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RESEARCH

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The value of adding T2 mapping sequence to the routine MRI protocol in the evaluation of cartilage lesions of the ankle joint

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Abstract

Background Ankle joint cartilage injury is frequently associated with degenerative changes, even in the absence of symptoms. Earlier treatment of cartilage damage with joint preservation is clearly more successful. The main limitation of morphologic cartilage magnetic resonance imaging sequences is that they are not very sensitivity in the detection of early cartilage degeneration. Recent advances in biochemical magnetic resonance imaging have yielded sequences that are sensitive to molecular changes in the composition of cartilage matrix. This includes water- and collagen-sensitive T2\T2* mapping. The aim of this study was to determine the extent of improvement of the diagnostic performance of routine magnetic resonance imaging protocol in the evaluation of ankle joint articular cartilage lesions following the addition of a T2 mapping sequence.

Results A total of 45 cases, 30 patients (12 male and 18 female) and 15 controls (10 male and 5 female) who underwent routine ankle magnetic resonance imaging with additional T2 mapping sequence, were included in the study. Out of 30 patients, four patients were misdiagnosed as being normal, while having changes of cartilage composition of early degenerative changes, discovered by T2 mapping sequence. The patients group as well as the-control groups had significantly higher T2-values in the superficial cartilage layer ($P < 0.001$) compared to the deep layer. When comparing between the medial and the lateral compartments at patients group, the T2-relaxation times were more pronounced in the medial talar cartilage compartment compared to the lateral talar cartilage compartment.

Conclusions Magnetic resonance imaging can observe not only the destruction of the structural integrity but also the change of the components in articular cartilage. In this study, the addition of a T2 mapping of the ankle cartilage sequence to a routine MR ankle protocol improved sensitivity and accuracy in the detection of early cartilage lesions within the ankle joint.

Keywords Ankle joint, Magnetic resonance imaging, Degenerative changes, T2 mapping, Osteoarthritis

Background

Ankle joint cartilage injury is frequently associated with degenerative changes, even in the absence of symptoms. Cartilage degeneration can be initiated by cartilage injury occurring with ankle sprain or fracture, or abnormal loading due to chronic ankle instability or anatomical variants [1].

Early detection of ankle joint articular cartilage degeneration is desirable because it facilitates earlier treatment that leads to favorable outcome, whether by autograft

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transplantation or by joint preservation operations, which include debridement and bone stimulation techniques [1]. Consequently, an increasing number of interventions for cartilage repair is performed, which has resulted in a growing demand for repetitive and objective assessment of cartilage [2].

Magnetic resonance imaging (MRI) is a useful modality in the identification of bone contusions, loose bodies, soft tissue pathology, and correlates reasonably well with arthroscopic findings [3]. Evaluation of articular cartilage in symptomatic patients undergoing routine MR imaging for joints is typically performed by using sequences that assess the morphological appearance of the cartilage. The main limitation of morphologic cartilage imaging sequences is that they are not very sensitivity in the early detection of cartilage degeneration [4].

Recent advances in biochemical MRI have yielded sequences sensitive to molecular changes in cartilage matrix composition, thus providing valuable insight into both early cartilage degeneration and maturation of repaired tissue on a molecular level. This includes water- and collagen-sensitive T2\T2* mapping which is very sensitive for the assessment of the molecular changes that could affect the cartilage before the anatomical changes [2, 5].

Compared with other biochemically sensitive MRI techniques, T2* mapping has unique features including speed of imaging, high image resolution, and the ability to perform isotropic three-dimensional (3D) cartilage evaluation. It is also easy to implement on clinical MRI systems, as pulse sequences and online processing software for generating quantitative T2* maps are available commercially. In addition, there is no need for contrast media administration or special hardware [6].

In cartilage, changes in T2-relaxation times are dependent upon the quantity of water and the integrity of the proteoglycan–collagen matrix. Early damage to the collagen matrix results in an influx of water. This increased permeability generates stress throughout the matrix and subsequent degeneration and loss of cartilage tissue. These changes are manifested as an increase in T2 signal. By measuring the spatial distribution of T2-relaxation times throughout articular cartilage, areas of increased or decreased water content (which generally correlate with cartilage damage) can be identified [7].

The aim of this study was to determine to what extent the addition of a T2 mapping sequence to a routine MR imaging protocol can improve the diagnostic performance in the evaluation of the articular cartilage lesions within the ankle joint. Also, to assess its role in quantitative assessment of ankle joint cartilage T2 values at different ankle joint articular diseases.

Methods

This is a prospective study over 2 years from August 2021 till August 2023. A total of 45 cases, 30 patients (12 males and 18 females, mean age 37.8 years and mean BMI of 26.54 ± 3.89) and 15 controls (10 males and 5 females, mean age 42 years and mean BMI of 24.5 ± 2.44) who underwent routine ankle MRI with T2 mapping post-processing, were included in the study.

Inclusion criteria

All included patients were adults (above 18 years old) who presented by current complaint of ankle joint pain with clinical suspicion of articular cartilage injury with no history of previous surgical intervention and no sex predilection. The control group included healthy volunteers who had no history of any ankle joint pain or injury within the 5 years prior to the study with no sex predilection. Written consents were taken from all the included cases prior to the examination.

Exclusion criteria

Pediatric patients (less than 18 years old), or patients with contraindication for MRI, for example, cardiac pacemaker and aneurysmal clips. Patients with weight more than 150 kg, suffering from claustrophobia, and those with history of previous surgical intervention were excluded as well.

None of the patients has arthroscopic evaluation during the study.

The study was approved by the ethical committee of Faculty of Medicine, Ain-Shams University (FMASU REC), under Fedral wide assurance No. FWA00017585 (FMASU MD 128/2021).

MRI ankle joint protocol

Magnetic resonance imaging (MRI) of the ankle joint in our MRI unit is performed in Enginea, Philips medical system, 1.5 T machine.

Routine MRI images were obtained including axial and sagittal T1-weighted images (T1WIs), axial, sagittal, and coronal fat-suppressed T2-weighted images (T2WIs), coronal gradient images, and axial and sagittal proton density (PD) weighted images. The time-to-repetition/time-to-echo (TR/TE) values used in T1WIs images are 400–600/15–25 ms with slice thickness 3 mm and field of view (FOV) 13–17 cm. The TR/TE values used in fat-suppressed T2WIs images are 4000–6000/110 ms with slice thickness 3 mm and FOV 13–17 cm. The TR/TE values used in Gradient images are 488/14 ms with slice thickness 3 mm and FOV 15–17 cm. The TR/TE values used in PD images are

3000–4000/15–20 ms with slice thickness 3 mm and FOV 13–17 cm.

Then additional T2 mapping sequence was taken for our study, Sagittal T2 mapping was displayed using these parameters: TR: 1083 ms, TE: 8,16,24,32,40,48,56 and 65 ms with slice thickness 3 mm and FOV 300×160 cm. The T2 mapping total acquisition time was 4–7 min.

Image interpretation

To eliminate any bias, three radiologists analyzed the T2 values while being blind to each other's reports. A musculoskeletal consultant with 12 years of experience, a musculoskeletal radiologist with 7 years of experience and a general radiologist with 4 years of experience.

Inter-reader agreement among the three participating radiologists was assessed by using percentage of agreement and kappa statistics.

To evaluate intra-observer reproducibility, measurements were repeated on the same slices in different reading sessions.

A dedicated software (Philips IntelliSpace Portal workstation, version 8.0) was used for analysis and post-processing. A T2 colored map was generated on automatic base. The color scale ranges from red to blue colors in which green or blue color corresponds to high T2 values on the color-coded scale.

In each case, four sagittal slices were chosen to make sure that the total coverage of the weight-bearing cartilage at talo-tibial joint is covered: one slice on the medial and lateral part of the talar and tibial sides and the adjacent more central slice on each side (as illustrated in Fig. 1).

To cover the whole thickness of the cartilage, ROI-analysis was performed in two layers: one superficial layer (from the articular surface to the outer half of the cartilage) and one deep layer (from the inner half of cartilage to the cartilage bone borderline).

In the antero-posterior dimension, the full length of cartilage was subdivided into three equal zones: one ventral zone; one central zone; and one dorsal zone standardized for each patient. Structural cartilage assessments were achieved in 6 equal-sized ROIs by imposing this pattern on the tibial and talar cartilage (Figs. 2 and 3). The four sagittal T2 maps corresponding to Fig. 1 are presented in Fig. 4.

The average T2 value was calculated by rectangular ROI which was manually created, considering a margin

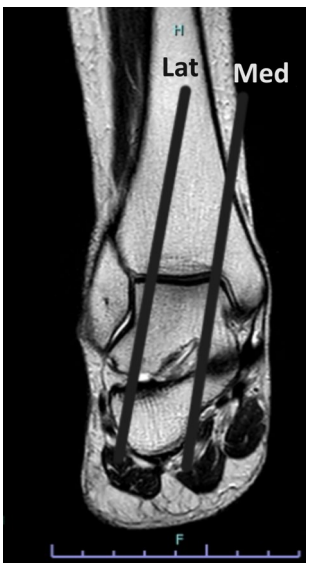

Fig. 1 Coronal MRI of the right ankle of a 32-year-old female patient. Of the 12 sagittal quantitative T2 mapping slices, two medial and two lateral slices were chosen

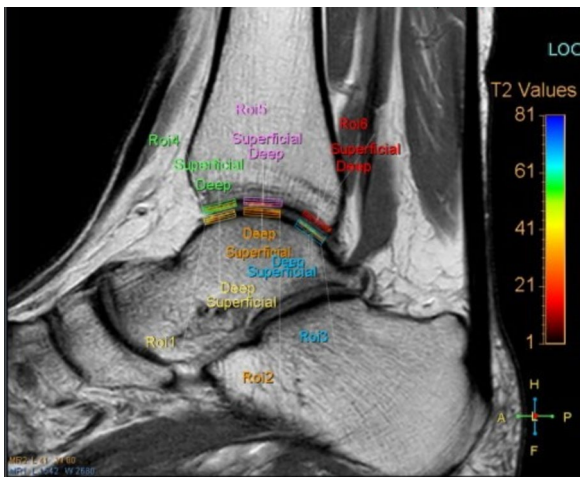

Fig. 2 Sagittal MRI of the right ankle of a 32-year-old female patient. To visualize ventro dorsal dimension. Structural cartilage assessments (T2 mapping) were achieved in 6 regions in which the ROI evaluation was performed

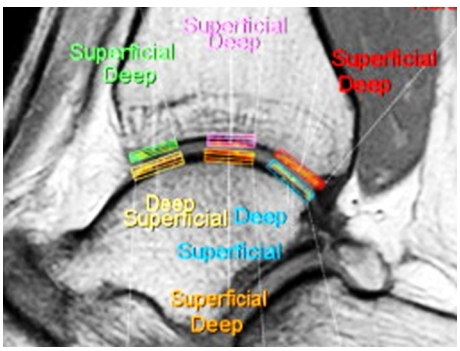

Fig. 3 Sagittal MRI of the left ankle of a 38-year-old male patient to clarify the ROI shape and size

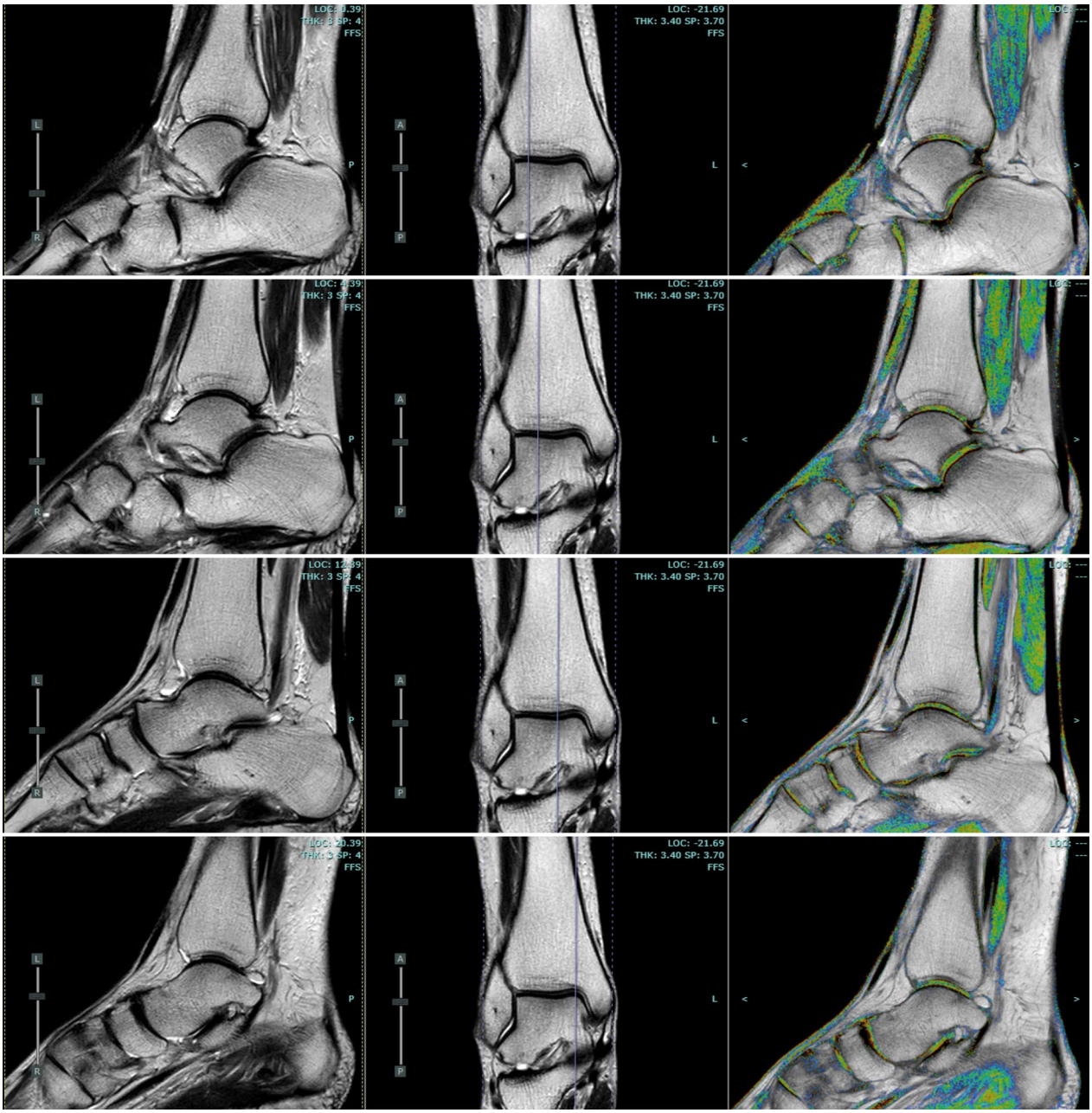

Fig. 4 Sagittal multi-echo SE quantitative T2 mapping images of the left ankle of a 32-year-old female patient. All four assessed slices (as marked in Fig. 2) are provided with quantitative T2 maps of the tibial and the talar cartilage

of 0.5–1 mm from the bone surface to prevent subchondral bone inclusion. Conventional MRI and a corresponding T2 map were visualized side by side (Fig. 4).

The T2-analysis for one patient required around 45 min. In our study, a total of 1080 ROIs were analyzed.

An intact articular cartilage on conventional MRI criteria included: uniform thickness and intermediate signal on PD-STIR sequence (sagittal, coronal, and axial).

An intact articular cartilage on T2 maps was defined as having normal T2 values not exceeding 60 ms and delineated by color-coded map ranging from red, orange, yellow to green represented on a color-coded scale with upper limit of 100 ms.

Articular cartilage affection on conventional MRI in degenerative changes was defined as an area with non-uniform thickness, or of altered signal intensity.

Cartilage affection on T2 maps in early degenerative changes can be delineated as it took a certain color (aqua or blue) corresponding to high T2 value on the color-coded scale found in the scanner software. Values higher than 60 ms are abnormal and correlated with blue color changes at the post-processing color coded images. Values lower than 60 ms are normal and correlated with (red, yellow, or green) color changes at the post-processing color coded images.

On T2 maps the hyaline cartilage lesions were graded according to an ICRS-like score (inspired by the International Cartilage Research Society score) [8] in each zone (ventral, central and dorsal), the T2 value of the severest lesion was the one considered.

- *No Degeneration: (grade 0–1)*: superficial and deep zones: normal. To be correlated at T2 color coded maps as (red, yellow, or green).
- *Grade 2 Degeneration*: superficial zone: abnormal with lesions extending down to < 50% of cartilage depth), deep zone: normal. To be correlated at T2 color-coded maps as superficial zone aqua/blue and deep zone is normal (red, yellow, or green)
- *Grade 3 Degeneration*: cartilage degeneration more than > 50% of cartilage depth so both superficial and deep zones: abnormal**.** To be correlated at T2 color-coded maps as superficial zone aqua/blue and deep zone aqua/blue with no associated bone degeneration.
- *Grade 4 Degeneration*: cartilage degeneration more than > 50% of cartilage depth so both superficial and deep zones: abnormal with associated bone degeneration**.** To be correlated at T2 color-coded maps as superficial zone aqua/blue and deep zone aqua/blue with associated bone degeneration.

Statistical analysis

By using Statistical package for science (SPSS 23), the data analysis was done. We used mean, variance (± SD) and range for parametric numerical data, while median and inter-quartile range (IQR) for nonparametric numerical data. Frequency and percentage of non-numerical data were included in our analysis as well.

The following tests were done, Chi-square (χ^2) test, which was used to correlate proportions between qualitative parameters, the arrogance interval was set to 95% and so the margin of error accepted was set to five. So, the p value significance was considered according to the following probabilities: P value < 0.05 = significant, P value < 0.001 = highly significant and P value > 0.05 = insignificant.

Inter-reader agreement between the three participating radiologists was assessed using percentage of agreement as well as kappa statistics.

K values interpretation as follows:

Poor agreement: $k < 0.1$
Slight agreement: $0.1 < k \leq 0.2$
Fair agreement: $0.2 < k \leq 0.4$
Moderate agreement: $0.4 < k \leq 0.6$
Substantial agreement: $0.6 < k \leq 0.8$
Almost perfect agreement: $0.8 < k \leq 1$

Results

There was almost perfect agreement between all the participating radiologists (K ranging from 0.83 to 0.945) with percentage of agreement ranging more than 87%.

Regarding conventional MRI findings patients were divided according to their findings of the ankle cartilage into normal, mild to severe osteoarthritis and patients with associated osteochondral defect (Table 1).

Regarding T2 mapping findings, the patients were categorized according to International Cartilage Repair Society (ICRS) grading system and are summarized in Table 2.

Because the quantitative T2 values of the 1080 measured ROIs were 6 different ROIs per slice and 24 different ROIs per case and these 24 ROIs were compared between two different groups (cases and control groups) as well as between the medial and lateral compartments of the joints, we could not provide all quantitative results. When considering the overall results of the quantitative T2-values, in the two groups (patients and controls) and in all compartments of the joint. For simplification, we averaged the two lateral slices into lateral compartment and the two medial slices into medial compartments.

The findings showed that the patients as well as the control groups had significantly higher T2-values in the superficial layer (P value < 0.001) in comparison with the deep cartilage layer (Tables 3 and 4).

When comparing the medial and the lateral compartments of the ankle joint at patients group, the alterations

Table 1 Conventional MRI findings of the studied patients

Conventional MRI findings	Patients group No. = 30
Normal	6 (20.0%)
Mild osteoarthritis	14 (46.7%)
Moderate osteoarthritis	6 (20.0%)
Severe osteoarthritis	4 (13.3%)
Associated osteochondral defect	4 (13.3%)

Table 2 Relation between ICRS grade and conventional MRI findings of the studied patients

Conventional MRI findings	ICRS grade			
	I (no. = 2)	II (no. = 12)	III (no. = 12)	IV (no. = 4)
Normal	2 (6.67%)	4 (13.33%)	0 (0.0%)	0 (0.0%)
Mild osteoarthritis	0 (0.0%)	8 (26.67%)	6 (20.0%)	0 (0.0%)
Moderate osteoarthritis	0 (0.0%)	0 (0.0%)	6 (20.0%)	0 (0.0%)
Severe osteoarthritis	0 (0.0%)	0 (0.0%)	0 (0.0%)	4 (13.33%)
Associated osteochondral defect	0 (0.0%)	0 (0.0%)	2 (6.67%)	2 (6.67%)

Table 3 Comparison between superficial and deep cartilage layers of patients group

		Superficial No. = 30	Deep No. = 30	Test value	*P* value	Sig.
Talar side (Lateral compartment)						
Ventral	Mean ± SD	91.36 ± 22.56	54.61 ± 32.60	6.562	< 0.001	HS
	Range	57.00–147.50	18.00–156.50			
Central	Mean ± SD	82.88 ± 22.33	36.81 ± 14.41	9.317	< 0.001	HS
	Range	32.00–140.00	20.00–78.00			
Dorsal	Mean ± SD	85.36 ± 17.35	52.43 ± 20.96	7.631	< 0.001	HS
	Range	48.00–117.00	28.50–111.50			
Talar side (medial compartment)						
Ventral	Mean ± SD	103.02 ± 14.70	64.43 ± 23.13	7.977	< 0.001	HS
	Range	81.25–133.25	25.00–130.50			
Central	Mean ± SD	100.20 ± 26.39	43.85 ± 7.30	10.074	< 0.001	HS
	Range	33.00–143.50	31.00–56.00			
Dorsal	Mean ± SD	99.69 ± 15.15	60.71 ± 23.94	7.672	< 0.001	HS
	Range	54.00–134.00	20.00–147.50			
Tibial side (Lateral compartment)						
Ventral	Mean ± SD	64.07 ± 26.06	42.66 ± 22.64	6.748	< 0.001	HS
	Range	23.00–113.50	0.00–98.00			
Central	Mean ± SD	59.88 ± 39.75	40.79 ± 39.89	3.958	< 0.001	HS
	Range	8.00–152.00	9.00–144.00			
Dorsal	Mean ± SD	67.87 ± 31.77	57.06 ± 24.85	3.716	0.001	HS
	Range	25.00–152.50	23.00–144.00			
Tibial side (Medial compartment)						
Ventral	Mean ± SD	73.29 ± 31.93	36.77 ± 16.08	7.408	< 0.001	HS
	Range	17.00–151.00	12.00–72.50			
Central	Mean ± SD	52.56 ± 26.99	31.41 ± 20.24	3.842	0.001	HS
	Range	10.00–106.00	11.50–103.00			
Dorsal	Mean ± SD	61.16 ± 22.22	50.95 ± 27.71	2.457	0.020	S
	Range	28.00–110.00	13.00–149.50			

in the T2-relaxation times are more pronounced in the medial talar cartilage compartment and there were no significant changes as for the tibial cartilage compartments (Tables 5 and 6).

Among the patients group, cases were categorized according to the compartment with highest grade of (ICRS) grading system (Table 7).

The following are some illustrative cases from our study,

- A 50-year-old male, presenting with ankle pain of 3 months duration.

Table 4 Comparison between superficial and deep layers of control group

		Superficial No. = 15	Deep No. = 15	Test value	*P* value	Sig.
Talar side (Lateral compartment)						
Ventral	Mean ± SD	37.97 ± 5.9	24.57 ± 2.71	7.435	< 0.001	HS
	Range	29–48	21–30			
Central	Mean ± SD	40.63 ± 5.21	22.17 ± 2.62	10.149	< 0.001	HS
	Range	30–48	18–27			
Dorsal	Mean ± SD	49.57 ± 3.75	29.37 ± 6.69	9.630	< 0.001	HS
	Range	42–56	19–39			
Talar side (medial compartment)						
Ventral	Mean ± SD	37.97 ± 5.9	24.57 ± 2.71	7.435	< 0.001	HS
	Range	29–48	21–30			
Central	Mean ± SD	40.63 ± 5.21	22.17 ± 2.62	9.019	< 0.001	HS
	Range	30–48	18–27			
Dorsal	Mean ± SD	49.57 ± 3.75	29.37 ± 6.69	9.630	< 0.001	HS
	Range	42–56	19–39			
Tibial side (Lateral compartment)						
Ventral	Mean ± SD	44.83 ± 7.68	28.93 ± 9.41	5.270	< 0.001	HS
	Range	32–56	18–46			
Central	Mean ± SD	44.6 ± 7.43	28.77 ± 5.97	9.353	< 0.001	HS
	Range	32–56	19–39			
Dorsal	Mean ± SD	53.9 ± 7.68	42.1 ± 9.93	5.547	< 0.001	HS
	Range	41–65	27–60			
Tibial side (Medial compartment)						
Ventral	Mean ± SD	44.83 ± 7.68	28.93 ± 9.41	5.270	< 0.001	HS
	Range	32–56	18–46			
Central	Mean ± SD	44.6 ± 7.43	28.77 ± 5.97	9.353	< 0.001	HS
	Range	32–56	19–39			
Dorsal	Mean ± SD	53.9 ± 7.68	42.1 ± 9.93	5.547	< 0.001	HS
	Range	41–65	27–60			

Table 5 Comparison between lateral compartment and medial compartment of TT cartilage (tibiotalar cartilage) at talar side in patients group

Talar side			Lateral compartment No. = 30	Medial compartment No. = 30	Test value	*P* value	Sig.
Ventral	Superficial	Mean ± SD	91.36 ± 22.56	103.02 ± 14.70	− 2.652	0.013	S
		Range	57.00–147.50	81.25–133.25			
	Deep	Mean ± SD	54.61 ± 32.60	64.43 ± 23.13	− 2.299	0.029	S
		Range	18.00–156.50	25.00–130.50			
Central	Superficial	Mean ± SD	82.88 ± 22.33	100.20 ± 26.39	− 2.625	0.014	S
		Range	32.00–140.00	33.00–143.50			
	Deep	Mean ± SD	36.81 ± 14.41	43.85 ± 7.30	− 2.697	0.012	S
		Range	20.00–78.00	31.00–56.00			
Dorsal	Superficial	Mean ± SD	85.36 ± 17.35	99.69 ± 15.15	− 3.954	< 0.001	HS
		Range	48.00–117.00	54.00–134.00			
	Deep	Mean ± SD	52.43 ± 20.96	60.71 ± 23.94	− 2.141	0.041	S
		Range	28.50–111.50	20.00–147.50			

Table 6 Comparison between lateral compartment and medial compartment of TT cartilage (tibiotalar cartilage) at tibial side in patients group

Tibial side			Lateral compartment No. = 30	Medial compartment No. = 30	Test value	*P* value	Sig.
Ventral	Superficial	Mean ± SD	64.07 ± 26.06	73.29 ± 31.93	− 1.612	0.118	NS
		Range	23.00–113.50	17.00–151.00			
	Deep	Mean ± SD	42.66 ± 22.64	36.77 ± 16.08	1.251	0.221	NS
		Range	0.00–98.00	12.00–72.50			
Central	Superficial	Mean ± SD	59.88 ± 39.75	52.56 ± 26.99	1.015	0.319	NS
		Range	8.00–152.00	10.00–106.00			
	Deep	Mean ± SD	40.79 ± 39.89	31.41 ± 20.24	1.174	0.250	NS
		Range	9.00–144.00	11.50–103.00			
Dorsal	Superficial	Mean ± SD	67.87 ± 31.77	61.16 ± 22.22	1.282	0.210	NS
		Range	25.00–152.50	28.00–110.00			
	Deep	Mean ± SD	57.06 ± 24.85	50.95 ± 27.71	1.080	0.289	NS
		Range	23.00–144.00	13.00–149.50			

Table 7 Relation between ICRS grade and location among the studied patients

ICRS location	ICRS grade				Test-value	*P* value	Sig.
	I (no. = 2	II (no. = 12)	III (no. = 12)	IV (no. = 4)			
Tibial medial	2 (100.0%)	4 (33.3%)	2 (16.7%)	0 (0.0%)	7.841	0.050	NS
Tibial lateral	0 (0.0%)	3 (25.0%)	1 (8.3%)	0 (0.0%)	1.154	0.764	NS
Talar medial	0 (0.0%)	3 (25.0%)	5 (41.7%)	4 (100.0%)	8.472	0.037	S
Talar lateral	0 (0.0%)	2 (16.7%)	4 (33.3%)	0 (0.0%)	2.917	0.404	NS

Conventional MRI ankle joint protocol and T2 mapping post-procession evaluation was done (Fig. 5).

Final diagnosis

Mild cartilage degeneration (mild osteoarthritis changes) by conventional MRI with blue color changes at the color-coded maps and high T2 relaxation values at the superficial and deep cartilage layers of central and dorsal zones of tibial and talar sides (ICRS grade III).

- A 38-year-old male presenting with ankle pain and swelling of 3 weeks duration with history of trauma.

Conventional MRI ankle joint protocol and T2 mapping post-procession evaluation was done (Fig. 6).

Final diagnosis

Osteochondral defect with no cartilage degenerative changes by conventional MRI with blue color changes at the color-coded maps and high T2 relaxation values at the superficial and deep cartilage layers of central and dorsal zones of talar side (ICRS grade III).

- A 35-year-old female, presenting with ankle pain and minimal swelling of one week duration.

Conventional MRI ankle joint protocol and T2 mapping post-procession evaluation was done (Fig. 7) .

Final diagnosis

Normal cartilage appearance by conventional MRI with blue color changes at the color-coded maps and high T2 relaxation values at the superficial cartilage layer of ventral and central zones of tibial side (ICRS grade II).

- A 60-year-old female presenting with ankle pain and swelling of months duration.

Conventional MRI ankle joint protocol and T2 mapping post-procession evaluation was done (Fig. 8).

Final diagnosis

Severe cartilage degeneration (Advanced osteoarthritis changes) by conventional MRI with blue color changes at the color-coded maps and high T2 relaxation values at the superficial and deep cartilage layers of dorsal zone of

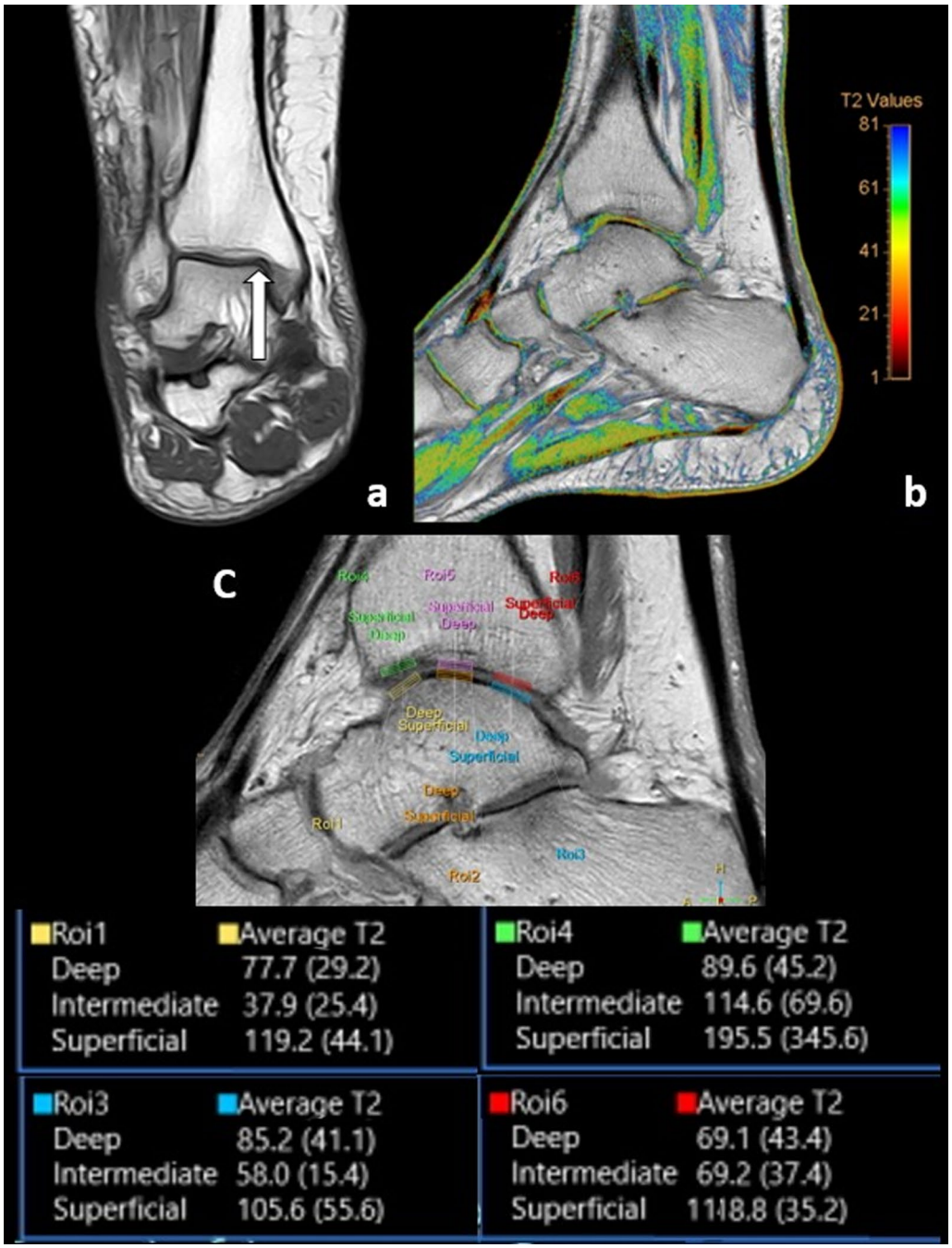

Fig. 5 Conventional MRI ankle joint and T2 mapping of a 50-year-old male, presenting with ankle pain of three months duration. Coronal T1WI (**a**) showing signs of mild cartilage degeneration in the form of non-uniform thinning of the articular cartilage covering the medial aspect of tibia and talus with narrowing of the joint space (white arrow). T2 mapping color-coded (**b**) with post-processing images (**c**) show color changes (blue color) with high T2 values (more than 60 ms) at the superficial and deep cartilage layers of ventral and dorsal zones of tibial and talar sides

tibial side along with bone degeneration changes (ICRS grade IV).

- A 28-year-old female, presenting with ankle pain of two weeks duration.

Conventional MRI ankle joint protocol and T2 mapping post-procession evaluation was done (Fig. 9.)

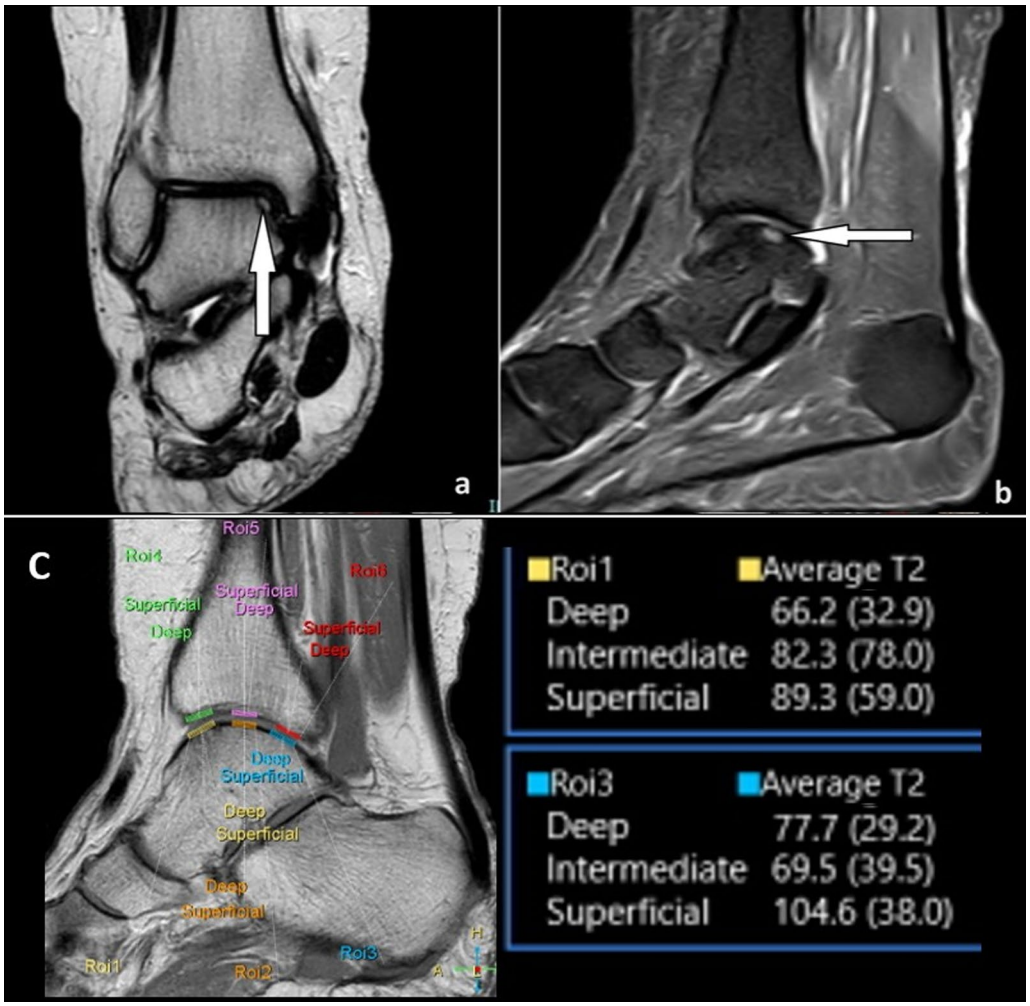

Fig. 6 Conventional MRI ankle joint and T2 mapping of A 38-year-old male presenting with ankle pain and swelling of 3 weeks duration with history of trauma. Coronal T2WI (**a**) and Sagittal STIR image (**b**) show osteochondral lesion at the talar dome (white arrows). T2 mapping color-coded with post-processing images (**c**) showing color changes (blue color) and high T2 values (more than 60 ms) at the superficial and deep cartilage layers of ventral and dorsal zones of talar side

Final diagnosis

Normal cartilage appearance by conventional MRI with no abnormality detected at the color-coded maps or by T2 relaxation values (ICRS grade 0-I).

Discussion

T2 mapping is one of the promising compositional MRI techniques used for assessment of articular cartilage in osteoarthritis. Numerous studies have proven the capabilities of compositional MRI assessment techniques for detecting early degenerative changes in articular cartilage prior to morphological manifestations on conventional MRI. Increased T2 relaxation time is closely related to increased water content and loss of collagen fiber integrity in the extracellular cartilage matrix [9].

The aim of this study was to determine the extent of improvement of the diagnostic performance of routine magnetic resonance imaging protocol in the evaluation of ankle joint articular cartilage lesions following the addition of a T2 mapping sequence.

Various studies have suggested T2 relaxation mapping enables detection of early cartilage abnormalities in the tibiotalar joint, especially in patients with lateral ankle instability. These study results are clinically relevant because early institution of specific treatment may be considered to prevent or delay the onset of osteoarthritis. However, in the evaluation of patients with lateral ankle

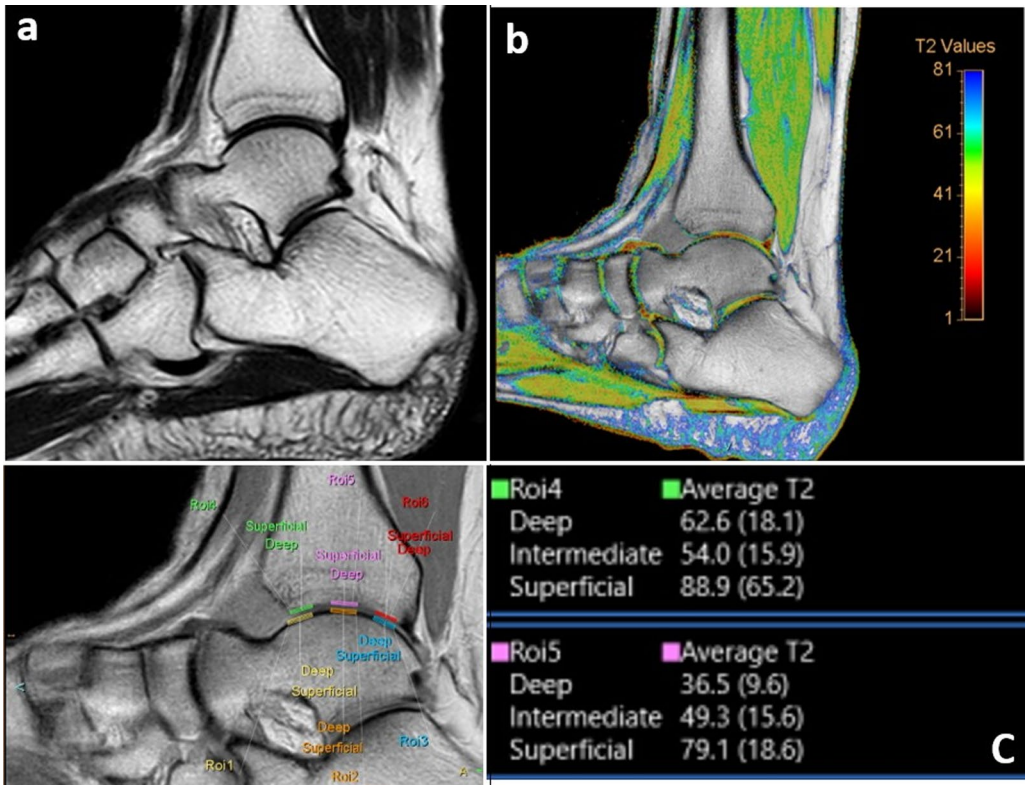

Fig. 7 Conventional MRI ankle joint and T2 mapping evaluation of a 35-year-old female, presenting with ankle pain and minimal swelling of one-week duration. Sagittal T2WI (**a**) showing no signs of cartilage degeneration nor detectable narrowing of the joint space. T2 mapping color-coded (**b**) with post-processing images (**c**) showing color changes (blue color) with high T2 values (more than 60 ms) at the superficial cartilage layer of ventral and central zones of tibial side

instability, little attention has been paid to the subtalar joint, and the potential role of quantitative T2 mapping of the subtalar joint cartilage has not been established [10].

The main finding in this study was color changes in post-processing color-coded images that correspond to cartilage degeneration. Variable increases in T2 values in the tibiotalar cartilage of ankle joint of the patients were also found. Most patients showed increases in T2 values and evidence of cartilage degeneration as compared to the control cases.

The average T2 values of tibio talar cartilage in tibial side of the control group was 40.52 ± 9.02 ms, while the average T2 values of tibio talar cartilage in talar side was 34.04 ± 9.5 ms, these T2 values are considered within the same range of the T2 values of the control group reported by Golditz et al. [11] which reported that the average T2 values, TT (tibial side) cartilage was 41.2 ± 8 ms,, while the average T2 values of TT (talus side) cartilage was 35.25 ± 9.58 ms.

In our study, we used ICRS grading system (inspired by the International Cartilage Research Society score) in each zone (ventral, central and dorsal) of tibio talar cartilage of ankle joint. The T2 value of the severest lesion was the one recorded. No previous studies were found to use this grading system for ankle joint evaluation by T2 mapping; however, many studies used this grading system for knee joint evaluation by T2 mapping; like the studies conducted by Anderson et al. [12] and Apprich et al. [13] The latter assessed the articular cartilage of the medial femoral condyle in 43 patients by using a T2 mapping sequence and a routine MR imaging protocol, showing a significant relation between the T2 relaxation time and the morphologic grade of the cartilage lesion.

Grading of osteoarthritis of tibiotalar joint was done subjectively by the study readers, which were specialized experienced musculoskeletal radiologists who relied on their experience to grade the osteoarthritis visually as mild, moderate, or severe. This was due to the absence scoring system for tibiotalar joint, as all scoring systems for ankle osteoarthritis graded all the joint compartments.

In this study, we found that 2/30 (6.67%) patients showed no abnormality in the conventional images with normal T2 values. This denoted normal water content and no degeneration of the either superficial or deep

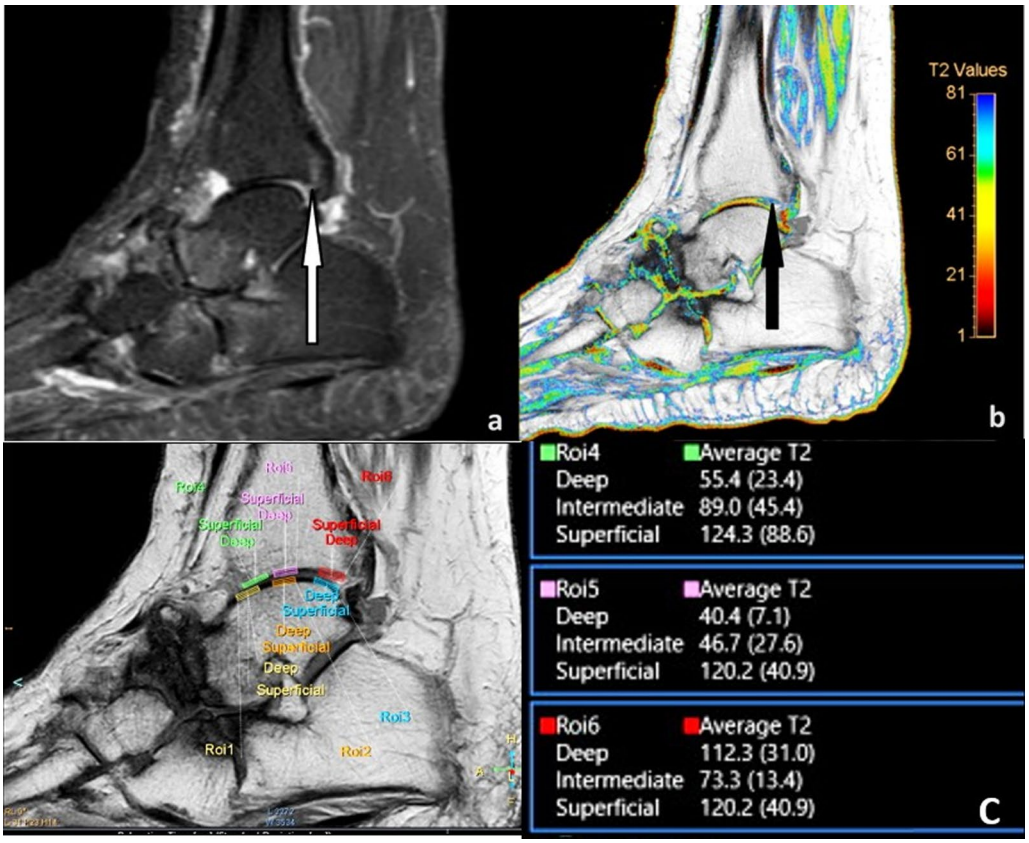

Fig. 8 Conventional MRI ankle joint and T2 mapping of a 60-year-old female presenting with longstanding ankle pain and swelling. Sagittal STIR image (**a**) showing signs of advanced cartilage degeneration in the form of irregularities of the cartilage contour with mild subchondral marrow edema at the dorsal aspect of the tibial side (white arrow). T2 mapping color-coded (**b**) with post-processing images (**c**) showing color changes (blue color) with high T2 values (more than 60 ms) at the superficial and deep cartilage layers of dorsal zone of tibial side (black arrow)

cartilage layers, in keeping with grade 0-I. On the other hand, 4/30 (13.3%) patients were misdiagnosed as having no abnormality on conventional images, yet they showed elevated T2 values, denoting increased water content/degeneration of the superficial cartilage layer on T2 mapping sequence, in keeping with grade II. Using T2 mapping sequence of the ankle cartilage improved the sensitivity in the detection of early cartilage lesions within the ankle joint with improvement of the examination accuracy.

In the current study, we illustrated that both the patients and the control groups had significantly higher T2-values in the superficial cartilage layer (*P* value < 0.001) compared to the deep layer. This came in alignment with Park et al. study [14] that showed a statistically significant higher T2 relaxation values in the superficial layer of the talar trochlear cartilage in the patient group than in the deep layer.

These results were also concordant with other two older studies performed in 2010 and 2012 by Apprich et al. [13] and Domayer et al. [15], respectively, where the former stated that there was a highly significant increase from deep to superficial T2 (21.1 ± 3.1 ms vs. 39.3 ± 5.9 ms, $P < 0.001$, zonal T2 index = 1.87). The latter study concluded that T2 relaxation time significantly increased with increasing morphologic cartilage defect grade globally and in the superficial layer of ankle joints.

Juras et al. [16] also found that the absolute values of the zonal analysis showed a greater difference of T2 values between the deep and superficial zones in ankles ($p < 0.001$).

In our study, we demonstrated that when differentiating between the medial and the lateral compartments of the ankle joint at patients group, the alterations in the T2-relaxation times are more pronounced in the medial talar cartilage compartment and there were no significant changes as for the tibial cartilage compartments.

These findings went in agreement with the results from Golditz et al. [11] that found that the changes in the T2-relaxation times are more pronounced in the medial talar dome for the FAI group (functional ankle instability

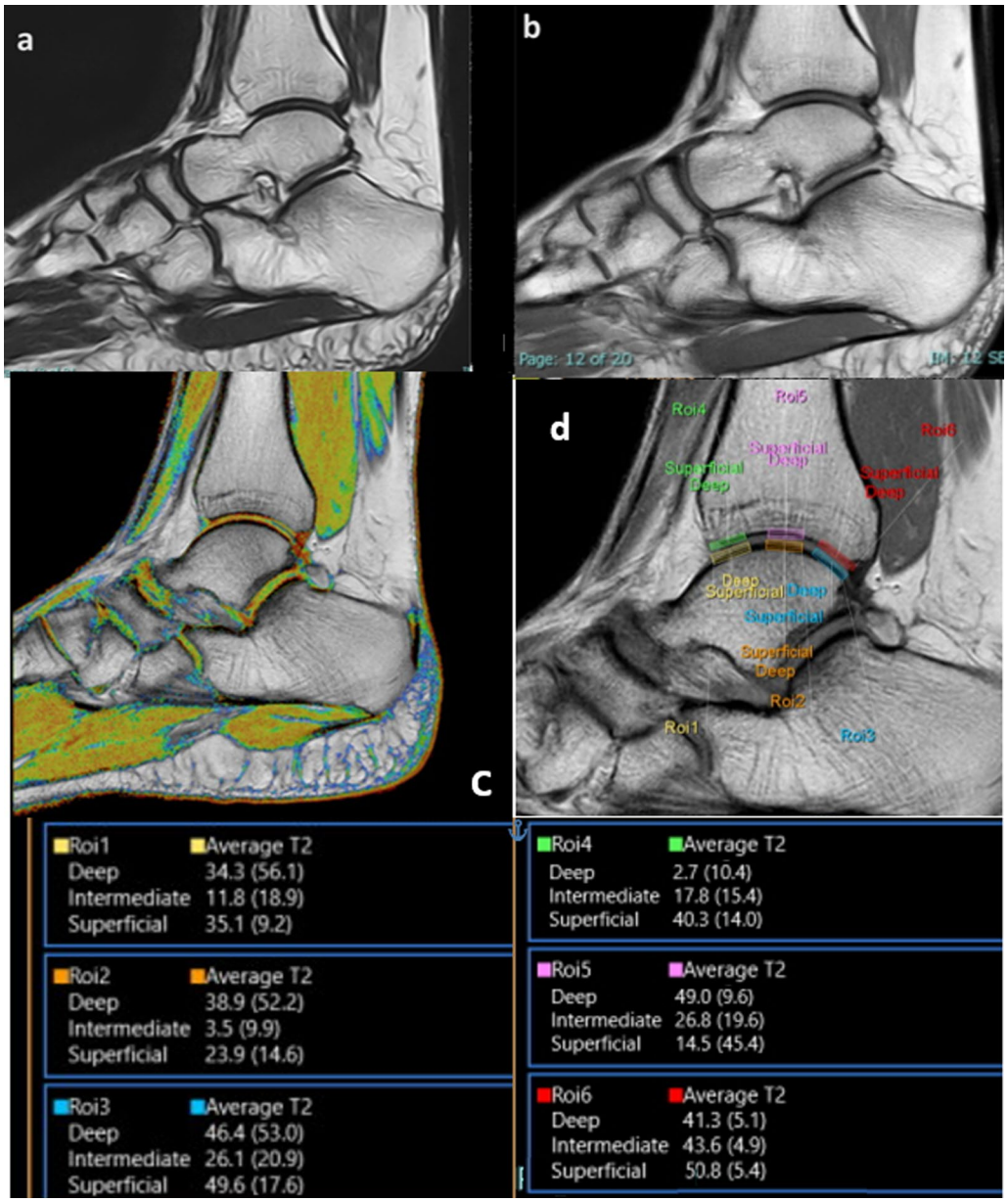

Fig. 9 Conventional MRI ankle joint and T2 mapping of a 28-year-old female, presenting with ankle pain of two weeks duration. Sagittal T2 weighted image (**a**) and PD image (**b**) showing no signs of cartilage degeneration and no detectable narrowing of the joint space. T2 mapping color-coded (**c**) with post-processing images (**d**) showing normal color (red, yellow or green) and T2 values (less than 60 ms)

group) and the tibial cartilage also showed no significant changes.

Park et al. [14] also reported that osteochondral lesions are statistically significantly more frequent in the medial talar dome than in the lateral zone and that anterior dome lesions are relatively uncommon compared to middle and posterior dome lesions. These observations are explained by the fact that inversion injury is the most common mechanism of traumatic ankle sprain, which frequently leads to lateral instability and osteochondral lesions. Inversion of the ankle can result in impaction of the medial talar dome on the medial or medial-anterior tibial plafond.

In the current study, we demonstrated that out of 30 cases, 12 (40%) were found to have the highest ICRS grade at the medial talar location, with was statistically significant correlation ($P=0.037$) between the ICRS grads and the medial talar location. This came in

alignment with Battaglia et al. [17] that found a statistically significant ($p=0.05$) relationship between the clinical score and the percentage of the lesion area of medial talar location.

Tao et al. [18] found that the T2 values of the medial talar cartilage of the posterior subtalar joint in combined CFL injury patients were negatively correlated with their ICRS scores. This finding suggested that the medial talar cartilage of the posterior subtalar joint is the main subregion that might affect the clinical symptoms and function of patients.

Limitations of the study

The limitations of our study include the following, first: our ability to characterize possible T2 mapping changes limited by relatively small numbers and sample size. Secondly, grading of osteoarthritis of tibiotalar joint was done subjectively by the study readers, which were specialized experienced musculoskeletal radiologists that relied on their experience to visually grade the osteoarthritis because there is no scoring system for tibiotalar joint and all scoring system for ankle osteoarthritis graded all the joint compartments. Lastly, in our study we did not correlate between T2 and clinical or surgical endoscopic findings.

Conclusions

In this study, the addition of a T2 mapping of the ankle cartilage sequence to a routine MR ankle protocol improved sensitivity and accuracy in the detection of early degenerative changes of the ankle joint. The improvement in sensitivity with use of the T2 maps was in the identification of early cartilage degeneration by the quantitative analysis of the collagen matrix; these alterations can be overlooked in purely morphologic MR studies, carrying a delay in diagnosis and treatment.

In conclusion, we observed high rates of ankle articular cartilage degenerative changes and high T2 values on patients presented with ankle pain compared to the control group.

Further studies with larger samples are needed to better understand the features of the reparative cartilaginous tissue in the ankle and implement the applicability of T2 mapping sequence as well as its correlation with the clinical data and the surgical endoscopic findings.

Abbreviations

MRI	Magnetic resonance imaging
ICRS	International Cartilage Research Society score
PG	Proteoglycans
GAG	Glycosaminoglycans
FOV	Field of view
ROI	Region-of-interest
GRE	Gradient recalled echo
PACS	Picture archiving and communications system
SPSS	Statistical Package for Social Science
T1WIs	T1-weighted images
T2WIs	T2-weighted images
PD	Proton density
TE	Time to echo
TR	Time to repetition

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Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by AMM, AMM, AMO and NMH. The first draft of the manuscript was written by AMM. The authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study was approved by the ethical committee of Faculty of Medicine, Ain-Shams University (FMASU REC), under Fedral wide assurance No. FWA00017585 (FMASU MD 128/2021).

Consent for publication

Identifying information about participants (patients' identity) did not appear in any part of the manuscript; therefore, consent for publication was not required.

Competing interests

The authors declare that they have no conflict of interest.

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