Eur Radiol (2010) 20: 2715–2722
DOI 10.1007/s00330-010-1843-2

Siegfried Trattnig
David Stelzeneder
Sabine Goed
Michael Reissegger
Tallal C. Mamisch
Tatjana Paternostro-Sluga
Michael Weber
Pavol Szomolanyi
Goetz H. Welsch

Lumbar intervertebral disc abnormalities: comparison of quantitative T2 mapping with conventional MR at 3.0T

Received: 20 January 2010
Revised: 30 April 2010
Accepted: 5 May 2010
Published online: 19 June 2010

S. Trattnig (✉) · D. Stelzeneder · S. Goed · M. Reissegger · P. Szomolanyi · G. H. Welsch
Department of Radiology,
MR Centre-Highfield MR,
Medical University of Vienna,
Lazarettgasse 14, 1090, Vienna, Austria
e-mail: siegfried.trattnig@meduniwien.ac.at
Tel.: +43-1-404006460
Fax: +43-1-404006475

S. Trattnig
Austrian Cluster for Tissue Regeneration,
Ludwig Boltzmann Institute for Clinical and Experimental Traumatology,
Vienna, Austria

T. C. Mamisch
Orthopedic Surgery Department,
Inselspital Berne, Berne, Switzerland

T. Paternostro-Sluga
Department of Physical Medicine and Rehabilitation,
Medical University of Vienna,
Vienna, Austria

M. Weber
Department of Radiology,
Medical University of Vienna,
Vienna, Austria

P. Szomolanyi
Department of Imaging Methods,
Institute of Measurement Science,
Slovak Academy of Sciences,
Bratislava, Slovakia

G. H. Welsch
Department of Trauma Surgery,
University Hospital of Erlangen,
Erlangen, Germany

Abstract

Objective To assess the relationship of morphologically defined lumbar disc abnormalities with quantitative T2 mapping. *Methods* Fifty-three patients, mean age 39years, with low back pain were examined by MRI at 3T (sagittal T1-fast spin echo (FSE), three-plane T2-FSE for morphological MRI, multi-echo spin echo for T2 mapping). All discs were classified morphologically. Regions of interest (ROIs) for the annulus were drawn. The space in between was defined as the nucleus pulposus (NP). To evaluate differences between the classified groups, univariate ANOVA with post hoc Games–Howell and paired two-tailed *t* tests were used. *Results* In 265 discs we found 39 focal herniations, 10 annular tears, 123 bulging discs and 103 "normal discs". T2 values of the NP between discs with annular tear and all other groups were statistically significantly different (all $p \leq 0.01$). Discs with annular tears showed markedly lower NP T2 values than discs without. The difference in NP T2 values between discs with focal herniation and normal discs ($p=0.005$) was statistically significant. There was no difference in NP T2 values between bulging and herniated discs ($p=0.11$) *Conclusion* Quantitative T2 mapping of the nucleus pulposus of the intervertebral disc in the lumbar spine at 3T reveals significant differences in discs with herniation and annular tears compared with discs without these abnormalities.

Keywords MRI · Quantitative T2 mapping · 3 Tesla · Lumbar spine · Disc herniation

Introduction

Disorders of the lumbar spine are common problems. In the USA, data from the National Center for Health Statistics [1] indicate that among chronic conditions, impairments of the back and spine are the most frequent cause of activity limitation in persons under the age of 45 years. Spinal problems ranked third after heart conditions, arthritis and rheumatism in persons aged 45 to 64 years. Most cases of disc herniation occur in persons between 20 and 64 years of age. Patients admitted to hospital for surgery for their lumbar disc prolapses are most frequently in the age group of 30–39 years [2]. When considering the demographic characteristics of all ages, a displaced intervertebral disc is third after chronic ischaemic heart disease and osteoarthritis [3].

It is speculated that a disc is at higher risk of prolapse during the transition from a healthy resilient

disc with high water content to a relatively dry, scarred one [4].

Magnetic resonance imaging (MRI) is a useful non-invasive tool for evaluating abnormalities of intervertebral discs. Standard MR protocols of the spine include sagittal T1-weighted spin-echo (SE) or fast spin-echo (FSE) and sagittal and axial T2-weighted FSE sequences [5].

Recently transverse relaxation time (T2) mapping has been applied to the spine which has the potential to quantitatively evaluate deterioration of the molecular composition and structural integrity of intervertebral discs [6]. T2 relaxation times are sensitive to water content and the arrangement of the collagen network structure and are also influenced by the dipolar interaction because of the anisotropic motion of water molecules in the collagen matrix [6–10]. A high T2 value for the nucleus pulposus (NP) has been shown in healthy intervertebral discs; T2 decreases with the decrease in water content associated with disc degeneration. Conversely, T2 for the annulus fibrosus (AF) was described to be low in healthy intervertebral discs, and it increases with increased water content and loss of collagen anisotropy in disc degeneration [6, 9, 10]. On the basis of these different T2 values, Watanabe et al. proposed a new classification system for intervertebral disc degeneration based on the visual borders between the AF and NP on axial T2 maps [11].

Apart from the analysis of disc degeneration, to the best of our knowledge the role of quantitative T2 mapping has not yet been evaluated in disc abnormalities such as bulging, annulus tear and herniation.

The objectives of our study were to answer the following questions:

1. Do the mean T2 relaxation time values in the AF and the NP differ between patients with disc herniation, annular tears, bulging and "normal discs"?
2. Do T2 values in the herniated disc material differ from the parent disc in patients with focal disc herniation?
3. What is the distribution of the T2 values of the different Pfirrmann grades in relation to disc herniation, annular tears, bulging and "normal discs"?

Materials and methods

Patient selection

The ethics commission of the Medical University provided ethical approval for this study, and written, informed consent was obtained from all patients before enrolment. Fifty-three patients (36 female, 17 male) aged 15–64 (mean 38.8, standard deviation [SD] ± 11.2) with single or recurrent episodes of low back pain were examined on a whole body 3.0 T MR (Magnetom Tim Trio, Siemens Medical Solutions, Erlangen, Germany) using a phased array spine coil.

Inclusion criteria were no radicular symptoms, no spine injury or surgery in the past and no known contra-indication to MRI. The patients were assigned from the Department of Physical Therapy and consecutively included in the study.

MRI parameters

The following sequences were applied for the evaluation of the lumbar spine: sagittal T1-FSE, sagittal, coronal and axial T2-FSE for morphological MRI, and sagittal multi-echo spin-echo sequence for biochemical T2 mapping. The sequence parameters are listed in Table 1.

T2 relaxation times were obtained from on-line reconstructed T2 maps using a pixel-wise, mono-exponential, non-negative least-squares (NNLS) fit analysis (MapIt, Siemens Medical Solutions, Erlangen, Germany). MR analysis was performed on the intervertebral discs L1/L2, L2/L3, L3/L4, L4/L5 and L5/S1. Among the 53 patients, no discs had to be excluded from MR analysis.

Image analysis

All discs were classified morphologically on sagittal and axial FSE images by two experienced radiologists (15 and 8 years' experience in musculoskeletal MRI, respectively) into the following categories: focal disc herniation (protrusion or extrusion), annular tears, disc bulging and discs without such lesions, referred to as "normal discs". If more than one type of abnormality was present in a single disc, the following order of priority was applied: annular tears > herniation > bulging > normal. Discs with vertical disc herniation (Schmorl's nodules) were excluded from the analysis.

For the evaluation of disc degeneration the Pfirrmann score [12] was applied.

The morphological analysis was performed without knowledge of the T2 relaxation time values. In the case of disagreement on the category of the disc abnormality a final decision was made in consensus.

On sagittal T2 maps regions of interest (ROIs) for the AF were drawn anteriorly and posteriorly in the outermost 20% of the disc on two adjacent mid-sagittal slices running through the centre of the spine. The ROIs covered the complete height of the disc, but care was taken that no partial volume effect with the adjacent vertebral bodies occurred. The space in between was assessed with three additional ROIs and defined as the NP (Fig. 1). In cases of focal disc herniation the herniated tissue itself was also assessed with an additional ROI. The central slices in the sagittal plane were planned on the coronal and axial T2-FSE images in order to minimise partial volume effects.

The intra- and interobserver variablity of the region of interest evaluation was assessed in 24 lumbar intervertebral discs of 12 patients with low back pain. Two central sagittal slices of the T2 maps were evaluated as already described. The evaluation was performed by three observers with different skill levels: Observer 1 was a radiologist with 15 years of experience; observer 2 was a

Table 1 MR parameters for morphological imaging and T2 mapping sequences

Parameter	Sequence				
	T1w-FSE sagittal	T2w-FSE sagittal	T2w-FSE transverse	T2w-FSE coronal	T2 map sagittal
Repetition time (ms)	900	4,400	5,080	4,500	1,200
Echo time (ms)	8.3	105	94	105	13.8 to 82.8
Field of view (mm)	300×300	280×280	210×210	280×280	220×220
Matrix	320×320	320×320	384×288	320×320	256×256
Voxel size (mm)	0.9×0.9×3	0.9×0.9×3	0.7×0.5×3	0.9×0.9×3	0.9×0.9×5
Slice thickness (mm)	3	3	3	3	5
Interslice gap (mm)	0.3	0.3	0.3	0.3	1
Number of slices	15	15	8x5	15	10
Echo trains/slice	111	20	18	20	–
Turbo factor	3	32	26	32	–
Examination time (min:s)	03:23	01:34	06:16	01:36	07:45

T1w-FSE T1-weighted fast spin-echo sequence, *T2w-FSE* T2-weighted fast spin-echo sequence

final-year medical student; observer 3 was an orthopaedic surgeon with 10 years' experience. The measurement itself was performed only once, but was evaluated repeatedly by observer 1 at baseline and evaluated again after a 3-month delay for the intraobserver reliability.

Statistical analysis

Statistical and graphical data analysis was performed with SPSS (Version 15.0, SPSS Inc., Chicago, IL, USA). Each T2 value represents the mean value of two corresponding ROIs from two adjacent central sagittal slices. Univariate ANOVA and post hoc Games–Howell tests were used for the comparison of normal, bulging, herniated discs and discs with annular tears and the comparison of normal non-degenerated discs (Pfirrmann grades 1+2, without herniation), discs with "normal degeneration" (Pfirrmann grades 3+4, without herniation) and herniated discs (all Pfirrmann grades). Paired two-tailed *t* tests were used for comparison of herniated tissue with the "parent disc".

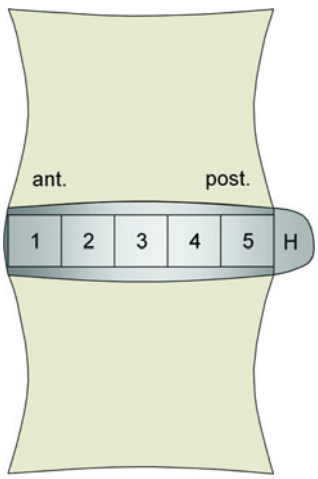

Fig. 1 Region of interest (ROI) evaluation in the sagittal plane. Each ROI measured 20% of the mid-sagittal disc-diameter (ROI *1–5*). When applicable, additional ROIs were drawn for herniated disc tissue (*H*)

Pfirrmann grading was summarised into normal (Pfirrmann grades 1+2) and abnormal discs (Pfirrmann grades 3+4). Chi-squared tests were used to assess differences in Pfirrmann grade (normal, abnormal) among the normal, bulging, herniation and annular tears groups.

Pearson's correlation was performed to evaluate if it is reasonable to integrate NP and AF ROIs into summary terms. If not stated otherwise the mean value ± standard deviation is given. A p value of less than 0.05 is considered significant.

For the evaluation of inter- and intraobserver variability Pearson's correlation and intraclass correlation (ICC) was applied.

Results

In 265 analysed discs we found 39 focal herniations, 10 annular tears, 123 bulging discs and 103 "normal discs" without the previously described abnormalities. Observer disagreement occurred for 31.4% of discs graded as herniation and bulging and for 11.4% of discs graded as annular tears. Thus 78.6% of grading decisions were made in concordance and 21.4% were made in consensus between the two observers. The mean number of pixels for each ROI was 42.8 (SD±11.6) which was calculated from 100 representative ROIs.

As mentioned above, T2 measurements of ROI 2, 3 and 4 were averaged and defined as a composite NP term, based on the following results: The highest bivariate correlations were found between ROI 2 and ROI 3 (r= 0.79) as well as between ROI 3 and ROI 4 (r=0.79). As the correlations between ROI 2 and ROI 4 (r=0.60) were sufficient and Cronbach's alpha was 0.88, these three ROIs, which fit into the NP region, could be summarised and defined as a common term by calculating the mean value out of ROI 2, 3 and 4. There was no correlation between anterior and posterior AF (ROI 1 and ROI 5, r= 0.05). Thus we focused on the evaluation of these three disc compartments: anterior (ROI 1) and posterior (ROI 5) AF and NP (ROI 2–4).

The respective mean T2 relaxation time values (in ms, ± SD) for the anterior AF, posterior AF and the NP were as follows: annular tear 40.7±7.2, 46.6±12.0 and 53.1±18.5; herniation 48.0±22.8, 48.6±15.7 and 87.1±51.1; bulging 44.6±16.6, 55.8±22.0 and 109.3±50.5; normal 39.7±10.5, 70.0±22.3 and 119.3±36.8 (Fig. 2).

The mean age within these groups was comparable to 38.3 (bulging) to 41.0 (annular tears) years ($p \geq 0.05$).

Annular tear findings

The differences in the T2 values of the NP between discs with annular tear and all other groups were statistically significant (all $p \leq 0.01$). Discs with annular tears showed markedly lower NP T2 values compared with discs without annular tears (Fig. 3). There was also a statistically significant difference for the posterior AF in comparison to normal discs ($p < 0.001$) but no differences were found in the anterior AF.

Disc herniation findings

The differences in the T2 values of the NP between discs with focal herniation and normal discs ($p = 0.005$) and discs with annular tears ($p = 0.01$) were statistically significant. Discs with herniation showed lower T2 values than normal discs, but higher T2 values than discs with annular tears. There was no difference in NP T2 values between bulging and herniated discs ($p = 0.11$). T2 values in the posterior annulus (ROI 5) were lower in herniated discs than in normal discs ($p < 0.001$).

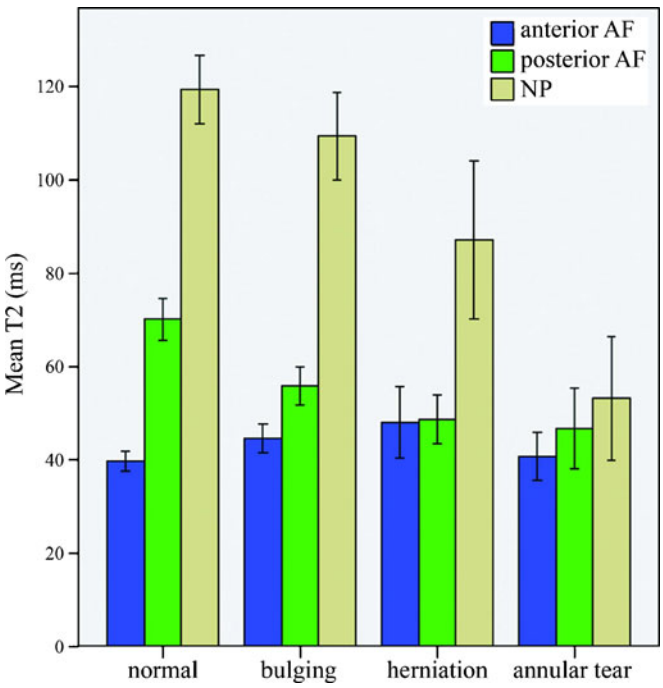

Fig. 2 Comparison of T2 values among normal, bulging, herniated discs and discs with annular tears in different disc compartments. *Error bars* represent 95% confidence intervals

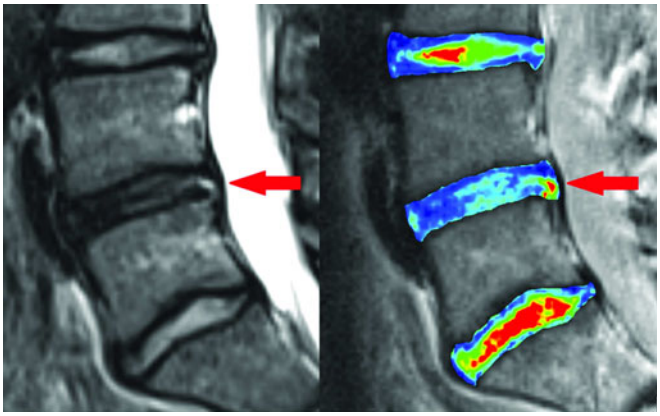

Fig. 3 Sagittal T2-FSE image and overlaid colour-coded image of the intervertebral discs demonstrating an annular fissure in the L4/L5 segment

Herniated disc material findings

T2 relaxation time values within the herniated disc material (39.0±10.8 ms) were significantly different from the parent disc with significantly lower T2 values in the herniated disc portion compared with T2 values in the anterior AF ($p = 0.03$), posterior AF ($p = 0.002$) and NP ($p = 0.001$) (Fig. 4).

The distribution of the different Pfirrmann grades in relation to disc dislocation

The comparison of the normal, bulging, herniation and annular tears groups concerning Pfirrmann grading showed highly significant differences between normal discs and all other groups (all $p < 0.001$). Discs with herniation were different from bulging discs ($p = 0.002$) but not from discs with annular tears ($p = 0.09$). There was also a difference between bulging discs and discs with annular tears ($p < 0.001$).

There was a marked difference in "normal non-degenerated discs" (Pfirrmann grades 1+2, without herniation) compared with herniated discs as well as with discs with "normal degeneration" (Pfirrmann grades 3+4, without herniation) in the posterior AF and NP (all $p < 0.001$). The posterior AF as well as the NP of normal non-degenerated discs showed higher T2 values than discs with herniations or normal degeneration. No significant differences were seen between discs with herniations and normally degenerated discs for the posterior AF and NP ($p \geq 0.05$). The NP T2 values in discs with herniation showed a tendency towards higher values in comparison to normally degenerated discs; however, this difference was not statistically significant. No statistically significant differences could be assessed within the anterior AF among the groups mentioned ($p \geq 0.05$) (Fig. 5, Table 2).

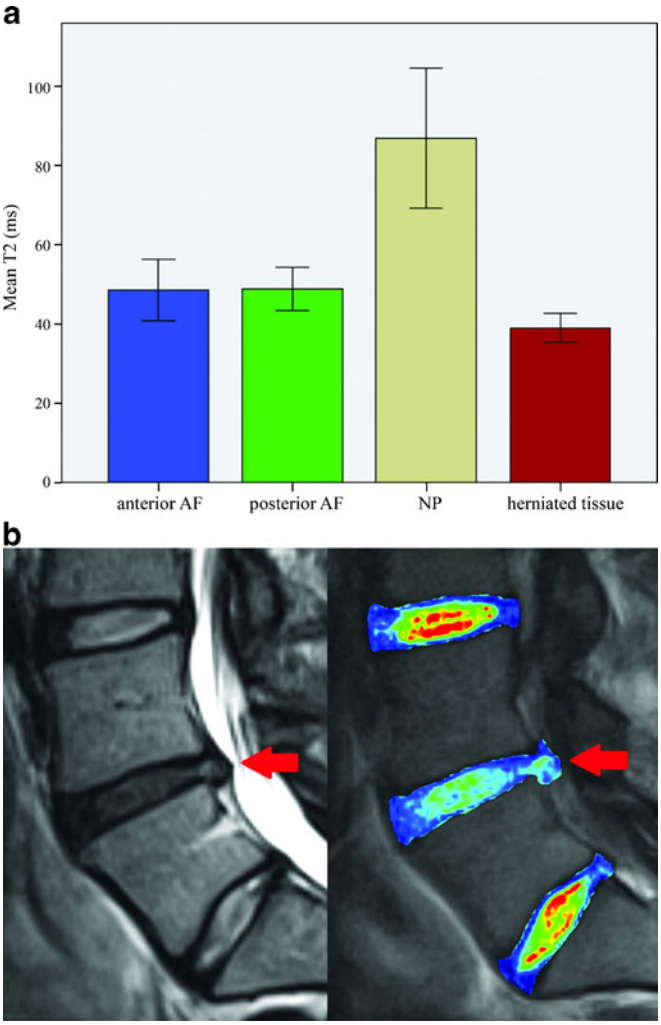

Fig. 4 **a** Comparison of T2 values in different compartments of the parent disc to the herniated disc tissue. *Error bars* represent 95% confidence intervals. **b** Sagittal T2-FSE image and overlaid colour-coded image of the intervertebral discs with focal median herniation of disc material in the L4/L5 segment

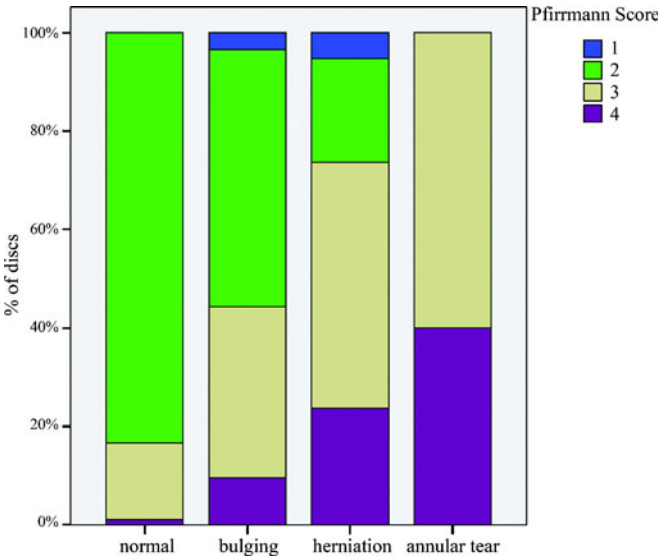

Fig. 5 The *bars* for normal, bulging, herniation and annular tear represent the corresponding disc percentages of the different Pfirrmann scores

The results of the interobserver variability analysis are shown in Table 3.

The intraobserver variability analysis demonstrated the following Pearson's correlation coefficients for different regions of interest: ROI 1 (anterior annulus fibrosus), r=0.71; ROI 5 (posterior annulus fibrosus), r=0.76; ROI 2–4 (nucleus pulposus), r=0.91.

Discussion

The application of quantitative T2 mapping in discs without and with focal herniation and annular tears revealed statistically significant differences (all $p<0.001$) in the T2 values of the NP. Discs with annular tears showed markedly lower NP T2 values compared with discs without annular tears. There was also a difference for the posterior AF (p=0.005) but not for the anterior AF (p=0.63).

Further results depicted statistically significant differences in T2 values of the NP between discs with focal herniation and normal discs (p=0.005) and discs with annular tears (p=0.01). Discs with herniation showed lower T2 values than normal discs, but higher T2 values than discs with annular tears. There was no difference in NP T2 values between bulging and herniated discs (p=0.11).

T2 values in the posterior annulus (ROI 5) were different between normal discs and all other groups ($p<$ 0.001). No significant difference in the posterior AF between any other groups was detected.

With respect to disc degeneration no significant difference was seen between discs with herniations and normally degenerated discs for the posterior AF and NP, while a significant difference was seen between discs with herniations and normally degenerated discs compared with non-degenerated discs without herniations.

These findings may imply that annular tears develop in degenerative discs and represent a later stage of disc degeneration.

The interobserver agreement with an intraclass correlation coefficient greater than 0.8 in the annulus fibrosus and greater than 0.95 in the nucleus pulposus is sufficient to

Table 2 Mean T2 values (± standard deviation) in different disc compartments of normal non-degenerated, normal degenerated and herniated discs

State of disc	Anterior AF	Posterior AF	NP
Normal non-degenerated	42.9±14.6	67.9±24.2	128.5±42.4
Normal degenerated	40.8±12.9	49.9±14.6	78.5±31.2
Herniation	47.9±225	48.9±15.5	85.8±51.0

Table 3 Pearson's correlation and intraclass correlation (ICC) for evaluation of interobserver variability

	Observer 1	Observer 2	Observer 3	ICC (single)[a]	ICC (average)[b]
Anterior annulus fibrosus (ROI 1)					
Observer 1		0.75	0.62	0.59	0.81
Observer 2	0.75		0.45		
Observer 3	0.62	0.45			
				$p<0.001$	$p<0.001$
Posterior annulus fibrosus (ROI 5)					
Observer 1		0.72	0.86	0.76	0.91
Observer 2	0.72		0.72		
Observer 3	0.86	0.72			
				$p<0.001$	$p<0.001$
Nucleus pulposus (mean of ROI 2–4)					
Observer 1		0.96	0.96	0.97	0.99
Observer 2	0.98		0.92		
Observer 3	0.92	0.98			
				$p<0.001$	$p<0.001$

ROI 1 anterior annulus fibrosus, *ROI 5* posterior annulus fibrosus, *ROI 2–4* nucleus pulposus

[a] Intraclass correlation coefficient for single measures

[b] Intraclass correlation coefficient for average measures

reproducibly evaluate intervertebral disc T2 values. The intraobserver agreement showed good reproducibility with r values of greater than 0.7 for the annulus and greater than 0.9 for the nucleus.

Disc herniation is more commonly associated with disc degeneration, although there is a tendency towards higher T2 values in the NP in disc herniation; however, this difference was not statistically significant. The T2 values in the posterior AF only differed from normal discs compared with all other abnormalities, but did not show a significant difference between annular tear, herniation or bulging.

The disc matrix consists of a complex and highly hydrated network of macromolecules [13] whose composition varies in different regions of the disc. The concentration of water varies with the location within the disc and also with age [14, 15]. In general, the NP is most highly hydrated. The water content of the nucleus may be as high as 80% in a healthy disc of a young adult [16]. The water content of the AF is lower than that of the NP, falling to around 65% in the outer annulus in normal, healthy adults. In disc degeneration the water content falls, particularly in the nucleus. However, it must also be taken into consideration that water content varies with load, and in the lumbar discs this gives rise to a diurnal change in hydration [17].

Collagen is the main macromolecular component of the disc [18]. Highly organised collagen fibrils form the framework of the disc anchoring it to the bone and providing it with tensile strength. The collagen content of the disc is highest in the outer annulus (as much as 70% by dry weight) falling to approximately 20–30% of the dry weight in the nucleus of the adult human lumbar disc [19]. This ultrastructural composition of the intervertebral disc can be depicted by T2 relaxation time mapping. In the present study, these differences between the NP and the AF are clearly visible and change according to the respective abnormalities.

The degeneration of the intervertebral discs is associated with the proteolysis of matrix macromolecules. These degraded molecules are no longer trapped in the tissue matrix and slowly diffuse out of the disc. The consequent fall in the concentration of disc components results in a loss of matrix integrity, a failure of appropriate biomechanical response to load, and ultimately to the morphological features of degeneration. The sequence of cause and effect is still not completely understood, but the earliest and most marked degenerative change in disc composition is loss of glycosaminoglycan (GAG) [20], which decreases parallel with the grade of disc degeneration. Loss of GAG leads to a fall in swelling pressure [21], loss of hydration and loss of disc height, with adverse effects on the disc's ability to respond appropriately to applied biomechanical loads. Degeneration also results in disorganisation and destruction of the collagen network [22]. Once the collagen network has been damaged, disc mechanics are dramatically disturbed and the potential for major annular tears or herniation increases [23].

T2 mapping has shown the potential to quantitatively evaluate this degeneration and hence the deterioration of disc molecular composition and structural integrity, as T2 mapping is sensitive to water content and arrangement of collagen network structure [6, 24]. This is mirrored in the results of the present study, when a degeneration of NP and the posterior AF, as measured by the Pfirrmann score, leads to significant differences between "normal non-degenerated discs" and herniated discs as well as discs with "normal degeneration".

It has been proposed that annular disruption is the critical factor in degeneration and, when a radial tear develops in the annulus, there is shrinkage with disorganisation of the fibrous cartilage of the NP and replacement of the disc by dense fibrous tissue with cystic spaces [25, 26]. This dense fibrous tissue may explain the low T2 values in the NP associated with annular tears in our

study. This finding is important, too, because recently the presence of a high-intensity zone (HIZ) within the posterior annulus seen on T2-weighted MRI has aroused great interest and even controversy among many investigators, particularly on whether the HIZ was closely associated with a concordant pain response on awake discography. On lumbar spine MRI, an HIZ within the annulus of a disc (separate from the NP) has a positive predictive value of 86% for a severely disrupted, painful disc [27]. It is claimed that the presence of an HIZ is diagnostic of painful disc disruption [28–31], but others found no such correlation [32–34]. These findings may be in line with the present study, where—when looking at the AF—most obvious changes could be described within the posterior part of the AF and hence within the place where the herniation occurs.

The T2 values in the disc herniation itself (herniated portion beyond the posterior border of the intervertebral disc) were significantly lower than the mean T2 values in NP and even in the posterior AF. Immunohistological studies have shown that cells from extruded discs demonstrated significantly greater levels of basic fibroblast growth factor which may result in dense fibrous tissue with consecutive low T2 relaxation time values [35].

Limitations of our study are (a) the relatively low number of patients with annular tears; (b) as only two central sagittal slices for T2 mapping were used only median and medio-lateral disc herniations could be included for further analysis, whereas lateral intra- and extraforaminal disc herniations could not be considered. Furthermore no gold standard was available; nevertheless for MRI of the intervertebral discs this might not be possible.

In summary, quantitative T2 mapping in the lumbar spine at 3 T yields significantly different T2 values in disc herniation and annular tears compared with disc without these abnormalities.

The clinical impact of this additional information has to be demonstrated in further studies and in particular in longitudinal studies as well as in the monitoring of conservative therapies in which standard MRI does not show any change even though clinical symptoms may improve or deteriorate.

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