr Cartil 17:1219–1227