BMC Musculoskeletal Disorders

RESEARCH

Open Access

A new four-area method for evaluating biochemical changes in lumbar facet joint degeneration on T2* mapping

Yi Ding[1,2], Shidong Ruan[3], Liping Liu[1], Xiaodong Zhang[4], Rongchun Chen[1], Qin Chen[1] and Shuaishuai Xu[5*]

Abstract

Purpose To investigate the diagnostic efficacy of a new four-area method for evaluating biochemical changes in lumbar facet joint (LFJ) degeneration on T2* mapping.

Methods LFJ degeneration was morphologically graded on T2-weighted imaging using the Weishaupt system. T2* value of LFJ was measured on T2* mapping using both all-inclusive and four-area methods. Inter-observer reliability for continuous and categorical variables was evaluated using intraclass correlation coefficient (ICC) and Kappa value, respectively. The correlation between continuous variables and ordered categorical variables was examined using one way ANOVA or Kruskal–Wallis test, as appropriate.

Results Fifty-eight patients with LBP underwent standard MRI protocols and axial T2* mapping. In all-inclusive method analysis, the median T2* value of grade 0 LFJ (21.32 [18.27, 26.05]) was higher than those of grade I (18.33 [15.47, 22.16], $p < 0.001$), grade II LFJ (17.99 [15.18, 20.97], $p < 0.001$), and grade III LFJ (18.29 [15.07, 25.47], $p = 0.178$). In four-area method analysis, the median T2* value of grade 0 LFJ (21.55 [18.2, 26.72]) was significantly higher than those of grade I (17.94 [15.45, 21.67], $p < 0.001$), grade II LFJ (17.28 [14.65, 20.38], $p < 0.001$) and grade III LFJ (18.25 [15.22, 22.41], $p = 0.028$). A downward trend in T2* value was observed as LFJ degeneration progressed, except for grade III. Additionally, the median T2* values obtained using all-inclusive method were generally higher than those from four-area method, except for grade 0. Four-area method demonstrated excellent inter-observer reliability with ICC of 0.992 ([0.99, 0.993], $p < 0.001$), higher than that of all-inclusive method (0.942 [0.931, 0.951], $p < 0.001$).

Conclusions Compared to all-inclusive method, four-area method provides higher reproducibility and accuracy in measuring T2* values. Thus, it is a more reliable approach for assessing biochemical changes in LFJ degeneration on T2* mapping.

Keywords Magnetic resonance imaging, T2* mapping, Lumbar facet joint

*Correspondence:
Shuaishuai Xu
shuaishuaixu1991@163.com
Full list of author information is available at the end of the article

Introduction

Low back pain (LBP) is a prevalent musculoskeletal disorder that affects up to 60% to 80% of the population during their lifetime, resulting in considerable negative impacts on quality of life and social economy[1–3]. Among its numerous etiologies, lumbar facet joint (LFJ) degeneration has been identified as a predominant contributor to chronic LBP[4–6], primarily through osteoarthritic changes and synovial fluid alterations in these small articular structures[4–6]. This underscores the critical need for accurate, objective, and reproducible methods to assess LFJ cartilage integrity.

Recent advances in MRI technology have enabled the development of biochemical quantitative imaging techniques, particularly T2, T2*, and T1ρ mapping[7–11]. While T1ρ imaging remains clinically challenging due to technical complexities[12], both T2 and T2* mapping have emerged as valuable tools for evaluating cartilage composition. These parameters are sensitive to water content and collagen-water interactions, with elevated values indicating increased hydration and greater water molecule mobility[13]. The T2* relaxation time, distinct from conventional T2 relaxation, incorporates both intrinsic transverse relaxation and magnetic field inhomogeneity effects[14]. Clinically, decreasing T2* values correlate with progressive cartilage degeneration, making this parameter particularly valuable for assessing joint deterioration in various anatomical locations including hips, knees, ankles, shoulders, and finger joints[13–16], as well as LFJs [7].

However, the unique anatomical characteristics of LFJs—their small size and narrow joint spaces—present distinct measurement challenges. Conventional "all-inclusive" measurement methods, which incorporate both articular cartilage surfaces and joint cavity within a single region of interest (ROI) [7, 8], are inherently limited by their inability to differentiate synovial fluid from cartilage tissue. This methodological constraint introduces measurement variability as synovial fluid content directly influences T2* values, potentially compromising the accuracy of cartilage assessment. To address these limitations, we developed a novel four-area measurement approach. This technique involves placing four circular ROIs at distinct cartilage regions and averaging their T2* values, thereby minimizing synovial fluid interference.

Thus, the aim of this study was to investigate the diagnostic efficacy of a new four-area method for evaluating biochemical changes in lumbar facet joint (LFJ) degeneration on T2* mapping.

Methods

This retrospective study received institutional review board approval with a waiver of informed consent. All patient data were anonymized and de-identified prior to analysis.

Patient population

Patients suffering from LBP and other impairments originating from lumbar spine including limited lumbar movement and sciatica who had undergone standard MRI protocols and axial T2* mapping between January 1, 2020 to June 1, 2023 were included in this study. Exclusion criteria: (1) patients with lumbar tuberculosis or other infections, multiple myeloma or other malignant tumors, or concomitant skeletal-rheumatoid disease involving the facet joints; (2) poor image quality of MRI for further analysis. Patient information was anonymized and de-identified prior to analysis.

Image acquisition and analysis

Patients were scanned using a 3.0 T MRI unit (Tim Trio, Siemens Medical Solutions, Erlangen, Germany) with a dedicated 8-channel spine coil. Axial T2* mapping used the following parameters: fast spin echo, repetition time 575 ms, echo time 4.2, 11.3, 18.5, 25.6, 32.7 ms, field of view 160 ×160 mm, voxel size 0.4 ×0.4 ×4.0 mm, interslice gap 0.3 mm, number of slices 15, examination time 3 min 41 s.

LFJ degeneration was morphologically graded on T2-weighted imaging using the Weishaupt system [17]: grade 0, normal facet joint space (2–4 mm width); grade 1, mild degenerative disease, narrowing of the facet joint space (< 2 mm) and/or small osteophytes and/or mild hypertrophy of the articular process; grade 2, moderate degenerative disease, narrowing of the facet joint space and/or moderate osteophytes and/or moderate hypertrophy of the articular process and/or mild subarticular bone erosions; and grade 3, severe degenerative disease, narrowing of the facet joint space and/or large osteophytes and/or severe hypertrophy of the articular process and/or severe subarticular bone erosions and/or subchondral cysts. Image analysis was performed by one radiologist and one spine surgeon to evaluate interobserver reliability.

T2*mapping image analysis was performed using syngo.via workstation (Siemens Healthineers). For the measurement of T2* value of LFJ, region of interest (ROI) was primarily delineated on first echo anatomical image and copied to the corresponding T2* mapping image using two methods. All-inclusive method: a ROI was drawn covering both superior and inferior articular process cartilage, and the joint cavity (Fig. 1). Four-area

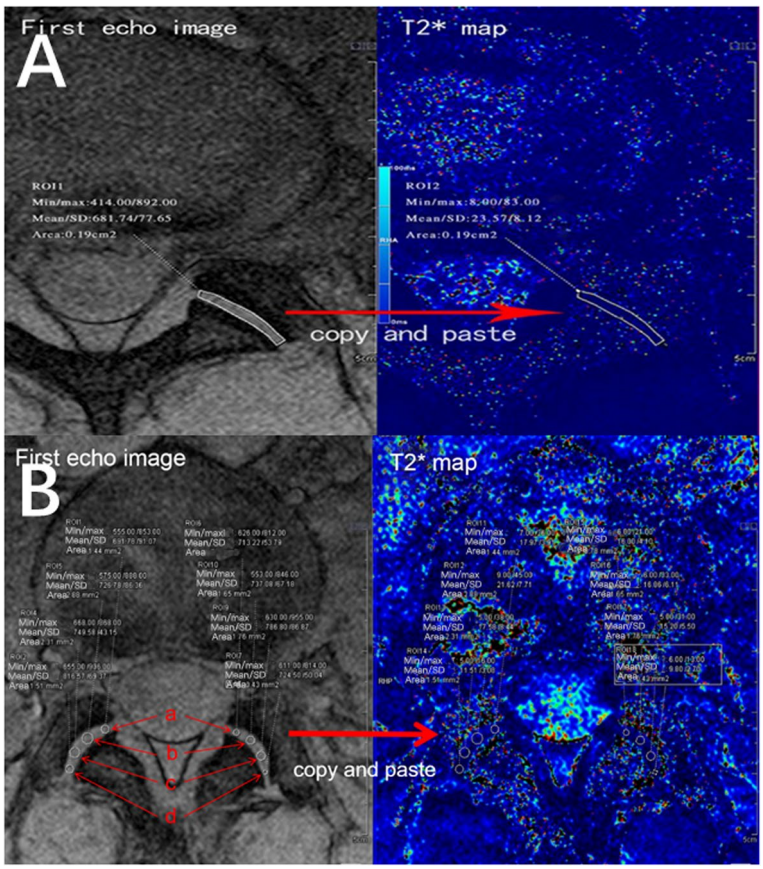

Fig. 1 Schematic illustration of T2* value measurement methods for lumbar facet joints. (**A**) All-inclusive method. Region of interest was primarily delineated on first echo anatomical image (left) and copied to the corresponding T2* mapping image (right). A ROI was drawn including both the upper and lower articular process cartilage, and the joint cavity. (**B**) Four-area method. Two round ROIs were drawn at the front and last points of cartilage area, and the other two round ROIs were drawn at the two tertile points between the front and last points

method: two round ROIs were drawn at the front and last points of both superior and inferior articular process cartilage, and the other two round ROIs were drawn at the two tertile points between the front and last points. During the process of outlining the ROI, we make every effort to avoid the contour line touching the bone. T2* values obtained from the four ROIs were averaged to obtain the final result (Fig. 1). The measurement of T2* value using two methods was performed by one radiologist and one spine surgeon to evaluate inter-observer reliability. Final T2* values represented the average of both observers'measurements for each method.

Statistical analysis

Shapiro–Wilk test was used to determine whether the continuous variables accord with normal distribution. Continuous variables were presented as means and SD (normal distribution), or as medians and quartiles (non-normal distribution). Inter-observer reliability for continuous and categorical variables were respectively evaluated using intraclass correlation coefficient (ICC) and Kappa value, interpreted as follows: 0–0.3, weak agreement; 0.3–0.5, moderate agreement; 0.5–0.7, substantial agreement; 0.7–1.0, excellent agreement. For evaluating the correlation between continuous variables and ordered categorical variables, one way ANOVA (normal distribution with equal variance) or Kruskal–Wallis test (non-normal distribution), and Spearman rank test were used.

All reported p values were two-sided. A p value of <0.05 was considered statistically significant. All statistical analyses were performed using R-4.2.3 (https://www.r-project.org).

Results

Morphological evaluation of LFJ

This study evaluated 580 LFJs from 58 patients (32 males, 26 females; mean age, 46.9 ±13.9 years; range, 19–79 years). Weishaupt grading results are summarized in Table 1. Inter-observer agreement was achieved in 395

Table 1 Weishaupt grading results of LFJ

		Observer 2				Total (%)
		0 (%)	I (%)	II (%)	III (%)	
Observer 1	0 (%)	38 (6.6)	14 (2.4)	0	0	52 (9.0)
	I (%)	18 (3.1)	271 (46.7)	73 (12.6)	3 (0.5)	365 (62.9)
	II (%)	3 (0.5)	55 (9.5)	58 (10.0)	6 (1.0)	122 (21.0)
	III (%)	1 (0.2)	7 (1.2)	5 (0.9)	28 (4.8)	41 (7.1)
Total (%)		60 (10.3)	347 (59.8)	136 (23.4)	37 (6.4)	580

LFJ lumbar facet joint

cases (68.1%), with moderate reliability (Kappa value = 0.431, $p < 0.001$).

T2* values of LFJ

Ten LFJs were excluded due to severe degeneration, fusion, or poor imaging quality, leaving 570 LFJs for T2* analysis (Figs. 2, 3 and 4, supplementary material 1).

Four-area method demonstrated excellent inter-observer reliability with ICC of 0.992 ([0.99, 0.993], $p < 0.001$), higher than that of all-inclusive method (0.942 [0.931, 0.951], $p < 0.001$). Additionally, inter-method consistency between the two methods was nearly perfect (ICC = 0.823 [0.795, 0.848], $p < 0.001$).

In all-inclusive method analysis, T2* value exhibited a declining trend with increasing LFJ grade, except for grade III (Fig. 5). The median T2* value of grade 0 LFJ (21.32 [18.27, 26.05]) was significantly higher than those of grade I (18.33 [15.47, 22.16], $p < 0.001$) and grade II LFJ (17.99 [15.18, 20.97], $p < 0.001$), and was higher than that of grade III LFJ but not reaching a significant difference

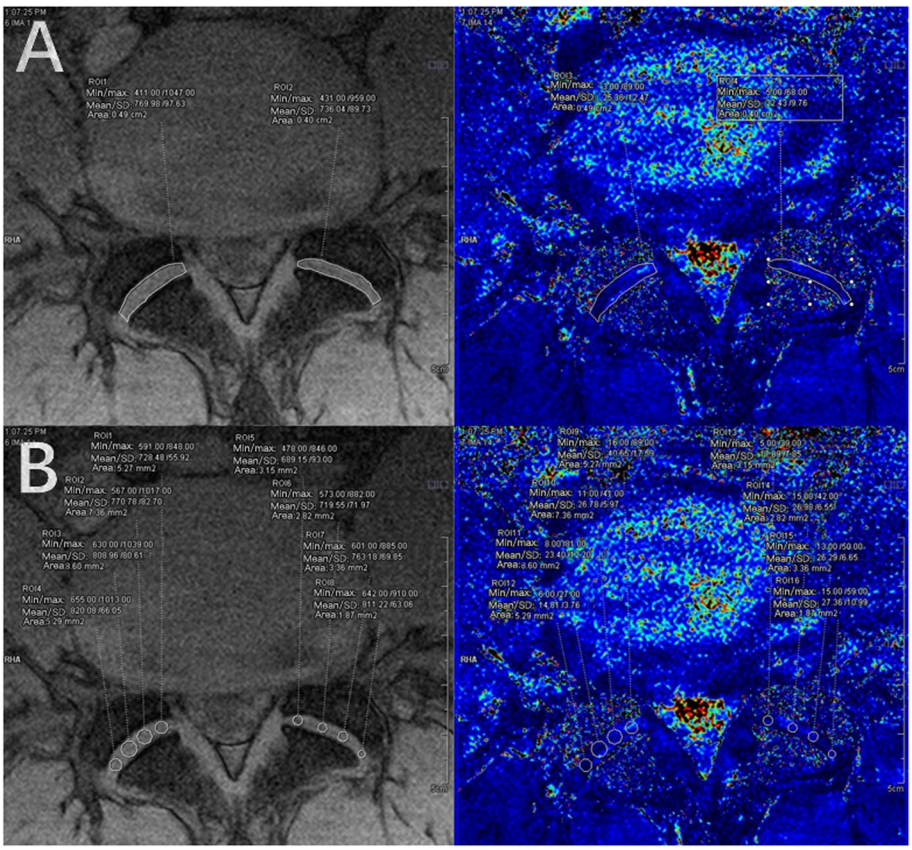

Fig. 2 A 52-year-old male patient with low back pain showed bilateral grade 0 lumbar facet joint. Measurement of T2* value using (**A**) all-inclusive method, and (**B**) four-area method, respectively

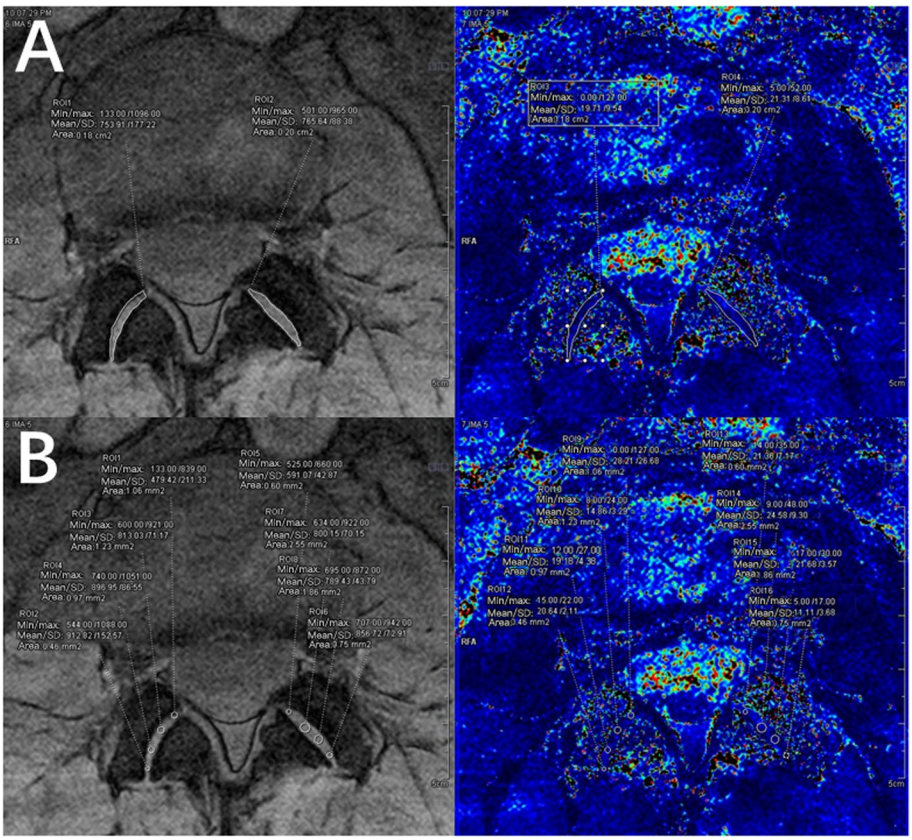

Fig. 3 A 39-year-old male patient with low back pain showed bilateral grade I lumbar facet joint. Measurement of T2* value using (**A**) all-inclusive method, and (**B**) four-area method, respectively

(18.29 [15.07, 25.47], $p = 0.178$). No significant difference was observed between the median T2* values of grade I and II LFJ ($p = 0.484$), grade I and III LFJ ($p = 0.833$), grade II and III LFJ ($p = 0.833$). A weak inverse correlation was observed between T2* value and LFJ grade (rho $= -0.132$, $p = 0.002$) (Table 2).

In four-area method analysis, T2* value decreased with higher LFJ grade, except for grade III (Fig. 5). The median T2* value of grade 0 LFJ (21.55 [18.2, 26.72]) was significantly higher than those of grade I (17.94 [15.45, 21.67], $p < 0.001$), grade II LFJ (17.28 [14.65, 20.38], $p < 0.001$) and grade III LFJ (18.25 [15.22, 22.41], $p = 0.028$). No significant difference was observed between the median T2* values of grade I and II LFJ ($p = 0.168$), grade I and III LFJ ($p = 0.947$), grade II and III LFJ ($p = 0.919$). A weak inverse correlation was observed between T2* value and LFJ grade (rho $= -0.17$, $p < 0.001$) (Table 2).

Discussion

In this study, four-area method showed superior reproducibility compared to all-inclusive method, as evidenced by its higher ICC (0.992 vs 0.942). Using four-area method, we observed a progressive decrease in T2* value with increasing LFJ degeneration grade (0 through II), with grade III showing an unexpected deviation from this trend. Specifically, grade 0 LFJs exhibited significantly higher median T2* value than all degenerated grades (I-III). In contrast, all-inclusive method, while showing a similar overall trend, failed to demonstrate a statistically significant difference between grade 0 and grade III LFJs. These findings suggest that four-area method provides more sensitive detection of biochemical changes in LFJ degeneration compared to all-inclusive method, particularly in advanced stages of joint degeneration.

As the sole synovial joint in spinal column, facet joint possesses a complete synovial joint structure comprising a joint capsule, articular cavity, synovial fluid, and articular cartilage [18]. Articular cartilage is primarily composed of chondrocytes embedded in an extracellular matrix containing water (65–80%), proteoglycans (10–15%), and type II collagen fibers (15–20%) [19]. The degenerative process of articular cartilage is initially characterized by increase in water content, early loss of proteoglycan, alterations in the size and arrangement of collagen fiber, and gradually followed by softening and disappearance of cartilage [4, 6]. This degenerative

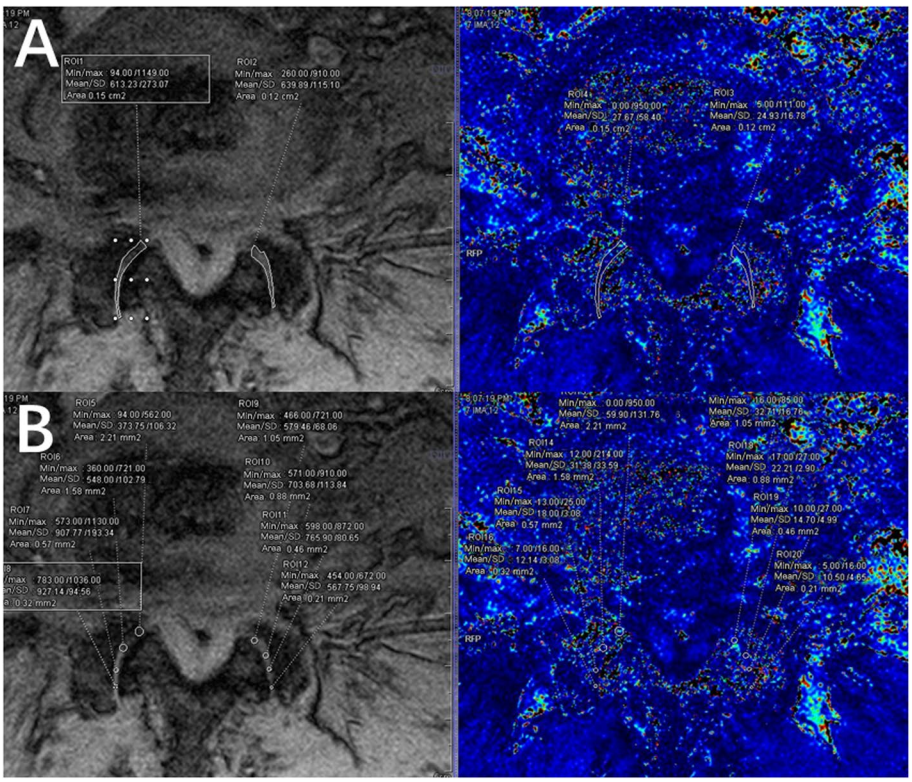

Fig. 4 A 65-year-old female patient with low back pain showed left grade III lumbar facet joint and right grade II lumbar facet joint. Measurement of T2* value using (**A**) all-inclusive method, and (**B**) four-area method, respectively

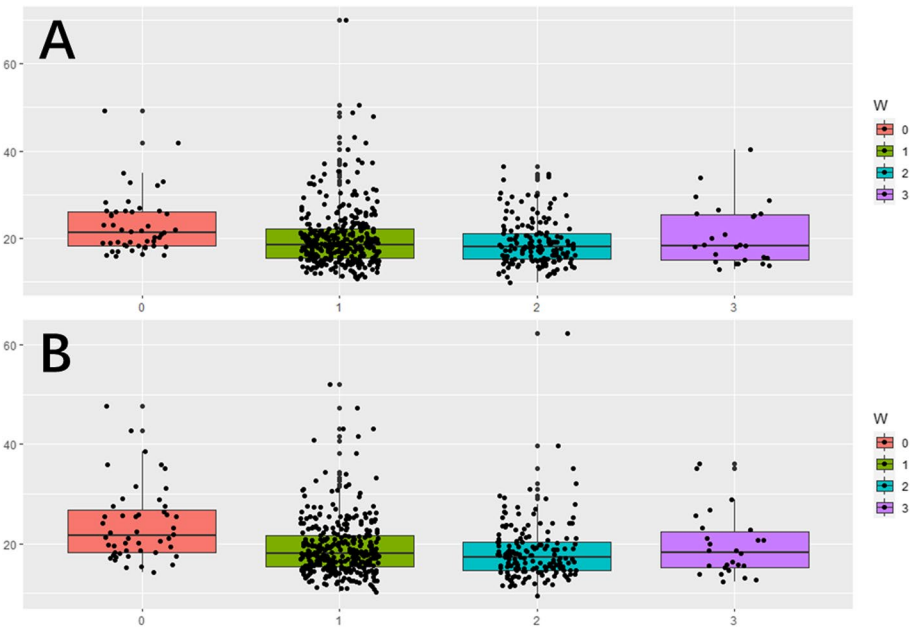

Fig. 5 A downward trend of T2* value was observed as the grade of lumbar facet joint raised except grade III. Measurement of T2* value using (**A**) all-inclusive method, and (**B**) four-area method, respectively

Table 2 T2* values of LFJ obtained by all-inclusive and four-area methods

Grade	LFJ (%)	T2* value A (quartile, ms)	T2* value B (quartile, ms)
0	48 (8.4)	21.32 (18.27, 26.05)	21.55 (18.2, 26.72)
I	335 (58.8)	18.33 (15.47, 22.16)	17.94 (15.45, 21.67)
II	161 (28.2)	17.99 (15.18, 20.97)	17.28 (14.65, 20.38)
III	26 (4.6)	18.29 (15.07, 25.47)	18.25 (15.22, 22.41)
p value	/	< 0.001	< 0.001
rho (*p* value)	/	−0.132 (0.002)	−0.17 (0.002)

LFJ lumbar facet joint, T2* value A, T2* value obtained by all-inclusive method; T2* value B

T2* value obtained by four-area method

cascade ultimately leads to the structural breakdown of articular cartilage, compromising joint function.

Over the past two decades, several biochemical quantitative imaging techniques have been developed for cartilage evaluation, including T2 mapping, T2* mapping, and T1ρ mapping [7–11]. Among these, T1ρ imaging demonstrates particular sensitivity for detecting early-stage cartilage degeneration and shows strong correlation with radiographic assessment findings. However, T1ρ imaging presents several technical limitations that hinder its widespread clinical and research application: (1) Requirement for high magnetic field strengths; (2) Dependence on high radiofrequency pulse energy levels; (3) Susceptibility to orientation-dependent variations in cartilage signal relative to the main magnetic field [12]. These constraints have limited the clinical adoption of T1ρ imaging despite its diagnostic potential for early cartilage damage detection.

Both T2 and T2* relaxation values are sensitive to water content and the interactions between water molecules and collagen fibers. Elevated T2/T2* values typically reflect increased water content and greater molecular mobility within the cartilage matrix[13]. Unlike T2 relaxation, which occurs in spin-echo sequences, T2* relaxation is specific to gradient-echo imaging. T2* incorporates both intrinsic T2 relaxation and additional signal decay due to local magnetic field inhomogeneities. Consequently, T2* values are inherently shorter than T2 values, as described by the following relationships, where γ is the gyromagnetic ratio: $1/T2^* = 1/T2 + \gamma\ \Delta B_{inhom}$,or $1/T2^* = 1/T2 + 1/T2'$, where $1/T2' = \gamma\ \Delta B_{inhom}$, and ΔB_{inhom} is the magnetic field inhomogeneity across a voxel[14]. T2* mapping offers unique insights into the spatial organization of macromolecules (e.g., collagen fibers) and their interactions with water mobility. As such, T2* has emerged as a robust biomarker for cartilage degeneration, validated not only in spinal structures (e.g., lumbar facet joints and intervertebral discs) but also in peripheral joints, including the knee, hip, and ankle [13, 14, 20, 21]. Clinically, T2* mapping has proven to be a reliable and feasible technique for biochemical cartilage assessment. Huang L et al. quantitatively evaluated the clinical value, and demonstrated the potential benefits of biochemical axial T2* mapping-based grading of early stages of degenerative disc disease in a clinical setting [21]. Its sensitivity to early degenerative changes, such as proteoglycan loss and collagen disorganization, makes it particularly valuable for evaluating lumbar facet joint osteoarthritis and disc degeneration [7, 21, 22].

Hu J et al. assessed the feasibility of axial T2, T2*, and T1 ρ mapping of LFJ cartilage for evaluation of early degeneration and found that T2* values were significantly different between Pfirrmann grade I and III disks [7]. Enokida S et al. investigated the T2 value of lumbar facet joint (FJ) LFJ in subjects without lumbar spinal disorders using T2 mapping, and to evaluate the correlation between age and T2 value. The results suggested that T2 mapping could detect the degenerative changes of LFJ related to aging even in subjects without lumbar spinal disorders [8]. In these studies, ROI encompassed both the superior and inferior articular cartilage surfaces along with the joint cavity [7, 8], namely all-inclusive measuring method. However, it is difficult to distinguish the synovial fluid from the LFJ cartilage. The water content in the joint cavity can directly affect the T2* value, causing errors in the quantitative evaluation of the cartilage and the final study results. This confounding effect is supported by our observation of paradoxically higher median T2* value in grade III versus grade II LFJs. Such findings suggest that synovial fluid contamination may obscure true cartilage biochemical changes in advanced degeneration. To reduce the effect of the synovial fluid in the joint cavity on the measurement of T2* value, we proposed a new four-area method.

An important finding of this study was that the T2* values obtained by all-inclusive method were higher than those obtained by four-area method, except grade 0 LFJ. Normal cartilage structure and absence of joint synovial fluid in grade 0 LFJ are possible explanations, resulting in consistent T2* values obtained by both

methods. In contrast, LFJs of grade I, II, and III have different degrees of cartilage degeneration accompanied by various amounts of joint synovial fluid. Lower T2* values obtained by four-area method indicated that this new method was less influenced by joint synovial fluid and more accurate than all-inclusive method in the measurement of T2* value.

The subjects we collected in this study were outpatient patients referred for LBP. Chronic LBP related to LFJ degeneration often results from the degeneration, osteoarthritis, and synovial fluid of joints, which are closely related to the damage and degeneration of joint cartilage. Although LFJ degeneration is regarded as common causes of LBP, it also can be caused by many other reasons, such as lumbar disc herniation, internal disc disruption, and sacroiliac joint pain [5, 6, 23]. Thus, accurately determining the direct cause of LBP plays an important role in the planning of treatment. As the level of T2* value can reflect the degree of LFJ degeneration, it may be useful to help clinicians determine whether the pain comes from LFJ or other reasons. Our results showed that the proposed new four-area method was more reproducible and accurate than conventional all-inclusive method in the measurement of T2* value. The demonstrated accuracy of this technique in assessing cartilage biochemical changes makes it a promising tool for comprehensive LBP evaluation. Future studies should validate its utility in therapeutic decision-making and outcome prediction.

Several limitations in the current study. First, there was no histopathological assessment of LFJ degeneration. This is difficult to achieve in humans, and further experimental research on animals is needed. Secondly, the imaging time of all participants was uncertain, ignoring the diurnal variation of facet joints as confirmed by prior studies. Thirdly, the number of participants was relatively small. Further investigation is necessary to assess whether our results would be obtained with a larger number of participants.

Conclusions

Compared to all-inclusive method, four-area method provides higher reproducibility and accuracy in measuring T2* values. Thus, it is a more reliable approach for assessing biochemical changes in LFJ degeneration on T2* mapping.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12891-025-08737-2.

Supplementary Material 1.

Acknowledgements
The authors thank their colleagues of their institute.

Authors' contributions
Guarantors of integrity of entire study, S.X.; study concepts/study design or data acquisition or data analysis/interpretation, Y.D., S.R.,L.L.,X.Z.,R.C.,Q.C.,S.X.; manuscript drafting or manuscript revision for important intellectual content, Y.D., S.R.,L.L.,X.Z.,R.C.,Q.C.,S.X.; approval of final version of submitted manuscript, Y.D., S.R.,L.L.,X.Z.,R.C.,Q.C.,S.X.; agrees to ensure any questions related to the work are appropriately resolved, Y.D., S.R.,L.L.,X.Z.,R.C.,Q.C.,S.X.; literature research, Y.D., S.R.; statistical analysis, Y.D., S.R.; and manuscript editing, Y.D., S.R., S.X..

Funding
This study was funded by Natural Science Foundation of Shandong Province (Youth Program ZR2022QH345) and Jiangxi Provincial Health Technology Project (202311842).

Data availability
Data is provided within the supplementary information files.

Declarations

Ethics approval and consent to participate
This retrospective study had received the institutional review board approval from Ganzhou People's Hospital. The study was performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Written informed consent was obtained from all participants.

Consent for publication
Written informed consent was obtained from the patient for publication of this study and accompanying images.

Competing interests
The authors declare no competing interests.

Author details
[1]Department of Spine Surgery, Ganzhou People's Hospital, Ganzhou, Jiangxi 341000, China. [2]Department of Spine Surgery, Ganzhou Hospital-Nanfang Hospital, Southern Medical University, Ganzhou, Jiangxi 341000, China. [3]Department of Radiology, Liaocheng People's Hospital, Liaocheng, Shandong 252000, China. [4]Department of Medical Imaging, Ganzhou People's Hospital, Ganzhou, Jiangxi 341000, China. [5]Department of Nuclear Medicine, Shandong Provincial Hospital Affiliated to, Shandong First Medical University, No.324 Jingwu Road, Jinan, Shandong 250021, China.

Received: 10 March 2024 Accepted: 9 May 2025
Published online: 15 May 2025

References

1. Hoy D, March L, Brooks P, et al. The global burden of low back pain: estimates from the Global Burden of Disease 2010 study. Ann Rheum Dis. 2014;73(6):968–74. https://doi.org/10.1136/annrheumdis-2013-204428. [Published Online First: 26 Mar 2014].
2. March L, Smith EU, Hoy DG, et al. Burden of disability due to musculoskeletal (MSK) disorders. Best Pract Res Clin Rheumatol. 2014;28(3):353–66. https://doi.org/10.1016/j.berh.2014.08.002. [Published Online First: 08 Dec 2014].
3. Hartvigsen J, Hancock MJ, Kongsted A, et al. What low back pain is and why we need to pay attention. Lancet (London, England). 2018;391(10137):2356–67. https://doi.org/10.1016/s0140-6736(18)30480-x. [Published Online First: 21 Mar 2018].
4. Gellhorn AC, Katz JN, Suri P. Osteoarthritis of the spine: the facet joints. Nat Rev Rheumatol. 2013;9(4):216–24. https://doi.org/10.1038/nrrheum.2012.199. [Published Online First: 14 Nov 2012].
5. Perolat R, Kastler A, Nicot B, et al. Facet joint syndrome: from diagnosis to interventional management. Insights Imaging. 2018;9(5):773–89. https://

doi.org/10.1007/s13244-018-0638-x. [Published Online First: 10 Aug 2018].
6. Chen Z, He L, Di J, et al. Lumbar facet joint osteoarthritis as the underlying reason for persistent low back pain after minimally invasive discectomy. Arch Orthop Trauma Surg. 2023;143(7):3811–21. https://doi.org/10.1007/s00402-022-04595-y. [Published Online First: 18 Sep 2022].
7. Hu J, Zhang Y, Duan C, et al. Feasibility study for evaluating early lumbar facet joint degeneration using axial T(1) ρ, T(2), and T2* mapping in cartilage. Journal of magnetic resonance imaging : JMRI. 2017;46(2):468–75. https://doi.org/10.1002/jmri.25596. [Published Online First: 06 Feb 2017].
8. Enokida S, Tanishima S, Tanida A, et al. Evaluation of age-related changes in lumbar facet joints using T2 mapping. Journal of orthopaedic science : official journal of the Japanese Orthopaedic Association. 2020;25(1):46–51. https://doi.org/10.1016/j.jos.2019.02.017. [Published Online First: 21 Mar 2019].
9. Raudner M, Schreiner M, Hilbert T, et al. Accelerated T2 Mapping of the Lumbar Intervertebral Disc: Highly Undersampled K-Space Data for Robust T2 Relaxation Time Measurement in Clinically Feasible Acquisition Times. Invest Radiol. 2020;55(11):695–701. https://doi.org/10.1097/rli.0000000000000690. [Published Online First: 11 July 2020].
10. Yang L, Sun C, Gong T, et al. T1ρ, T2 and T2* mapping of lumbar intervertebral disc degeneration: a comparison study. BMC Musculoskelet Disord. 2022;23(1):1135. https://doi.org/10.1186/s12891-022-06040-y. [Published Online First: 28 Dec 2022].
11. Takashima H, Yoshimoto M, Ogon I, et al. T1rho, T2, and T2* relaxation time based on grading of intervertebral disc degeneration. *Acta radiologica (Stockholm, Sweden : 1987).* 2023;64(3):1116–21. https://doi.org/10.1177/02841851221113936. [Published Online First: 26 July 2022].
12. Wang P, Block J, Gore JC. Chemical exchange in knee cartilage assessed by R1ρ (1/T1ρ) dispersion at 3T. Magn Reson Imaging. 2015;33(1):38–42. https://doi.org/10.1016/j.mri.2014.07.008. [Published Online First: 02 Aug 2014].
13. Hesper T, Hosalkar HS, Bittersohl D, et al. T2* mapping for articular cartilage assessment: principles, current applications, and future prospects. Skeletal Radiol. 2014;43(10):1429–45. https://doi.org/10.1007/s00256-014-1852-3. [Published Online First: 20 Mar 2014].
14. Chavhan GB, Babyn PS, Thomas B, et al. Principles, techniques, and applications of T2*-based MR imaging and its special applications. *Radiographics : a review publication of the Radiological Society of North America, Inc.* 2009;29(5):1433–49. https://doi.org/10.1148/rg.295095034. [Published Online First: 17 Sep 2009].
15. Krause FG, Klammer G, Benneker LM, et al. Biochemical T2* MR quantification of ankle arthrosis in pes cavovarus. Journal of orthopaedic research : official publication of the Orthopaedic Research Society. 2010;28(12):1562–8. https://doi.org/10.1002/jor.21192. [Published Online First: 01 July 2010].
16. Newbould RD, Miller SR, Toms LD, et al. T2* measurement of the knee articular cartilage in osteoarthritis at 3T. Journal of magnetic resonance imaging : JMRI. 2012;35(6):1422–9. https://doi.org/10.1002/jmri.23598. [Published Online First: 09 Feb 2012].
17. Weishaupt D, Zanetti M, Boos N, Hodler J. MR imaging and CT in osteoarthritis of the lumbar facet joints. Skeletal Radiol. 1999;28(4):215–9. https://doi.org/10.1007/s002560050503. [Published Online First: 29 June 1999].
18. Kapetanakis S, Gkantsinikoudis N. Anatomy of lumbar facet joint: a comprehensive review. Folia Morphol (Warsz). 2021;80(4):799–805. https://doi.org/10.5603/FM.a2020.0122. [Published Online First: 21 Oct 2020].
19. Dijkgraaf LC, de Bont LG, Boering G, Liem RS. The structure, biochemistry, and metabolism of osteoarthritic cartilage: a review of the literature. Journal of oral and maxillofacial surgery : official journal of the American Association of Oral and Maxillofacial Surgeons. 1995;53(10):1182–92. https://doi.org/10.1016/0278-2391(95)90632-0. [Published Online First: 01 Oct 1995].
20. Murphy BJ. Evaluation of grades 3 and 4 chondromalacia of the knee using T2*-weighted 3D gradient-echo articular cartilage imaging. Skeletal Radiol. 2001;30(6):305–11. https://doi.org/10.1007/s002560100330. [Published Online First: 24 July 2001].
21. Huang L, Liu Y, Ding Y, et al. Quantitative evaluation of lumbar intervertebral disc degeneration by axial T2* mapping. Medicine. 2017;96(51):e9393. https://doi.org/10.1097/md.0000000000009393. [Published Online First: 03 Feb 2018].
22. Hoppe S, Quirbach S, Mamisch TC, et al. Axial T2 mapping in intervertebral discs: a new technique for assessment of intervertebral disc degeneration. Eur Radiol. 2012;22(9):2013–9. https://doi.org/10.1007/s00330-012-2448-8. [Published Online First: 01 May 2012].
23. DePalma MJ, Ketchum JM, Saullo T. What is the source of chronic low back pain and does age play a role? Pain medicine (Malden, Mass). 2011;12(2):224–33. https://doi.org/10.1111/j.1526-4637.2010.01045.x. [Published Online First: 27 Jan 2011.

Publisher's Note