Eur Spine J (2009) 18 (Suppl 1):S40–S48
DOI 10.1007/s00586-009-0996-7

ORIGINAL ARTICLE

Molecular MR imaging for the evaluation of the effect of dynamic stabilization on lumbar intervertebral discs

Stefania Vaga · M. Brayda-Bruno · F. Perona · M. Fornari · M. T. Raimondi · M. Petruzzi · G. Grava · F. Costa · E. G. Caiani · C. Lamartina

Accepted: 14 March 2009 / Published online: 25 April 2009

Abstract The dynamic stabilization of lumbar spine is a non-fusion stabilization system that unloads the disc without the complete loss of motion at the treated motion segment. Clinical outcomes are promising but still not definitive, and the long-term effect on instrumented and adjacent levels is still a matter of discussion. Several experiments have been devised in order to gain a better understanding of the effect of the device on the intervertebral disc. One of the hypotheses was that while instrumented levels are partially relieved from loading, adjacent levels suffer from the increased stress. But this has not been proved yet. The aim of this study was to investigate the long-term effect of dynamic stabilization in vivo, through the quantification of glycosaminoglycans (GAG) concentration within instrumented and adjacent levels by means of the delayed Gadolinium-Enhanced Magnetic Resonance Imaging of Cartilage (dGEMRIC) protocol. Ten patients with low back pain, unresponsive to conservative treatment and scheduled for Dynesys implantation at one to three lumbar spine levels, underwent the dGEMRIC protocol to quantify GAG concentration before and 6 months after surgery. Each patient was also evaluated with visual analog scale (VAS), Oswestry, Prolo, Modic and Pfirrmann scales, both at pre-surgery and at follow-up. Six months after implantation, VAS, Prolo and Oswestry scales had improved in all patients. Pfirrmann scale could not detect any change, while dGEMRIC data already showed a general improvement in the instrumented levels: GAG was increased in 61% of the instrumented levels, while 68% of the non-instrumented levels showed a decrease in GAG, mainly in the posterior disc portion. In particular, seriously GAG-depleted discs seemed to have the greatest benefit from the Dynesys implantation, whereas less degenerated discs underwent a GAG depletion. dGEMRIC was able to visualize changes in both instrumented and non-instrumented levels. Our results suggest that the dynamic stabilization of lumbar spine is able to stop and partially reverse the disc degeneration, especially in seriously degenerated discs, while incrementing the stress on the adjacent levels, where it induces a matrix suffering and an early degeneration.

Keywords Dynamic stabilization · Lumbar spine · Molecular MRI · dGEMRIC

S. Vaga (✉) · M. Brayda-Bruno · F. Perona · M. Fornari · M. T. Raimondi · M. Petruzzi · G. Grava · F. Costa · E. G. Caiani · C. Lamartina
IRCCS Istituto Ortopedico Galeazzi,
via R. Galeazzi 4, 20126 Milan, Italy
e-mail: stefania.vaga@hotmail.it

M. T. Raimondi
Department of Structural Engineering,
Politecnico di Milano, Milan, Italy

E. G. Caiani
Department of Biomedical Engineering,
Politecnico di Milano, Milan, Italy

Introduction

Painful lumbar motion segment, as proposed by Mulholland and Sengupta [1], is mainly due to a disc disorganization occurring in degenerative events leading to abnormal patterns of load transmission at the interested level. Nowadays, the surgical treatment of this condition is still controversial. Spinal stabilization was initially advocated with only a partial clinical effectiveness: it reduced pain, but the increased stress on the adjacent segments was a new cause of instability and pain [2–5]. Due to the

improvement in surgical devices, the concept of dynamic stabilization was proposed, in order to reduce the mechanical loading of the treated motion segment by unloading the disc without the complete loss of motion required by fusion surgery. Indeed, for this reason, dynamic stabilization could provide a reduction of the negative effect of fusion on the adjacent spinal segments and on the global functioning of the spine [6]. Up to now, promising clinical results have been described using this technique [7–13], but still not definitive. Also, the long-term effects of dynamic stabilization are still under discussion, with a specific focus on the remodeling of the disc cartilage matrix, both at the implanted and at the adjacent levels, caused by the spinal biomechanics which is modified by the implanted device.

Finite element analysis and other laboratory simulations have been devised to quantify the biomechanical effect of dynamic stabilization on models of the implanted lumbar spine [14–17]. Schmoelz [18] found a reduction in the lumbar spine range of motion in flexion after the dynamic stabilization device implantation, but negligible effects on the range of motion of the segments adjacent to the implanted one. Animal studies demonstrated that a prolonged compression caused disc degeneration, and that subsequent stabilization was able to stop the degeneration process. This was demonstrated on lumbar discs in vivo in a rabbit model of stabilization, through measures of intradiscal pressure variations [19]. In implanted patients, dynamic stabilization has been shown to influence the spine biomechanics through a reduction in the lumbar spine range of motion, especially in extension, with a negligible impact on the range of motion at the adjacent levels [20]. Dynamic stabilization was also demonstrated to be able to prevent the progression of the initial disc degeneration in nucleotomy patients [21].

The aim of this study was to investigate the effects of dynamic stabilization on disc tissue reorganization in implanted patients, through the quantification of glycosaminoglycan (GAG) concentration in disc tissue, both in the instrumented and in the adjacent levels. Patient evaluation was performed with established clinical and radiological grading methods and with a newer diagnostic protocol based on molecular magnetic resonance (MR) imaging.

Materials and methods

This is a prospective study of a group of patients scheduled for implantation of the Dynesys® stabilization system (Zimmer GmbH, Winterthur, Switzerland). The same clinical and radiological data were collected both before and 6 months after surgery, in order to study the effect of the implanted device on the lumbar intervertebral discs (IVDs).

Population

Patients with low back pain, unresponsive to conservative treatment for at least 6 months, were enrolled in this study. The low back pain of these patients was due to mono-, bi- or tri-segmental painful lumbar discopathy, with or without mild segmental instability and/or with or without narrow spinal canal. Exclusion criteria included osteoporosis, spinal tumors, psychogenic pain, pregnancy, claustrophobia, contraindications to gadolinium MRI contrast agent subministration and impossibility to take part to the follow-up. The selected population included four male and six female subjects, with a mean age of 43 ± 9 years (age range 27–54) at the time of surgery (Table 1). Each patient

Table 1 Details of the patient population enrolled in this study

Patient ID	Age	Weight	Sex	Job	Implanted levels
1	31	82	M	Gas station clerk	L3–L4, L4–L5
2	37	49	F	Housewife	L3–L4, L4–L5
3	48	65	F	Housewife	L3–L4, L4–L5
4	54	83	M	Civil engineer	L4–L5, L5–S1
5	49	74	F	Tailor	L3–L4, L4–L5, L5–S1
6	27	59	F	Teacher	L4–L5
7	43	84	M	Bricklayer	L4–L5, L5–S1
8	46	63	F	Housewife	L4–L5
9	51	51	F	Office worker	L4–L5
10	49	74	M	Office worker	L3–L4, L4–L5
Mean ± S.D.	43.5 ± 9	68.4 ± 13			

received detailed information regarding the study protocol and gave her/his consent to be enrolled.

Clinical evaluation

Pain was evaluated by means of a visual analog scale (VAS) without leg and back pain differentiation [22]. The Oswestry low back pain disability questionnaire was used to assess subjective functional impairment [23], while the Prolo semiquantitative scale was used to evaluate the functional and economic status of each patient [24].

Radiological evaluation

Magnetic resonance images of the lumbar spine were obtained with a 1 T scanner (Harmony®, Siemens) with a phased-array back coil.

IVD degeneration was assessed through Pfirrmann radiological grading [25], which evaluates the possibility to clearly discriminate the nucleus from the annulus, the IVD height and the signal intensity from routine T2-weighted MR sagittal images (TR/TE, 4,000/108). Moreover, Modic classification of all lumbar levels was applied in order to identify signal intensity changes in the vertebral body marrow, which have been demonstrated to be connected with specific degenerations of the adjacent IVD [26].

The delayed Gadolinium-Enhanced Magnetic Resonance Imaging of Cartilage (dGEMRIC) protocol, specifically adapted to lumbar IVDs [27], was used to quantify local concentration of GAG within lumbar IVDs. This protocol requires the intravenous injection of 0.55 ml/kg of gadolinium diethylene triamide penta-acetic acid (Gd-DTPA^{2-}), and the acquisition of seven consecutive fast spin echo inversion-recovery sequences with fixed TR (2,960 ms) and TE (13 ms); TI was set to 50, 150, 350, 700, 1,050, 1,400 and 2,000 ms; FOV 300 mm, acquisition matrix 512 × 512. Single 3-mm thick slices, centered in the mid-height of each disc and parallel to the adjacent endplate planes, were acquired with these sequences (slice selection was performed on the same sagittal T2-weighted images acquired for Pfirrmann grading). dGEMRIC acquisition was performed before and 4 h after contrast agent subministration.

All the T2-weighted MRIs and the pre-contrast injection dGEMRIC images were acquired in the afternoon, approximately at 4:00 p.m., while all post-contrast injection dGEMRIC images were acquired in the evening, after the post-contrast 4 h delay. This rule was applied in order to minimize the effect of night water influx within the IVD due to bed rest that has been demonstrated to alter the T2-weighted signal intensity by 25% as well as the height of IVDs [28].

dGEMRIC data analysis

The seven inversion-recovery images relevant to the same IVD, acquired during the pre-contrast phase, were used to generate a first parametric image of the T1 recovery amplitude ($T1_{PRE\text{-}ENH}$). The same procedure was applied to the MR images acquired after contrast injection, resulting in a second parametric image of T1 post-gadolinium enhancement ($T1_{POST\text{-}ENH}$). Both parametric images were then subdivided into 60 segments (12 for nucleus and 48 for the annulus), and each was assigned to its respective average T1 value. Finally, the ΔT1 of each of the 60 segments was obtained as $\Delta T1 = T1_{PRE\text{-}ENH} - T1_{POST\text{-}ENH}$ (Fig. 1) and visualized in a color-encoded ΔT1 parametric image, where negative values were set to 0 [27]. Red tonalities have been demonstrated to be associated with

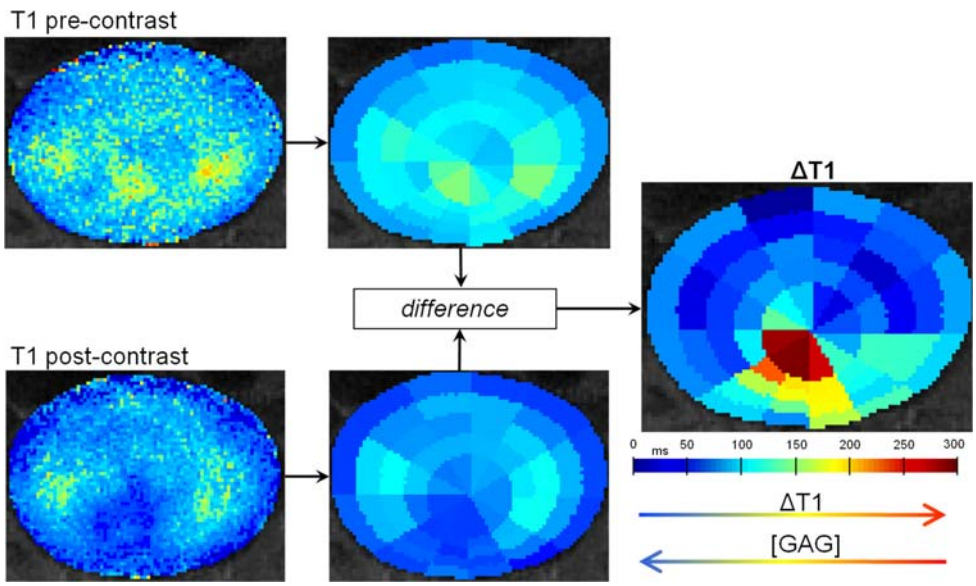

Fig. 1 dGEMRIC data analysis scheme. Both T1 color-encoded maps, computed from pre- and post-contrast enhancement MR acquisitions, are subdivided into 60 segments. The segmented post-contrast map is then subtracted from the pre-contrast one, in order to obtain the ΔT1 map. The *color bar* of the ΔT1 map is reported under the map itself, along with its interpretation scheme: higher values of ΔT1 correspond to lower GAG concentrations [27]

low GAG concentrations, whereas blue tonalities are associated with high GAG concentrations [27].

Surgery

Each patient was in prone position with neutral lordosis and a support for chest and iliac crests; the abdominal cavity was left free to avoid increased abdominal pressure. The approach was through a midline incision with bilateral opening of the lumbar aponeurosis for a transmuscular approach according to Wiltse; in case of narrow canal or disc herniation, a midline approach for decompression by flavectomy, laminotomy and foraminotomy was used.

The Wiltse approach enables to implant the screw with an almost always correct angulation, without disruption of joints capsules. Once the screw implantation was completed (while monitoring the procedure with the fluoroscopic image intensifier), through posterior compression or distraction of screw heads, it was possible to determine the size of the spacer at each level. This choice depends on the pathology and on the desired degree of neutralization to be achieved. In all cases, through interpedicular distraction, the length of the spacer must ensure that the relative vertebral endplates are perfectly parallel, otherwise a local kyphosis may occur. On the contrary, the restoration of a physiological lordosis of those segments may be left to the surgeon discretion. Overcompression of the posterior facet joints should be avoided in all circumstances, because it may be detrimental for the correct functioning of the implanted device.

The system was then pretensioned to 300 N, which is the ideal value for the device. In case of a multisegmental implantation of Dynesys, each segment was pretensioned step by step. Closure was carried out in the traditional manner, with complete suture of the lumbar aponeurosis back underneath the midline supraspinal ligament (see Table 1 for details).

Follow-up

The clinical and the radiological evaluations previously described were all performed both before and 6 months after the Dynesys implantation, with the exception of Modic grading which was only applied before implantation. To evaluate the entity of improvement, as measured by each of the clinical and radiological methods previously described (except Modic grading), differences were computed between the pre-surgery and the 6-month follow-up data so that, for each measure, a *positive* difference indicated an *improvement*:

- VAS_difference = VAS_PreSurgery − VAS_Follow-up;
- Oswestry_difference = Oswestry_PreSurgery − Oswestry_Follow-up;
- Prolo_difference = Prolo_Follow-up − Prolo_PreSurgery;
- Pfirrmann_difference = Pfirrmann_PreSurgery − Pfirrmann_Follow-up;
- ΔT1_difference = ΔT1_PreSurgery − ΔT1_Follow-up.

In particular, an improvement of the tissue implies regeneration of the cartilage matrix, and therefore a GAG increases, which can be highlighted through dGEMRIC by a decrease in the ΔT1 value [27].

Statistical analysis

Paired t test ($P < 0.05$) was used to evaluate the significance of the variation of clinical and radiological scores between the pre-operative and the 6 months follow-up data. The values computed in the 60 segments with the dGEMRIC analysis were averaged, in order to evaluate the variation between pre-surgery and 6-month follow-up for each lumbar disc (paired t test, $P < 0.05$).

Results

All ten patients enrolled in the study took part in the follow-up. The total number of levels studied both at pre-surgery and at follow-up was 46: 18 were the implanted levels, 28 the adjacent ones. No artifact impaired the quality of the MR images except in one case, where a slight shading was visible in one of the implanted levels because of the pronounced proximity of the screws to the endplate.

Table 2 reports the clinical grading at pre-surgery and at 6-month follow-up. At follow-up, both VAS and Oswestry clinical evaluation results showed an improvement in 10/10 patients. In particular, VAS improved from 7.6 to 3.1 ($P = 0.0014$), and Oswestry from 54 to 25% ($P = 0.00023$). Prolo evaluation results showed an improvement in 9/10 patients, with the exception of patient no. 6 who had lost 1 point, resulting in a total improvement from 6 to 7 ($P = 0.06$).

Figure 2 shows a representative example of the dGEMRIC results from patient no. 8, who was implanted at one disc level, L4–L5. The dGEMRIC maps computed from the pre-surgery acquisitions are reported on the left half of the figure, one for each lumbar IVD; the corresponding T2-weighted image is also shown for clarity. On the right, the dGEMRIC maps computed from the follow-up data are reported in the same order. Disc levels with the implanted device are highlighted by the red brackets on the right T2-weighted MR image. The color map used for the dGEMRIC maps is the same reported in Fig. 1.

Table 2 Clinical evaluation results, at pre-surgery and at follow-up, with their difference

ID	VAS				Oswestry (%)				Prolo			
	Pre-surgery	Follow-up	Difference	*P*	Pre-surgery	Follow-up	Difference	*P*	Pre-surgery	Follow-up	Difference	*P*
1	8	3	5	0.0014*	56	24	32	0.00023*	5	6	1	0.06
2	8	4	4		52	28	24		3	6	3	
3	7	0	7		62	12	50		6	9	3	
4	5	4	1		46	42	4		7	7	0	
5	8	0	8		54	10	44		5	5	0	
6	8	4	4		46	14	32		8	7	−1	
7	10	0	10		32	0	32		8	10	2	
8	7	7	0		52	46	6		5	5	0	
9	9	7.5	1.5		76	54	22		5	5	0	
10	6	2	4		68	22	46		7	8	1	
Mean ± S.D.	7.6 ± 1.4	3.1 ± 2.7	4.4 ± 3.2	–	54 ± 12	25 ± 12	29 ± 12	–	6 ± 2	7 ± 2	1 ± 1	–

The significance of these variations in the whole population is also reported

* Statistically significant

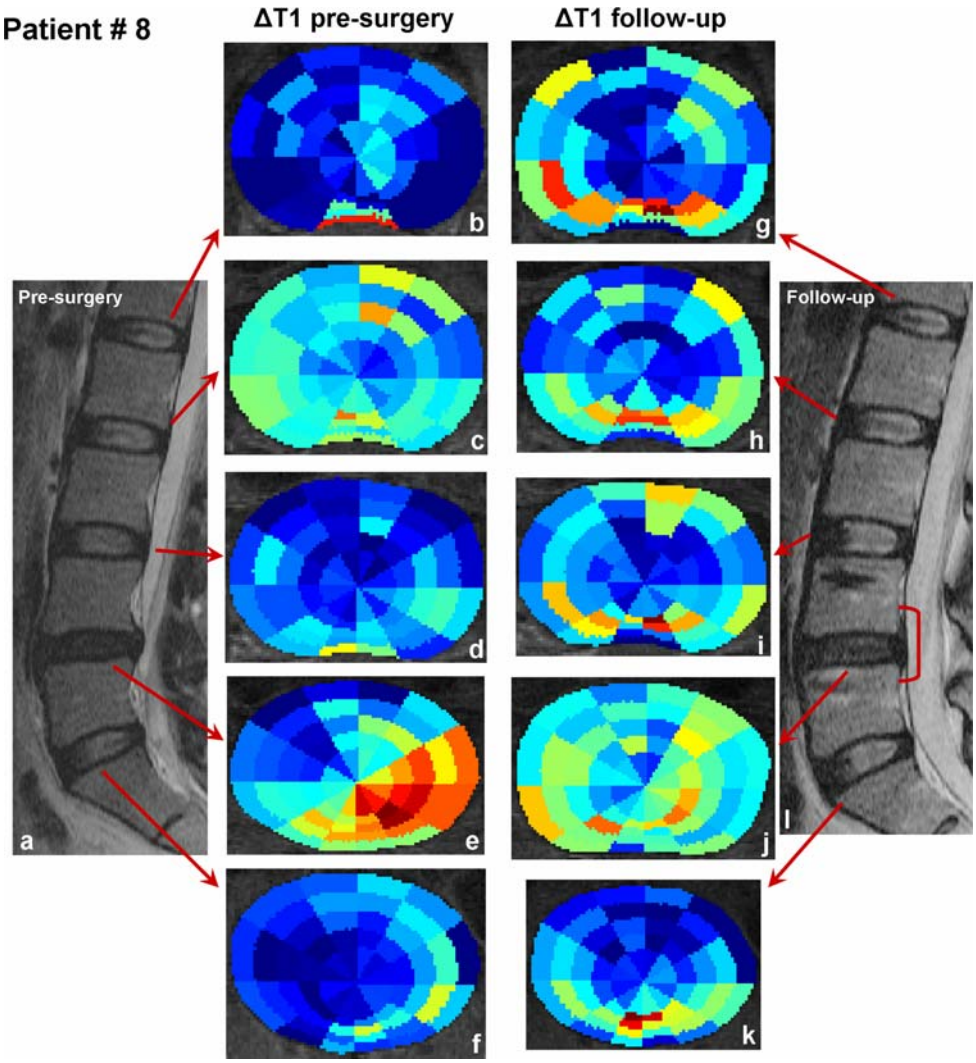

Fig. 2 dGEMRIC results of patient no. 8, who was implanted at one disc level (L4–L5). *Panels* **a–f** refer to the pre-surgery study, while *panels* **g–l** refer to the 6-month follow-up. For each lumbar IVD, two ΔT1 maps are reported: on the *left* the pre-surgery map, on the *right* the follow-up map. The *color bar* to interpret these maps is reported in Fig. 1

Patient no. 8 showed a pre-surgery wide GAG depletion in the posterior and lateral-left portions of L4–L5, the level meant for implantation. Six months after the device implantation, the same disc showed an increased GAG concentration especially in the previously depleted portion. However, three of the non-implanted lumbar levels, L1–L2, L3–L4 and L5–S1, showed a decrease in GAG concentration in the posterior portion of the discs (see also patient no. 8 data reported in Table 3).

Figure 3 (in the same format of Fig. 2) shows another example of the dGEMRIC results from patient no. 5, which had a device implanted at three disc levels, L3–L4, L4–L5 and L5–S1. Only L5–S1 reported a definite GAG increase at 6-month follow-up with respect to the pre-surgery dGEMRIC acquisitions, while both L3–L4 and L4–L5 reported an increased GAG depletion. The dGEMRIC maps of the two adjacent levels L1–L2 and L2–L3 showed partially degenerated discs already at pre-surgery; 6 months after surgery, L1–L2 showed a widely increased degeneration in the tissue.

Table 3 reports the radiological data collected at pre-surgery and at 6-month follow-up with the relevant variations. Only a few lumbar levels in the whole population showed a Modic alteration at pre-surgery (patients no. 1, 3, 4 and 7). Pfirrmann grading did not detect any radiological changes at 6 months as compared to pre-surgery, either at the implanted levels or at the adjacent ones. In contrast, dGEMRIC data demonstrated significant GAG changes already at 6-month follow-up, as compared to the pre-surgery condition. In particular, 61% of the implanted discs (11/18) showed a significant GAG increase ($P = 0.0012$), while 68% of the adjacent discs (19/28) showed a significant GAG decrease ($P = 0.00016$).

Implanted levels global $\Delta T1$ variations are resumed in Table 4.

Discussion

The aim of this preliminary study was to apply a new minimally invasive diagnostic method to the evaluation of a limited number of patients implanted with a dynamic stabilization device, in order to detect changes in the composition of the disc tissue, specifically in terms of GAG concentration, 6 months after the implantation. While VAS and Oswestry gradings showed an expected improvement due to the reduced pain sensation, Pfirrmann radiological grading was unable to detect any significant change after 6 months, probably because the technique is not sensitive enough to early changes in the tissue. On the contrary, the new dGEMRIC protocol was able to quantify significant changes in both instrumented and adjacent levels.

To our knowledge, this is the first application of the dGEMRIC protocol to a prospective study of the disc to evaluate an implanted device. The imaging protocol applied has a few differences with respect to the one we previously described [27]: the main difference is the use of a higher TR value (2,960 ms instead of 1,800 ms). This allowed us to set higher values of TI as well, the maximum TI value being 2,000 ms instead of the previously used 1,400 ms. This choice was aimed at reducing the error in the fitting-computation algorithm that generates the T1 maps. Despite this change, the $\Delta T1$ values computed with these parameters are still comparable with those computed with our previous protocol [27], as T1 depends principally on the features of the tissue as well as on the strength of the static magnetic field. The pitfall was that the acquisition time was increased up to about 45 min.

The changes detected through the dGEMRIC protocol were statistically significant, and allowed visual and quantitative evaluations of the local reorganization of the cartilage tissue in terms of GAG. Specifically, 61% of the implanted levels reported an increase in GAG already at 6 months post-surgery, particularly pronounced in the posterior portion. This is likely an effect of the load release induced by the implanted device. Similarly, the decrease in GAG shown by 68% of the lumbar levels adjacent to the implanted ones may be interpreted as a consequence to the different load distribution generated by the device. An alternative explanation could be that the discopathy is spontaneously evolving at multiple lumbar levels in these patients because of their genetic disposition [29, 30].

This was particularly evident in patient no. 5 (Fig. 3) who was implanted at three different levels. The pre-surgery dGEMRIC study revealed a wide GAG depletion also in the two non-implanted levels (L1–L2 and L2–L3), and 6 months after the implantation one of the two (L1–L2) showed a definite progression of the already existing degeneration.

When compared with the $\Delta T1$ values of our previous study [27], we noticed that the levels with the implanted device that reported an increased GAG concentration at 6-month follow-up (improved levels) had a mean pre-surgery $\Delta T1 > 100$ ms, typical of a GAG-depleted disc, which was partially restored to a $\Delta T1$ equal to about 80 ms at follow-up, close to the $\Delta T1$ value found in healthy discs (about 70 ms).

On the contrary, the levels with the implanted device that reported a decreased GAG concentration at the follow-up (worsened levels) had a mean pre-surgery $\Delta T1$ of 66 ms, which may indicate that these levels were not degenerated in terms of GAG prior to the intervention. These results, if confirmed by a larger population study, suggest that a pre-surgery $\Delta T1$ analysis could guide the surgeon decision regarding which levels to implant with a

Table 3 Radiological evaluation results, at pre-surgery and at follow-up, with their difference

ID	Level	Modic pre-surgery	Pfirrmann grading			ΔT1 (dGEMRIC parameter)		
			Pre-surgery	Follow-up	Difference	Pre-surgery	Follow-up	Difference
1	L2–L3	–	2	2	0	71	77	−7
	L3–L4[a]	–	4	4	0	113	76	37
	L4–L5[a]	1	4	4	0	112	81	31
	L5–S1	–	1	1	0	59	48	11
2	L2–L3	–	2	2	0	73	45	27
	L3–L4[a]	–	3	2	1	84	45	39
	L4–L5[a]	–	5	5	0	126	125	2
	L5–S1	–	2	2	0	59	80	−20
3	L1–L2	2	3	2	1	56	61	−5
	L2–L3	–	3	2	1	67	16	51
	L3–L4[a]	2	4	4	0	101	57	45
	L4–L5[a]	–	4	4	0	115	91	24
	L5–S1	–	3	2	1	56	64	−8
4	L1–L2	–	3	3	0	7	0	7
	L2–L3	2	3	3	0	9	37	−28
	L3–L4	–	3	3	0	21	176	−155
	L4–L5[a]	–	4	3	1	52	147	−95
	L5–S1[a]	–	4	3	1	47	93	−46
5	L1–L2	–	2	2	0	112	156	−44
	L2–L3	–	2	2	0	123	88	35
	L3–L4[a]	–	4	4	0	52	83	−31
	L4–L5[a]	–	3	4	−1	54	126	−72
	L5–S1[a]	–	4	4	0	170	89	81
6	L1–L2	–	1	1	0	60	64	−4
	L2–L3	–	2	2	0	32	10	22
	L3–L4	–	1	1	0	17	36	−19
	L4–L5[a]	–	4	4	0	84	87	−3
	L5–S1	–	4	4	0	132	71	61
7	L1–L2	–	3	4	−1	50	129	−79
	L2–L3	–	2	3	−1	30	65	−35
	L3–L4	–	2	3	−1	11	71	−60
	L4–L5[a]	1	5	5	0	122	210	−88
	L5–S1[a]	–	5	5	0	49	183	−134
8	L1–L2	–	2	2	0	32	87	−55
	L2–L3	–	2	2	0	113	101	12
	L3–L4	–	2	2	0	55	95	−40
	L4–L5[a]	–	4	4	0	135	128	7
	L5–S1	–	2	2	0	52	72	−20
9	L1–L2	–	2	2	0	83	100	−17
	L3–L4	–	2	2	0	32	97	−64
	L4–L5[a]	–	4	4	0	100	82	19
	L5–S1	–	2	2	0	54	76	−22
10	L2–L3	–	2	2	0	18	86	−69
	L3–L4	–	3	3	0	66	45	21
	L4–L5[a]	–	4	4	0	64	47	16
	L5–S1[a]	–	2	2	0	50	41	9
Mean ± S.D.	–	–	3 ± 1	3 ± 1	0.04 ± 0.5	69 ± 39	84 ± 44	−14 ± 49

[a] Implanted levels

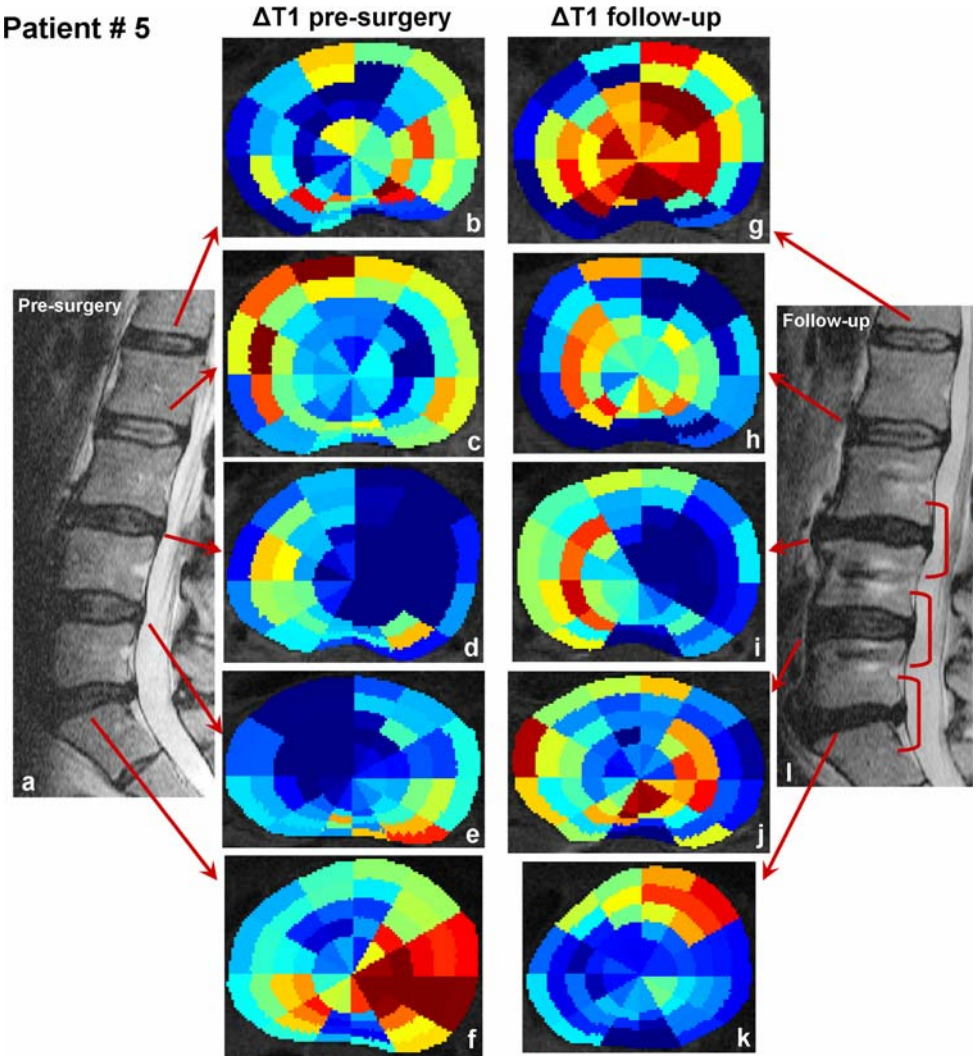

Fig. 3 dGEMRIC results of patient no. 5, who was implanted at three disc levels (L3–L4, L4–L5, L5–S1). *Panels* **a–f** refer to the pre-surgery study, while *panels* **g–l** refer to the 6-month follow-up. For each lumbar IVD, two ΔT1 maps are reported: on the *left* the pre-surgery map, on the *right* the follow-up map. The *color bar* to interpret these maps is reported in Fig. 1

Table 4 Average ΔT1 values, at pre-surgery and at follow-up, of implanted levels with either increased or decreased GAG concentration

	No. (%)	Mean ΔT1 ± S.D.	
		Pre-surgery	Mean ± follow-up
Implanted levels with INCREASED [GAG]	11 (61)	108 ± 31	79 ± 29
Implanted levels with DECREASED [GAG]	7 (39)	66 ± 28	133 ± 50

dynamic stabilization device, thus limiting its use only to those levels that are more compromised according to a GAG analysis. Also, our results show that the Dynesys device seems able to lead to tissue regeneration in the more severely degenerated levels, with benefits to the patient.

The main limitation of this study was the limited number of patients enrolled. Further patients need to be enrolled in order to collect more data and obtain more consistent conclusions. The long acquisition time required by dGEMRIC protocol, as described here, can be greatly reduced by means of a smaller acquisition matrix: 256 × 256 can reduce the acquisition time up to about 20 min even with a 1-T scanner, without compromising the quality of the resulting ΔT1 maps. This would make the exam more apt for future clinical applications.

In conclusion, this study showed, with a quantitative in vivo molecular MRI technique, the effects of dynamic stabilization of IVDs on GAG concentration, providing new insights into a biomechanical process that is still only partially understood. If confirmed in a large study population, useful information for surgical planning could be obtained using the reported procedure.

Acknowledgments Financial support by Zimmer GmbH (Winterthur, Switzerland) is gratefully acknowledged.

Conflict of interest statement None of the authors has any potential conflict of interest.

References

1. Mulholland RC, Sengupta DK (2002) Rationale, principles and experimental evaluation of the concept of soft stabilization. Eur Spine J 11(Suppl 2):S198–S205
2. Harrop JS, Youssef JA, Maltenfort M, Vorwald P, Jabbour P, Bono CM et al (2008) Lumbar adjacent segment degeneration and disease after arthrodesis and total disc arthroplasty. Spine 33(15):1701–1707
3. Min JH, Jang JS, Jung BJ, Lee HY, Choi WC, Shim CS et al (2008) The clinical characteristics and risk factors for the adjacent segment degeneration in instrumented lumbar fusion. J Spinal Disord Tech 21(5):305–309
4. Bono CM, Bawa M, White KK, Mahar A, Vives M, Kauffman C et al (2008) Residual motion on flexion–extension radiographs after simulated lumbar arthrodesis in human cadavers. J Spinal Disord Tech 21(5):364–371
5. Korovessis P, Papazisis Z, Koureas G, Lambiris E (2004) Rigid, semirigid versus dynamic instrumentation for degenerative lumbar spinal stenosis: a correlative radiological and clinical analysis of short-term results. Spine 29(7):735–742
6. Nockels RP (2005) Dynamic stabilization in the surgical management of painful lumbar spinal disorders. Spine 30(16 Suppl):S68–S72
7. Sapkas GS, Themistocleous GS, Mavrogenis AF, Benetos IS, Metaxas N, Papagelopoulos PJ (2007) Stabilization of the lumbar spine using the dynamic neutralization system. Orthopedics 30(10):859–865
8. Schwarzenbach O, Berlemann U, Stoll TM, Dubois G (2005) Posterior dynamic stabilization systems: DYNESYS. Orthop Clin North Am 36(3):363–372
9. Stoll TM, Dubois G, Schwarzenbach O (2002) The dynamic neutralization system for the spine: a multi-center study of a novel non-fusion system. Eur Spine J (11 Suppl 2):S170–S178
10. Rohlmann A, Burra NK, Zander T, Bergmann G (2007) Comparison of the effects of bilateral posterior dynamic and rigid fixation devices on the loads in the lumbar spine: a finite element analysis. Eur Spine J 16(8):1223–1231
11. Cheng BC, Gordon J, Cheng J, Welch WC (2007) Immediate biomechanical effects of lumbar posterior dynamic stabilization above a circumferential fusion. Spine 32(23):2551–2557
12. Bothmann M, Kast E, Boldt GJ, Oberle J (2008) Dynesys fixation for lumbar spine degeneration. Neurosurg Rev 31(2):189–196
13. Grob D, Benini A, Junge A, Mannion AF (2005) Clinical experience with the Dynesys semirigid fixation system for the lumbar spine: surgical and patient-oriented outcome in 50 cases after an average of 2 years. Spine 30(3):324–331
14. Bellini CM, Galbusera F, Raimondi MT, Mineo GV, Brayda-Bruno M (2007) Biomechanics of the lumbar spine after dynamic stabilization. J Spinal Disord Tech 20(6):423–429
15. Schmoelz W, Huber JF, Nydegger T, Claes L, Wilke HJ (2006) Influence of a dynamic stabilisation system on load bearing of a bridged disc: an in vitro study of intradiscal pressure. Eur Spine J 15(8):1276–1285
16. Freudiger S, Dubois G, Lorrain M (1999) Dynamic neutralisation of the lumbar spine confirmed on a new lumbar spine simulator in vitro. Arch Orthop Trauma Surg 119(3–4):127–132
17. Niosi CA, Zhu QA, Wilson DC, Keynan O, Wilson DR, Oxland TR (2006) Biomechanical characterization of the three-dimensional kinematic behaviour of the Dynesys dynamic stabilization system: an in vitro study. Eur Spine J 15(6):913–922
18. Schmoelz W, Huber JF, Nydegger T, Dipl-Ing ClaesL, Wilke HJ (2003) Dynamic stabilization of the lumbar spine and its effects on adjacent segments: an in vitro experiment. J Spinal Disord Tech 16(4):418–423
19. Guehring T, Unglaub F, Lorenz H, Omlor G, Wilke HJ, Kroeber MW (2006) Intradiscal pressure measurements in normal discs, compressed discs and compressed discs treated with axial posterior disc distraction: an experimental study on the rabbit lumbar spine model. Eur Spine J 15(5):597–604
20. Beastall J, Karadimas E, Siddiqui M, Nicol M, Hughes J, Smith F et al (2007) The Dynesys lumbar spinal stabilization system: a preliminary report on positional magnetic resonance imaging findings. Spine 32(6):685–690
21. Putzier M, Schneider SV, Funk JF, Tohtz SW, Perka C (2005) The surgical treatment of the lumbar disc prolapse: nucleotomy with additional transpedicular dynamic stabilization versus nucleotomy alone. Spine 30(5):E109–E114
22. Chapman CR, Casey KL, Dubner R, Foley KM, Gracely RH, Reading AE (1985) Pain measurement: an overview. Pain 22(1):1–31
23. Fairbank JC, Couper J, Davies JB, O'Brien JP (1980) The Oswestry low back pain disability questionnaire. Physiotherapy 66(8):271–273
24. Prolo DJ, Oklund SA, Butcher M (1986) Toward uniformity in evaluating results of lumbar spine operations. A paradigm applied to posterior lumbar interbody fusions. Spine 11(6):601–606
25. Pfirrmann CWA, Matzdorf A, Zanetti M, Hodler J, Boos N (2001) Magnetic resonance classification of lumbar intervertebral disc degeneration. Spine 17:1873–1878
26. Modic MT, Steinberg PM, Ross JS, Masaryk TJ, Carter JR (1988) Degenerative disk disease: assessment of changes in vertebral body marrow with MR imaging. Radiology 166(1 Pt 1):193–199
27. Vaga S, Raimondi MT, Caiani EG, Costa F, Giordano C, Perona F et al (2008) Quantitative assessment of intervertebral disc glycosaminoglycan distribution by gadolinium-enhanced MRI in orthopedic patients. Magn Reson Med 59(1):85–95
28. Paajanen H, Lehto I, Alanen A, Erkintalo M, Komu M (1994) Diurnal fluid changes of lumbar discs measured indirectly by magnetic resonance imaging. J Orthop Res 12(4):509–514
29. Battié MC, Videman T, Parent E (2004) Lumbar disc degeneration: epidemiology and genetic influences. Spine 29(23):2679–2690
30. Battié MC, Videman T (2006) Lumbar disc degeneration: epidemiology and genetics. J Bone Joint Surg Am 88(Suppl 2):3–9