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Prediction of Lumbar Disk Herniation and Clinical Outcome Using Quantitative Magnetic Resonance Imaging A 5-Year Follow-Up Study

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Abstract

Objectives—The aim of this study was to assess the predictive value of T2 mapping at baseline with regard to the development of disk herniation and clinical outcome at a 5-year follow-up in patients with low back pain.

Materials and Methods—Twenty-five symptomatic patients (13 male; mean age, 44.0 years; range, 24–64 years at baseline) were examined at 3 T magnetic resonance imaging, with a 5-year follow-up. Region of interest analysis was performed on 125 lumbar intervertebral disks on 2 central sagittal T2 maps. Absolute T2 relaxation times and a T2 value ratio of the posterior annulus fibrosus as a percentage of the nucleus pulposus (NPAF) were evaluated for each disk. All disks were graded morphologically using the Pfirrmann score. Roland-Morris Disability Questionnaires (RMDQ) and a visual analogue scale (VAS) were assessed for each patient at follow-up as a clinical end point and compared with diagnosed lumbar disk herniation. Statistical analysis was conducted by a biomedical statistician.

Results—Using the baseline NPAF ratio, follow-up development of herniation was predicted with an area under the curve (AUC) of 0.893 in a receiver operating characteristic curve. The same was done using the baseline nucleus pulposus T2, resulting in an AUC of 0.901. Baseline and follow-up NPAF, as well as baseline and follow-up nucleus pulposus T2, differed significantly ($P < 0.001$) between disks with no herniation, disks with herniation at baseline, and disks with new herniation at follow-up. Difference was still significant (all $P < 0.001$), when only testing for

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difference in degenerated discs with Pfirrmann score III to V. Calculating sensitivity and specificity for herniation prediction only in discs with Pfirrmann III to V using a receiver operating characteristic, AUC was 0.844 with baseline herniations excluded.

The lowest baseline nucleus pulposus T2 per patient correlated significantly with follow-up RMDQ ($r = -0.517$; $P = 0.008$) and VAS ($r = -0.494$; $P = 0.012$). The highest baseline NPAF correlated significantly with RMDQ ($r = 0.462$; $P = 0.020$), but not VAS ($r = 0.279$; $P = 0.177$).

Conclusions—Quantitative T2 mapping may serve as a clinically feasible, noninvasive imaging biomarker that can indicate disks at risk for herniation and correlates with clinical outcome and subjective patient burden in a representative cohort of patients with low back pain.

Keywords

T2 mapping; lumbar disk herniation; degenerative disk disease; quantitative MRI; intervertebral disk; spine

According to the Global Burden of Disease Study 2016, low back pain (LBP) is the leading global cause for years lived with disability.¹

Approximately two thirds of the adult population experience clinically relevant LBP in their lifetime, with every sixth patient describing sciatica and pain radiating below 1 or both knees.² Every fourth patient experiences relapse during the first 12 months.³

Degenerative disk disease (DDD) can be defined as progressive structural failure that is irreversible and closely associated with mechanical dysfunction and pain.⁴

Degenerative disk disease potentially causes 45% of LBP cases with annular fissures and herniations as the main catalysts for progressive pain and further degeneration.⁵ With the resulting inflammatory granulation, neovascularization, as well as sprouting of sinuvertebral nerve endings, is fostered at later stages of DDD.⁵ These nerve endings are thought to be of a visceral type, thus causing the distinctly excruciating qualities of back pain.⁶

Magnetic resonance imaging (MRI) is the method of choice for patients who do not benefit from conservative treatment after 4 to 6 weeks, or for those who are scheduled to undergo surgery due to, for example, neurological deficits.⁷

However, imaging studies still show weak correlation between clinical symptoms and morphological findings in MRI. Approximately one third of the asymptomatic population 50 years of age or older shows at least 1 herniated disk.⁸ Lumbar disk herniation, nonetheless, is an important finding in symptomatic patients as it significantly worsens the prognosis.⁷

Qualitative MRI-based assessment of spine pathology has been increasingly complemented by standardized, semiquantitative assessment (eg, Pfirrmann score, Modic changes). However, these classifications remain subjective, observer-dependent, and categorical. T2 mapping, however, promises objective, quantitative assessment that reflects tissue ultrastructure and composition.

Numerous studies have demonstrated the potential of T2 mapping.^{9–13} However, longitudinal or prospective studies that have examined the potentially predictive value of T2 mapping in patients who experience LBP are scarce.

The main hypothesis of this study was an assumed significant difference in intervertebral disks with and without lumbar disk herniation and the possible predictability of future herniation using T2 values.

The purposes of this study were (a) to measure T2 relaxation time changes that depict DDD over the course of 5 years, (b) to test for significant differences in T2 at baseline as a potentially predictive quantitative biomarker in disks with herniation present at baseline or diagnosed at follow-up, (c) to assess whether disk degeneration is accelerated when pathology is present at baseline, and (d) to test for a correlation between baseline T2 values and clinical symptoms at follow-up.

Materials and Methods

Patients and Study Design

This study presents the results of a prospective, 5-year follow-up MRI study investigating the diagnostic and predictive value of T2 relaxation time measurements. Upon the approval of the institutional review board, 66 symptomatic patients were enrolled in the baseline study from September 2008 until December 2009. Twenty-five completed follow-up from January to October 2014 (12 female, 13 male; mean age at follow-up, 44.0 years; range, 24–64 years), with a mean time to follow-up of 5.2 years (range, 4.4–5.8 years). Baseline data were presented in a prior publication.¹⁴

Inclusion criteria were reported LBP and age between 15 and 65 years at baseline. Exclusion criteria were neurological deficits of the lower limbs, radicular pain, body mass index greater than 30, previous surgical interventions involving the lumbar disks, scoliosis with a Cobb angle exceeding 15 degrees, recent disk herniation (<12 months) at baseline, and contraindications for MRI. The only exclusion for follow-up investigation was a surgical procedure that affected a lumbar intervertebral disk.

Every participant of the baseline study was contacted and invited for follow-up recruitment. Nine patients declined participation, 5 relocated, and the remaining 27 could not be contacted or did not respond to a written invitation.

Of the 25 recruited follow-up patients, 15 underwent more than 10 sessions of physiotherapy, 12 indicated an exercise schedule of another kind (gymnastics, yoga, swimming, or Pilates), 5 reported regular massage sessions, 2 patients went for regular infiltrations of the lumbar spine, and 5 did not undergo any therapy (more than 1 answer possible per individual). No invasive treatment—aside from infiltrations—was reported by any patient.

Thus, 125 lumbar intervertebral disks of 25 conservatively treated patients were examined both at baseline and at follow-up.

Magnetic Resonance Imaging

All MR examinations were performed on a 3 T Siemens MAGNETOM Trio with a gradient strength of 40 mT/m and a dedicated 8-channel spine coil (Siemens Healthineers, Erlangen, Germany).

T2 mapping was conducted in the sagittal plane view after the morphological sequences to examine all disks in an equally rested state. For a detailed overview of sequences and parameters used, please see Table 1.

To ensure the technical consistency of the T2 value generation, hardware was identical, and both baseline and follow-up T2 maps were calculated with the MapIt version (Siemens Healthineers, Erlangen, Germany) available at follow-up.

Image Analysis

A radiologist with 25 years of experience in musculoskeletal imaging issued radiological reports. Degenerative disk disease was classified according to Pfirrmann et al.¹⁵

Herniation was categorized with strict adherence to the nomenclature 2.0 proposed by Fardon et al.¹⁶

An already existing disk segmentation pattern was used for this study.¹⁷ The disk was subdivided into 20% regions of the sagittal diameter. The anterior and posterior 20% regions roughly represented the annulus fibrosus area and the inner 60% the nucleus pulposus (NP) area of the disk. The posterior annulus fibrosus was sampled and quantified as the posterior half of the region of interest (ROI) that covered the posterior 20%. Therefore, the posterior 10% of the disk was labeled the posterior annulus fibrosus (PAF10). This was done because the degradation of annular fibers or fissures that reach the posterior outer region is more relevant and because of a more distinct separation of nuclear and annular tissue based on this pattern. For a graphical depiction of the ROI placement, see Figure 1.

After segmentation, a ratio was calculated by dividing the mean PAF10 per disk by the T2 of the respective disk's mean NP, multiplied by 100, which resulted in PAF10 T2 as a percentage of NP T2. This ratio was labeled the NPAF^{***} and was calculated to allow quantitative disk assessment with one dimensionless variable that was independent of absolute values and was less dependent on sequence parameters or hardware. The NPAF combines the ultrastructure of the NP and the posterior annulus fibrosus in one quantitative variable that allows a depiction of disk integrity and supposedly health.

Favorable interobserver ($r = 0.92$ for the annulus fibrosus and $r = 0.99$ for the NP) and intraobserver ($r = 0.84$ for the annulus fibrosus; $r = 0.99$ for the NP) agreement has already been shown for this manual disk segmentation¹⁴ using 3 independent readers. Still, radiology and orthopedic resident with 3 years in musculoskeletal MRI segmented all T2 maps in a blinded fashion, and intraclass correlation coefficient was calculated for each ROI alongside the resulting T2 ratios. The interobserver agreement was 0.966 for the NP T2, 0.923 for the PAF10, and 0.954 for the NPAF.

The coefficient of variation for each respective variable was 0.38 (baseline NPAF), 0.30 (baseline NP), 0.18 (baseline PAF10), 0.38 (follow-up NPAF), 0.34 (follow-up NP), and 0.18 (follow-up PAF10). For the rest of this article, baseline T2 values are called the bNPAF (baseline T2 of the posterior 10% of the outer annular region), the bNP (baseline T2 of the NP), and the bPAF10 (baseline T2 of the posterior 10% of the annulus fibrosus), whereas follow-up T2 values are referenced as fNPAF (follow-up T2 of the posterior 10% of the outer annular region), fNP (follow-up T2 of the NP), and fPAF10 (follow-up T2 of the posterior 10% of the annulus fibrosus).

Statistical Evaluation

Statistical analysis was performed by a biomedical statistician using IBM SPSS for Windows version 24.0.1 (IBM, Chicago, IL). Metric data are presented using mean $\pm$ standard error of the mean (SE).

A power analysis was calculated assuming the mean difference between the T2 of the NP of disks with and without herniations to be 35 milliseconds, with a generous estimated standard deviation of ± 35 milliseconds. To obtain a power of 0.80 or greater and a level of significance of 0.05 or less, the required sample size was 21. Thus, this study yielded sufficient data on a disk basis. Pilot data for this analysis were taken from the baseline study.

Acquired ROI T2 values were aggregated for the respective disk compartment (NP and PAF10). Disk compartment changes between baseline and follow-up were compared using a paired Student *t* test. To assess differences in T2 values between Pfirrmann scores, 1-way analysis of variance was used with an additionally calculated correlation (Spearman rho). One-way analysis of variance and Bonferroni-corrected post hoc tests were used to assess significant differences between 3 groups of disks: herniation at baseline, new herniation at follow-up, and no herniation at either examination. Receiver operating characteristic (ROC) curves were calculated to assess the predictive and discriminative potential of a given variable.

Spearman rho was used to correlate clinical end points (Roland-Morris Disability Questionnaire [RMDQ] and visual analogue scale [VAS]) with the minimum NP T2 and maximum NPAF and PAF10 T2.

A *P* value of 0.05 or less was considered significant. To avoid an increasing error of the second type, no multiplicity corrections were performed.

Results

Mean T2 Value Changes

Over the course of 5 years, the mean T2 value of the NP decreased from 107.7 ± 3.2 milliseconds to 102.5 ± 3.6 milliseconds ($P = 0.005$). The PAF10 did not change significantly and increased from 45.5 ± 0.8 milliseconds to 46.5 ± 0.8 milliseconds ($P = 0.280$). The NPAF increased significantly from $47.2\% \pm 1.8\%$ to $51.0\% \pm 1.9\%$ ($P = 0.001$), primarily due to the decrease in NP T2.

At baseline, 22 herniations were diagnosed. At follow-up, 11 new herniations were observed.

NP T2 and the NPAF ratio differed significantly between discs with different Pfirrmann scores ($P < 0.001$), both at baseline and follow-up.

Grouping discs according to their baseline Pfirrmann score, there was no significant difference in T2 changes between groups. Degeneration over 5 years, therefore, was not dependent on baseline Pfirrmann scoring. For group comparisons (see Table 2). Overall, 29 disks in 17 patients (3 group I, 12 group II, 12 group III, 2 group IV) increased their Pfirrmann score by 1 grade between baseline and FU.

A coefficient of variation was calculated for disks with baseline herniation, follow-up herniation, or no herniation, as seen in Table 3.

T2 Values for Herniation Prediction

At baseline, disks without herniation showed a mean NPAF of $38.4\% \pm 1.2\%$, disks with herniation $69.6\% \pm 3.8\%$, and disks with future herniation at follow-up $56.7\% \pm 3.5\%$. Baseline NPAF of disks with and without herniation at follow-up differed significantly ($P < 0.001$).

At baseline, NP T2 also differed significantly (all $P < 0.001$) between disks with without herniation 118.0 ± 3.2 milliseconds, with herniation 74.5 ± 6.1 milliseconds and with follow-up herniation with 81.2 ± 83 milliseconds. For a detailed overview, see Table 3.

With baseline herniation cases ($n = 22$) excluded, the bNPAF showed an area under the curve (AUC) of 0.893 in an ROC curve. With a cutoff of 44.1% and higher for bNPAF, 100.0% sensitivity and 76.5% specificity were calculated.

Without censoring baseline herniation, the bNPAF AUC was 0.939, with 93.8% sensitivity and 83.1% specificity at a cutoff value of 46.2% or higher.

The bNP showed an AUC of 0.901 with baseline herniation cases excluded. At a cutoff of 102.4 milliseconds or less for bNP, sensitivity was 90.9% with 82.9% specificity. For a graphical illustration, see Figure 2. Not censoring cases showed an AUC of 0.945. At 98.5 milliseconds cutoff and lower, bNP showed 90.9% sensitivity and 88.0% specificity.

For a case example, see Figure 3.

Herniation Prediction in Moderately to Highly Degenerated Disks

Disks with baseline Pfirrmann grades of I or II were censored.

Only disks with a Pfirrmann score of III, IV, and V ($n = 61$) were used to reevaluate potential risk assessment. NP T2 and NPAF differed significantly between disks with no herniation, baseline herniation, and follow-up herniation (all $P < 0.001$) (Fig. 4).

Area under the curve of an ROC was 0.859 for the baseline NP T2 and 0.880 for follow-up NP T2 without censoring baseline herniation. Excluding baseline herniation cases, the

respective AUC was 0.776 for bNP and 0.948 for fNP T2. Baseline NPAF showed an AUC of 0.844 and follow-up NPAF of 0.864 at follow-up without excluding baseline cases.

Correlating Patient Burden With T2 Relaxation

There was a significant correlation of T2 and RMDQ for mean baseline NP T2 ($r = -0.202$; $P = 0.030$), baseline NPAF ($r = 0.233$; $P = 0.012$), and follow-up NP T2 ($r = -0.203$; $P = 0.036$). Similar results were shown when correlating mean T2 with VAS for baseline NP T2 ($r = -0.302$; $P = 0.001$), baseline NPAF ($r = 0.279$; $P = 0.002$), follow-up NP T2 ($r = -0.192$; $P = 0.048$).

In addition, the disks with the lowest NP T2 and highest NPAF were analyzed per patient with the idea of possible linkage between patient burden and the most advanced degenerated discs. Correlation was significant for each patient's lowest bNP ($r = -0.517$; $P = 0.008$) and fNP ($r = -0.488$; $P = 0.013$), as well as for the highest bNPAF ($r = 0.462$; $P = 0.020$) and fNPAF ($r = 0.420$; $P = 0.036$).

Assessing pain using a VAS at follow-up, bNP ($r = -0.494$; $P = 0.012$) and fNP ($r = -0.447$; $P = 0.025$) both correlated significantly, whereas bNPAF ($r = 0.279$; $P = 0.177$) and fNPAF ($r = 0.290$; $P = 0.160$) did not.

Discussion

The main finding of the assessed data shows that disks with herniation and worsened clinical outcome can be significantly differentiated from the rest via prediction based on quantitative baseline T2 mapping data. The NPAF ratio and NP T2 differed significantly between disks with and without new herniation at follow-up.

This facilitates the established hypothesis that T2 values change significantly before morphological changes of the disk are noted,^{18,19} and this is further supported by the calculated AUCs ranging from 0.893 to 0.945 when assessing herniation risk using baseline T2 data.

This study is, to the best of our knowledge, the first study to longitudinally investigate the prognostic potential of T2 mapping to predict future disk herniation in a 5-year follow-up.

Over the course of 5 years, there was a significant change in NP T2 and NPAF ratios, but not in the posterior annular region.

Concordant with other studies, the T2 values differed significantly between Pfirrmann classifications at both baseline and follow-up.^{14,18,20–22}

Excluding Pfirrmann I and II, the remaining $n = 61$ disks showed significant differences in baseline and follow-up NP T2 and NPAF ratio between disks with no herniation, herniation at baseline, and herniation at follow-up, indicating the high discriminative potential of T2 values.

Another major finding was the significant correlation of T2 values and ratios, at both baseline and follow-up, with clinical outcome (RMDQ and VAS). A cohort study by Ogon et al²³ had already reported a similar finding, but without follow-up data. With the additional baseline values, our data show significant correlation of patient burden and T2 mapping with regard to both baseline and follow-up.

The correlation of lowest baseline and follow-up NP T2 per patient with RMDQ and VAS at follow-up also is noteworthy, indicating patient burden resulting primarily from the most incapacitated intervertebral segment.

T2 mapping has already been reported to show significant differences in patients with and without disk herniation.²⁴ Our data support the idea of not only being able to reliably separate herniated from nonherniated disks using T2 mapping data, but also to assess each disk's respective risk of future herniation.

It is crucial to note that the mean NP T2 values per patient correlated less with clinical end points (RMDQ and VAS) than the single worst disk. The maximum PAF10 region per patient, indicating posterior annular degradation, did not correlate with patient burden. However, we believe that degenerative changes of the annulus affect the T2 relaxation time less when compared with the nucleus.

The ability of T2 mapping to depict this biochemical state of the disk has been used in other MRI studies that have investigated symptomatic LBP patients. T2 values have been correlated with water stored and change inversely with alterations in tissue density, which is represented by the collagen fiber network and concentration. The surveyed data are in accordance with the current literature, which suggests significant quantifiable degeneration over the course of 5 years in the NP. Lower T2 in the NP, indicative of less water stored in the disk, and higher values in the annular region, indicative of decreasing fiber orientation and density, are factors that increase the prevalence of degeneration and disk pathology.^{14,17,18,20,21,23–28}

The limitations of our study are a potential patient selection bias, with only 25 patients participating in the follow-up study. Every baseline patient was given a chance to be recruited for the follow-up study, but 41 patients were lost to follow-up. Still, 5-year follow-up data from a representative patient cohort involving quantitative data have, to the best of our knowledge, not yet been reported. Sagittal assessment of only 2 central images, which led to only median to mediolateral disk herniations included for quantitative ROI assessment and analysis, are also an important limitation that was known and was intended to keep methodological coherence and reproducibility of the image analysis high.

This study shows that T2 mapping might be feasible in clinical routine when assessing LBP patients given the chronic nature of the associated symptoms. The clinical correlation, in conjunction with the aforementioned findings, suggests that T2 mapping might be a feasible biomarker for individual patient risk assessment of lumbar disk herniation.

Conclusions

We conclude that T2 mapping may quantitatively indicate the risk of lumbar disk herniation and significantly correlate with individual disease burden, as reported by patients in this 5-year follow-up study. However, further studies are needed to corroborate these findings and to reliably assess reproducibility, even if interobserver agreement was high in this study.

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Figure 1.

Image analysis and region of interest placement. The T2 mean of the posterior annular region (red, posterior 10%; region of interest of 6 labeled as PAF10) is divided by the mean nucleus pulposus value (mean region of interest of 2, 3, and 4) and multiplied by 100.

Figure 2.

Receiver operating characteristic curve with an area under the curve of 0.901 for the prediction of new follow-up lumbar disk herniation using the baseline nucleus pulposus T2. Sensitivity was 90.9% with 82.9% specificity at a cutoff value of 102.4 milliseconds. Baseline herniations (n = 23) were excluded for the prediction of new herniations at follow-up using baseline nucleus pulposus T2.

Figure 3.

A 51-year-old female patient with a Roland-Morris Disability Questionnaires score of 6 and a visual analogue scale score of 4 at follow-up, presenting with 2 new disk herniations in L3/L4 and at L4/L5 (right). These 2 disks were at risk at baseline (left) already, with a T2 of the nucleus pulposus of 55.4 (L3/L4).

Figure 4.
Overview of different T2 values grouped for baseline Pfirrmann grading, showing significant differences with different stages of degenerative disk disease.

Table 1
Overview of Magnetic Resonance Sequence Parameters

	T1w TSE sag	T2w TSE sag	T2w TSE tra	T2w TSE cor	T2w TSE STIR sag	T2 map sag
TR, ms	900	4400	5080	4500	3500	1200
TE, ms	8.3	105	94	105	35	13.8; 27.6; 41.4; 55.2; 69.0; 82.8
FoV, mm	300 × 300	280 × 280	210 × 210	280 × 280	300 × 300	220 × 220
Matrix size	320 × 320	320 × 320	384 × 384	320 × 320	320 × 320	256 × 256
Voxel size, mm	0.9 × 0.9	0.9 × 0.9	0.7 × 0.7	0.9 × 0.9	0.9 × 0.9	0.9 × 0.9
Interslice gap distance, mm	3	3	3	3	4.0	5
Interslice gap, mm	0.3	0.3	0.3	0.3	0.4	1
Slices	15	15	8 × 5	15	15	10
Scan time, min:s	03:23	01:34	06:16	01:36	3:25	07:45

T1w indicates T1-weighted; T2w, T2-weighted; TSE, turbo spin-echo; sag, sagittal; tra, transversal; cor, coronal; STIR, short tau inversion recovery; TR, time to repetition; TE, time to echo; FoV, field of view.

Table 2
Degeneration Based on the Pfirrmann Classification Over 5 Years, With Significant Differences Between Groups at Baseline and Follow-Up

Disk Degeneration Via Pfirrmann Scoring—Overview and Changes Over Time						
Baseline Scoring						
	I (n = 11)	II (n = 53)	III (n = 32)	IV (n = 28)	V (n = 1)	P
bNPAF, %	27.1 ± 1.9	35.8 ± 1.0	48.0 ± 2.0	68.4 ± 3.2	80.8	<0.001
bNP, ms	158.8 ± 8.3	128.4 ± 2.1	100.0 ± 3.1	68.7 ± 2.7	45.1	<0.001
bPAF10, ms	41.9 ± 1.6	45.5 ± 1.1	47.0 ± 1.8	45.7 ± 1.7	36.4	0.403
Follow-Up Scoring						
	I (n = 8)	II (n = 44)	III (n = 32)	IV (n = 38)	V (n = 2)	P
fNPAF, %	24.4 ± 1.2	37.9 ± 1.9	47.0 ± 1.6	68.6 ± 2.0	101.7 ± 24.9	<0.001
fNP, ms	172.3 ± 11.0	124.0 ± 2.7	104.8 ± 2.6	67.7 ± 2.2	42.9 ± 1.4	<0.001
fPAF10, ms	44.1 ± 1.9	46.3 ± 1.2	48.6 ± 1.7	45.4 ± 1.3	43.3 ± 9.3	<0.457
T2 Value Changes Reflecting Degeneration Over 5 Years (Baseline Scoring)						
	I (n = 11)	II (n = 53)	III (n = 32)	IV (n = 28)	V (n = 1)	P
NPAF	−0.2 ± 1.8	3.9 ± 1.8	5.3 ± 2.1	1.8 ± 2.1	−3.5	0.220
NP, ms	−0.0 ± 3.5	−11.2 ± 2.9	−7.4 ± 2.6	−3.6 ± 2.3	45.8	0.002
PAF10, ms	2.5 ± 1.7	1.1 ± 1.4	1.3 ± 1.9	−0.8 ± 2.0	16.2	0.455

No significant difference in degeneration over time was seen between groups.

bNPAF indicates baseline T2 of the posterior 10% of the outer annular region; bNP, baseline T2 of the NP; bPAF10, baseline T2 of the posterior 10% of the annulus fibrosus; fNPAF, follow-up T2 of the posterior 10% of the outer annular region; fNP, follow-up T2 of the NP; fPAF10, follow-up T2 of the posterior 10% of the annulus fibrosus; NPAF, T2 value ratio of the posterior annulus fibrosus as a percentage of the nucleus pulposus; NP, nucleus pulposus; PAF10, posterior 10% of the disk was labeled the posterior annulus fibrosus.

Table 3
T2 Value Comparison of Disks With No, Baseline, or Follow-Up Herniation, Including Mean T2 and Bonferroni-Adjusted *P* Values

T2 Differences for Herniation at Follow-Up					
Variable	Group	Mean $\pm$ SE	CoV	Comparison	<i>P</i>
bNPAF, %	I, no herniation (n = 85)	41.6 $\pm$ 1.6	28.1	I vs II	<0.001
	II, new herniation (n = 8)	64.2 $\pm$ 5.3	19.5	I vs III	<0.001
	III, baseline herniation (n = 17)	65.2 $\pm$ 4.2	25.9	II vs III	1.000
	Overall				<0.001
bNP, ms	I, no herniation (n = 85)	118.0 $\pm$ 3.2	20.1	I vs II	0.002
	II, new herniation (n = 8)	81.2 $\pm$ 8.3	24.8	I vs III	<0.001
	III, baseline herniation (n = 17)	74.5 $\pm$ 6.1	31.1	II vs III	1.000
	Overall				<0.001
bPAF10, ms	I, no herniation (n = 85)	45.5 $\pm$ 0.8	16.9	I vs II	0.322
	II, new herniation (n = 8)	50.5 $\pm$ 4.8	30.2	I vs III	1.000
	III, baseline herniation (n = 17)	45.8 $\pm$ 2.1	18.3	II vs III	0.586
	Overall				0.272
fNPAF, %	I, no herniation (n = 79)	44.8 $\pm$ 1.8	33.8	I vs II	0.002
	II, new herniation (n = 9)	64.7 $\pm$ 4.3	17.3	I vs III	<0.001
	III, baseline herniation (n = 16)	71.2 $\pm$ 5.2	25.8	II vs III	1.000
	Overall				<0.001
fNP, ms	I, no herniation (n = 79)	114.4 $\pm$ 3.9	25.3	I vs II	0.001
	II, new herniation (n = 9)	70.7 $\pm$ 6.3	27.0	I vs III	<0.001
	III, baseline herniation (n = 16)	73.9 $\pm$ 6.3	31.6	II vs III	1.000
	Overall				<0.001
fPAF10, ms	I, no herniation (n = 81)	46.8 $\pm$ 1.0	17.2	I vs II	0.936
	II, new herniation (n = 9)	43.7 $\pm$ 1.6	10.8	I vs III	1.000
	III, baseline herniation (n = 16)	48.9 $\pm$ 2.3	20.3	II vs III	0.476
	Overall				0.367

The baseline NPAF ratio (posterior annular region divided by the nucleus pulposus value, multiplied by 100) and baseline nucleus pulposus value clearly showed the most significant results.

CoV indicates coefficient of variation; bNPAF, baseline T2 of the posterior 10% of the outer annular region; bNP, baseline T2 of the NP; bPAF10, baseline T2 of the posterior 10% of the annulus fibrosus; fNPAF, follow-up T2 of the posterior 10% of the outer annular region; fNP, follow-up T2 of the NP; fPAF10, follow-up T2 of the posterior 10% of the annulus fibrosus.