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DIAGNOSTICS

ISSLS Prize Winner: The Anatomy of Failure in Lumbar Disc Herniation

An In Vivo*, Multimodal, Prospective Study of 181 Subjects*

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Study Design. A prospective multimodal study including clinical, radiological, serial postcontrast magnetic resonance imaging, intraoperative findings, and histopathological study.

Objective. To document *in vivo*, the site of anatomical failure in lumbar disc herniation (LDH).

Summary of Background Data. Although *in vitro* mechanical disruption studies have implicated both the endplate junction (EPJ) and the annulus fibrosus (AF) as the site of failure in LDH, there are no *in vivo* human studies to document the exact anatomy of failure.

Methods. One hundred eighty-one consecutive patients requiring microdiscectomy at a single level formed the study group. The status of the endplate and AF in the operated level (study discs) and the other discs (control) were evaluated by plain radiograph, thin slice computed tomographic scan, plain and contrast magnetic resonance imaging, intraoperative examination, and histopathological analysis.

Results. LDH due to EPJ failure (EPJF- type I herniation) was more common (117; 65%) than annulus fibrosis rupture. Herniated discs had a significantly higher incidence of EPJF than control discs ($P < 0.0001$). The EPJF was evident radiologically as vertebral corner defect in 30 patients, rim avulsion in 46, frank bony avulsions in 24, and avulsion at both upper and lower EP in 4. Thirteen discs with normal EP radiologically had cartilage or bone avulsion intraoperatively. Sixty-four discs (35%) had intact EP of which annular high intensity zone was found in 21 (11%), suggesting a disruption of AF (type II herniation). Postcontrast magnetic resonance image of 20 patients showed dye leak at the EPJ proving EPJF as main cause of LDH.

Conclusion. Our study provides the first *in vivo* evidence that LDH in humans is more commonly the result of EPJF than AF rupture and offers clinical validation of previous *in vitro* mechanical disruption studies. Future research must focus on the EPJ as a primary area of interest in LDH.

Key words: disc herniation, endplate junction, annulus rupture, anatomy of failure.

Level of Evidence: N/A

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The anatomical site of failure in LDH has not been clearly documented *in vivo*. The general teaching implicates annulus fibrosus (AF) rupture in the genesis of LDH and the role of endplate (EP) and EP junction (EPJ) is still not clear. Though many studies have reported the presence of cartilaginous endplate within the herniated material,[1–3] none have probed EPJ failure as the direct cause for LDH in humans. Mechanical disruption studies of discs have implicated the cartilage and vertebral EPJ as the site of failure in LDH.[4–21] EP fractures and rim avulsions are associated with LDH in adolescents, but the actual incidence of EPJ disruptions in adult LDH is still not clear.

As future strategies will aim at repair and biological interventions, a clear understanding of the true anatomy of failure is important.

MATERIALS AND METHODS

Study Material

One hundred eighty-one patients (142 males; 39 females) requiring a single level lumbar microdiscectomy formed the study group. The study was a prospective evaluation of consecutively admitted patients for lumbar microdiscectomy. It was a single center study and all the surgical procedures were performed by the senior author. Ethical approval was obtained from the institutional review board of the institute before initiating the study. Written informed consent was acquired from all the patients before recruiting them into the study. Patients were included if they were below 60 years of age, had no canal stenosis or other spinal disorders, no previous lumbar spinal surgical procedures, and a normal BMD. The 181 operated discs was the study material and the 724 nonoperated discs served as control. In all of them, AF and EP failure was probed by plain radiographs, thin slice computed tomographic (CT) scans at the level of EPs, and magnetic resonance imaging (MRI). EP avulsion identity in radiographs is depicted in Figure 1[22] (see Supplemental Digital Content Figure 1 available at http://links.lww.com/BRS/A779).

Discs with clear evidence of EPJF were considered to have type I herniation and this was evidenced in thin slice CT either by occult evidence of irregularity of EP or vertebral corner defects (type IA), thin rim avulsions of the EP (type IB), large bony avulsions (type IC), and EP avulsions at both the upper and lower levels (type ID) (Figure 1). Discs that had normal EP radiologically but had intraoperative evidence of cartilaginous or bony endplate were classified as type IE. A validation process to check the intra- and interobserver reliability of this new classification was performed among 3 spine surgeons of varying experience. The mean interobserver reliability to classify as type 1 or 2 disc prolapse was kappa 0.61 (good). The reliability for subclassifications of type 1 prolapse (A, B, C, and D) and type 2 was 0.57 (moderate). The mean intraobserver reliability was 0.84 (very good).

MR images (1.5 T) were analyzed to document the type of disc herniation, the presence and location of high intensity zone (HIZ), total EP damage score (TEPS)[23] and Pfirrman grading, and the presence of Schmorl nodes (Figure 2). The extent of associated EP damage was documented using the TEPS.[23] Other evidences of EP damage in MRI such as vertebral corner defects, irregularities, and defects at the posterior margin of the vertebral body were also documented (Figure 3).

Postcontrast Diffusion MR Study

Postcontrast diffusion MR study[24] capable of identifying the presence of EP breaks were performed in 20 patients (10 each of type I and type II herniation discs) toward the end of the study to supplement the findings observed in the multimodal study protocol (thin slice CT, MRI). A scout MRI was followed by intravenous injection of contrast gadodiamide (0.3 mmol/kg body weight; Omniscan, GE Health Care, Shanghai, China) and postcontrast images were taken at 10 minutes and 2 hours. The presence and the site of EP breaks were identified by the presence of early leakage and pooling of contrast and absence of the typical diffusion march phenomena.[23,24]

Intraoperative Assessment

The operating surgeon carefully checked for the presence of AF tear. If no tear was found, the annulus was carefully incised taking care not to disturb the EPs and herniated material removed. The excised material was visualized under the operating microscope and also palpated to identify the presence of bits of EP cartilage or bony fragments.

Histological Analysis

The tissue samples were examined with hematoxylin & eosin standard histochemical protocols for presence of EP or bony fragments attached to the disc fragment in all the patients. A

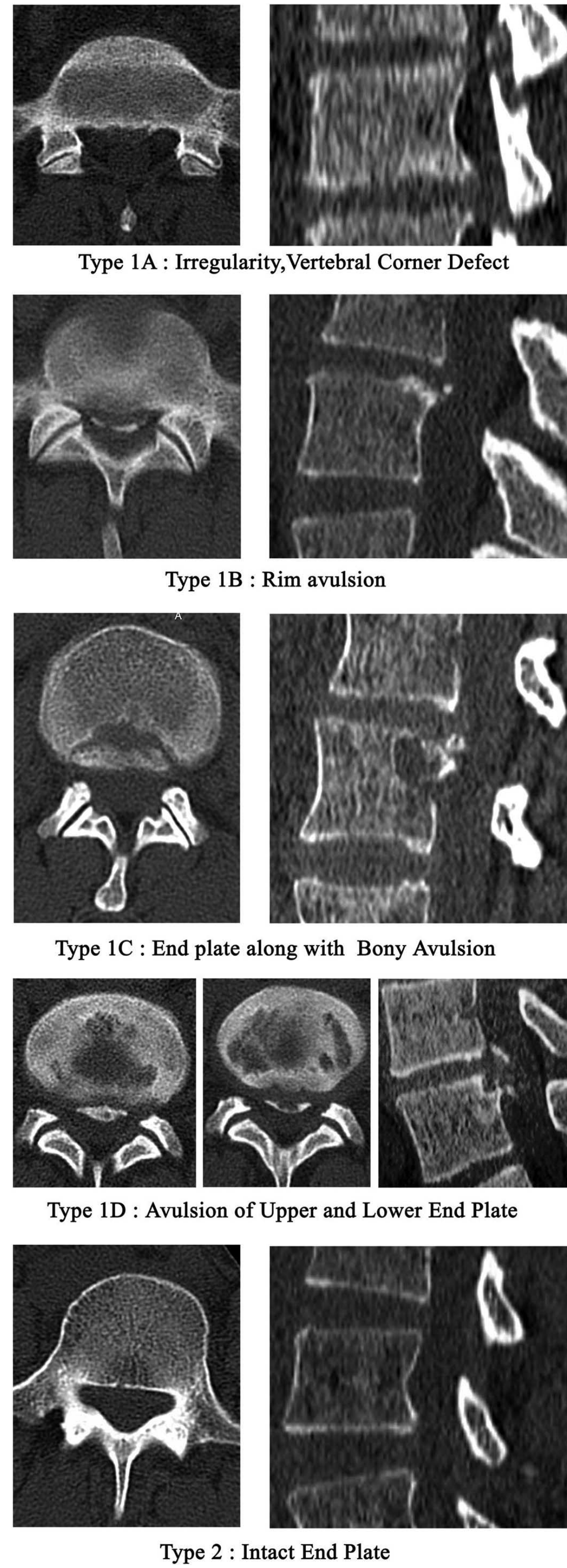

Figure 1. CT scan appearances of endplate in discs with herniation. Evidence of endplate junctional avulsion was termed as "Type I" herniation. This can be either by the presence of irregularity of the endplate margins without an obvious free fragment (**1A**), or by the presence of an avulsion evidenced by a thin rim of bone (**1B**), or by frank avulsion of a bony fragment (**1C**) or the presence of bony avulsion at the corners of both endplates (**1D**). Herniation without any evidence of endplate junctional failure was termed as "Type II" herniation.

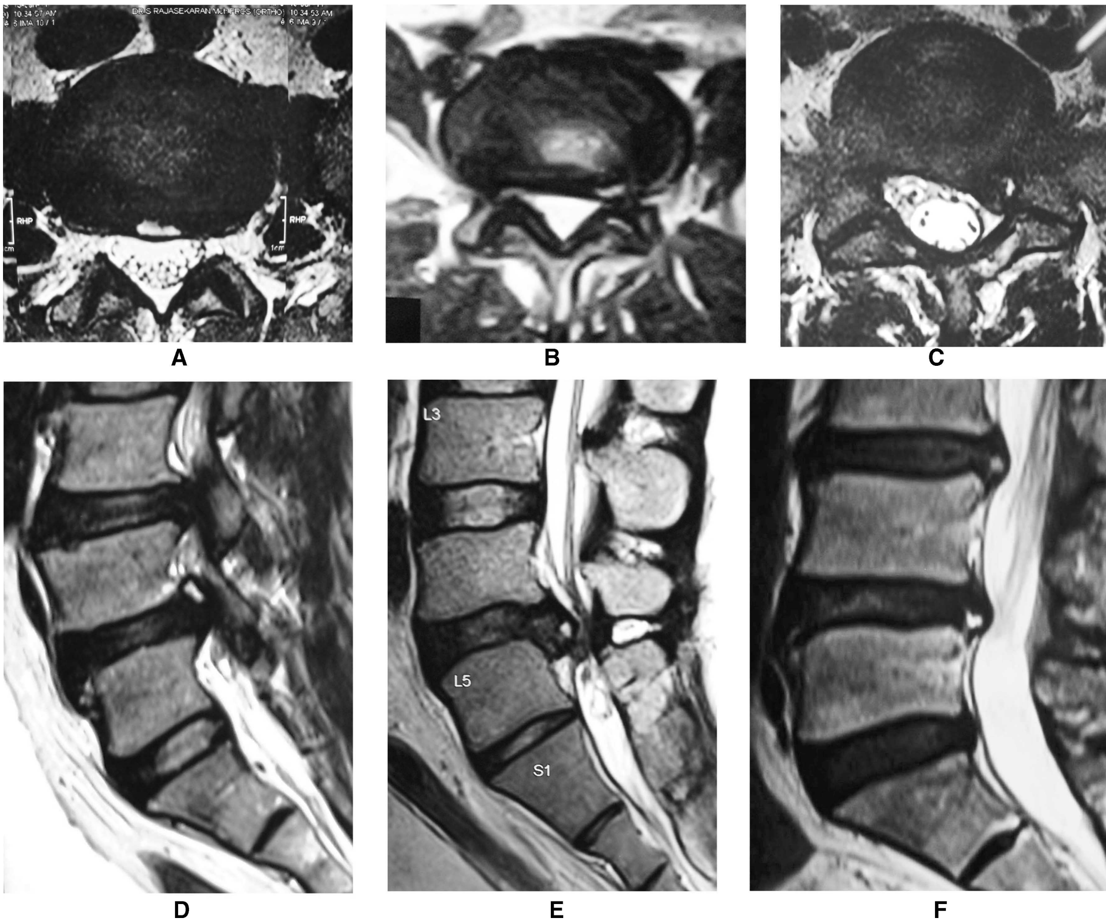

Figure 2. The presence of the HIZ was variable and documented as per the location in both the axial and saggital views of MRI. In the axial section, the HIZ was found to be either in the central (**A**), or paracentral (**B**), or beyond the foramen and far lateral (**C**). In the saggital sections, the HIZ was either located at the region of the superior endplate junction (**D**), or in the middle of the annulus fibrosus (**E**), or at the inferior endplate junction (**F**). MRI indicates magnetic resonance imaging. HIZ indicates high intensity zone.

subjective assessment of the proportion of EP fragment, AF, and NP in the disc sample and presence of revascularization was done by a senior pathologist.

RESULTS

Radiological Results

Of the 181 patients, 142 were males and 39 females (average, 37 yr; 13–66 yr). Seventeen patients were below the age of 20 years, 103 were between 21 and 40 years, and 61 were between 41 and 60 years. L4–L5 disc was the most common level in 89 (49%) followed by L5–S1 in 78 (43%), L3–L4 in 11 (6%), and L2–L3 in 3 (2%). The herniation was central in 17 (10%), paracentral in 150 (82%), foraminal in 10 (6%), and far lateral in 4 (2%). The LDH was a bulge in 21 (12%), a protrusion in 81 (45%), extrusion in 60 (33%), and sequestration in 19 (10%). The LDH was at the same level in 101 (56%), inferiorly migrated in 61 (34%), and superiorly migrated in 19 (10%).

Type 1 Herniation

There was a significant difference between the incidence of EPJF between the study and control discs (104/181 *vs*. 84/724; $P < 0.001$).

Of the 181 study discs, obvious EPJ avulsion was seen in CT scans in 104 (58%) discs (Figure 1). Of them, 30 (16%) had gross irregularity or a vertebral corner defect (type IA), 46 (26%) had rim avulsion fractures (type IB), 24 (14%) had large bony avulsions (type IC), and 4 (2%) had EPJF at both upper and lower EP (type ID). The failure was predominantly in lower EPJ in 89 (86%), and lesser in upper EP (11.9%) or in both EP (4.3%).

In 78% of rim avulsions and 80% of frank bony avulsions, the endplate avulsions were centrally located (Figure 4). However, the disc herniation was predominantly posterolateral in 124 (69%), indicating that irrespective of site of EPJ failure, interlamellar migration routes may locate the herniation more laterally (Figure 5).

The avulsed endplate fragments were observed to be either free or healed with or without stenosis (Figure 6). In 6 patients, eburnated healing was the cause for a secondary canal stenosis.

Type II Herniations

Sixty-four discs (35%) had intact EP and were classified as type II herniation. Of them, 21 (50%) had a HIZ in the central zone in the axial cuts and 18 in the paracentral area and 6 in the far lateral area, which may indicate the site of

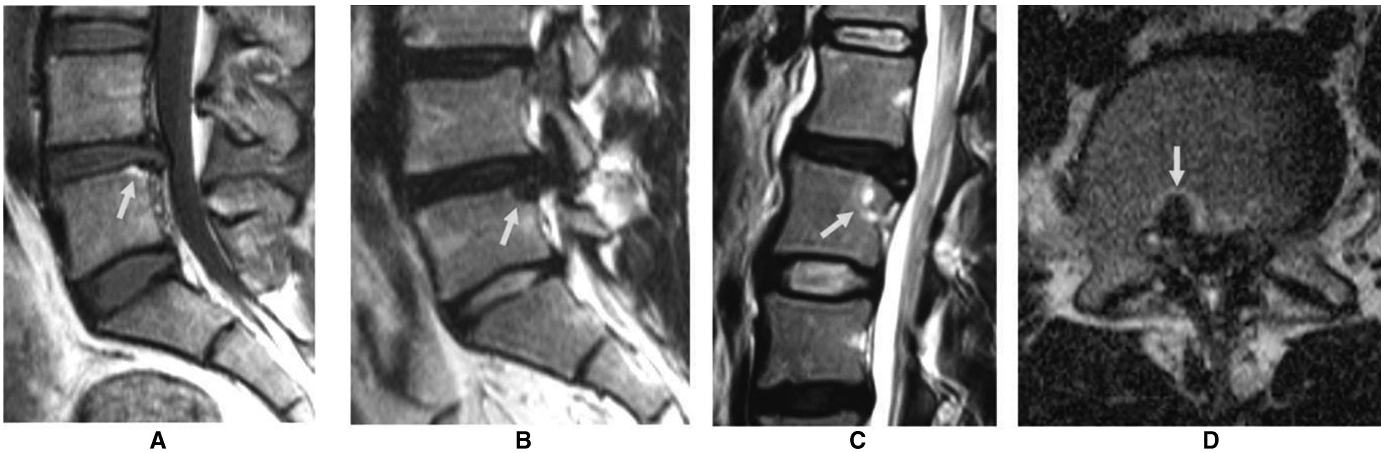

Figure 3. Evidence of endplate junction avulsion in the MRI was found either as a corner irregularity with Modic change (**A**), or as a well delineated small vertebral corner defect (**B**), a large vertebral corner defect (**C**) or as a defect of the bony margin in the axial view (**D**).

AF tears or failure. Although HIZ was centrally located in 18 discs, the herniation was however posterolateral in 14 of them. Comparing patients with type I and type II herniations, there was no significant difference in the age (35.9 and 37.1; P = NS), sex incidence, or duration of the symptoms.

Results of Serial Postcontrast MRI

Serial postcontrast MRI using gadodiamide was performed in 20 patients (10 each with type I and type II discs). Eight type I discs and 5 type II discs showed evidence of dye leakage at the EP junction (see Supplemental Digital Content Figures 2 and 3 available http://links.lww.com/BRS/A780 and http://links.lww.com/BRS/A781, respectively). The site of leakage could be pinpointed to the region close to the lower endplate junction in 11 and 2 in the superior EPJ. Early leakage was observed in all the 13 discs and 6 of them had complete pooling of the contrast within the disc space at 2 hours (see Supplemental Digital Content Figure 3 available at http://links.lww.com/BRS/A781).

EP damage was more severe in discs with LDH than those without. The average TEPS at the affected discs was 6.02 compared with 3.2 of the control discs ($P < 0.01$).

High Intensity Zone

HIZ was present in total 66 levels (25/181 study discs *vs.* 41/724 control discs). In sagittal T2 images, it was seen at inferior EPJ in 26 discs, in the middle in 12 and in the superior EPJ in 2 discs. In the axial T2 images, HIZ was seen in the posterior rim of AF in 36 levels and within the LDH in 30 discs. HIZ was most commonly seen at L4–L5 level (18 of type I and 48 of type II) corresponding with the most common level of disc herniation.

Intraoperative Findings

Thirteen of the excised discs that did not show any evidence of EPJF radiologically were observed to have cartilaginous or small bony endplate intraoperatively (Figure 7). Addition of these discs to the 104 radiological type I herniation increased the incidence of type I herniation to 65% (n = 117).

Frank evidence of AF rupture with herniation was present only in 28 (15%) of which 9 were preoperatively diagnosed to have sequestration. There was thinning of the annulus with near rupture in 32 (16%) discs. In the remaining 121 discs, there was a need for proper anulotomy to achieve disc excision.

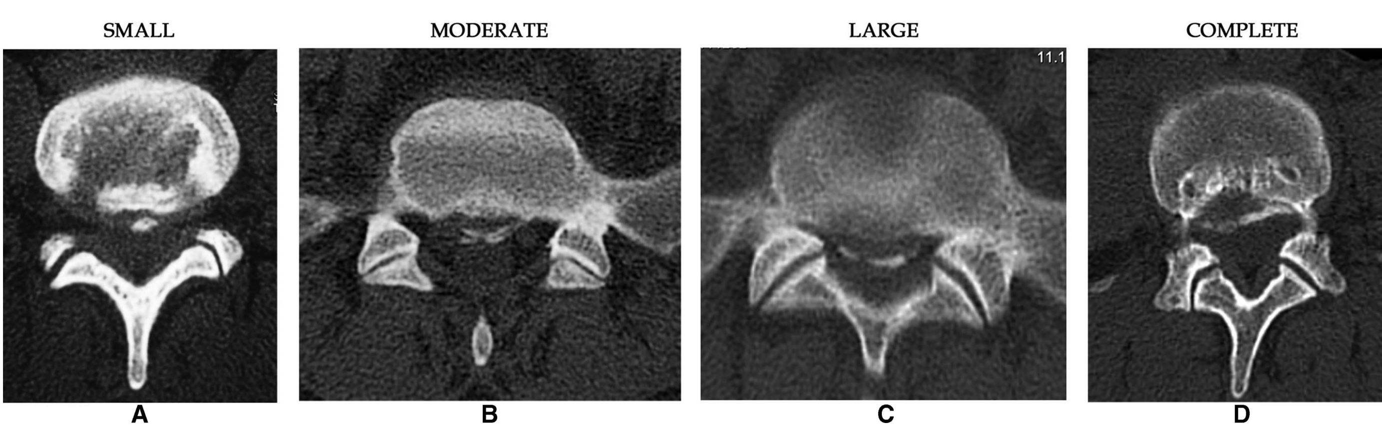

Figure 4. The failure of the endplate (Type Ib) by a rim avulsion can be visualized in the axial CT either as a **small** bony fragment (**A**), **moderate** covering upto 50% of the endplate margin (**B**), **large,** which is in excess of 50% of the endplate margin, and (**C**) and **complete** where the entire endplate margin is avulsed (**D**).

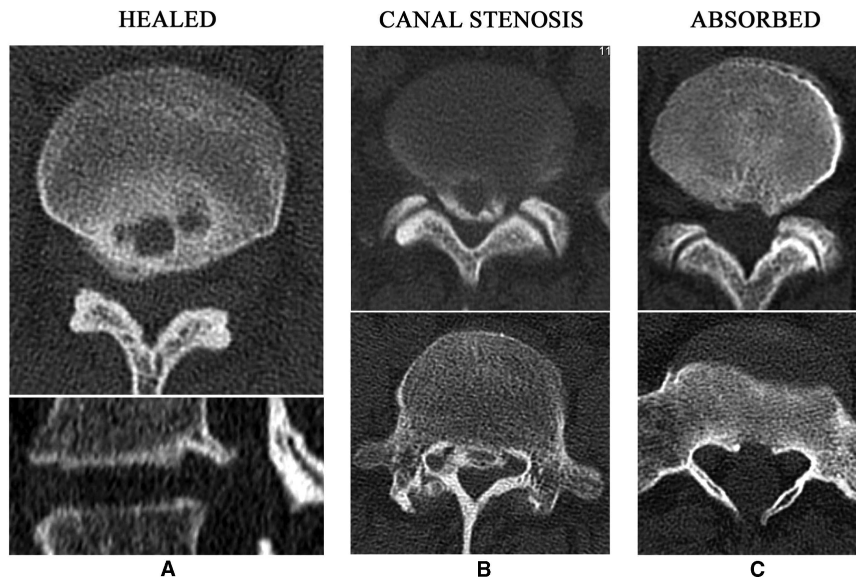

Figure 5. Many of the end plate junction changes were found to be chronic. Three types of sequelae was possible. The fragments were found to be either healed in the avulsed portion (**A**), or healed with bony eburnation and possible callus formation leading to canal stenosis (**B**). The other sequelae was that the fragment was completely absorbed and the vertebral defect was the only sign of the avulsion (**C**).

Histology Findings

In specimens with macroscopic evidence of endplate, histology showed cartilage with or without bony component attached to the annulus (see Supplemental Digital Content Figure 4A,B available at http://links.lww.com/BRS/A782). Histological evidence of EP material in the herniated disc was observed in 126 specimens (70%). Neovascularization of varying degrees was also observed in different regions of the removed material including nucleus pulposus, AF, and EP in 88 (49%) samples (see Supplemental Digital Content Figure 4C available at http://links.lww.com/BRS/A782).

Study Versus Control Discs

The study and control discs showed a significant difference in the incidence of HIZ, EPJ failure, presence of large Schmorl nodes, and TEPS ($P < 0.01$ for all).

DISCUSSION

The central aim of this study was to address the question—does the disc fail *in vivo* at the annulus as commonly thought[25–28] or the EPJ?

In vitro mechanical disruption of the disc has been studied in compression,[18,29–33] compression and flexion,[7,10,11,19,20,34] and in compression + flexion + torsion.[14,15,17,21] They have found that AF failure rarely occurs in compression alone and addition of torsion acted as a "failure catalyst" increasing the number of endplate disruptions.[14,15,21,35] There are however some concerns in extrapolating these results to clinical situa-tions,[17,36] and there is a need to verify through *in vivo* studies. We studied 181 consecutive patients with single level LDH. Patients older than 60 years or with multilevel disc changes were excluded to avoid the influence of disc degeneration on the results.

The 2 possible patterns of failure, AF failure and EPJF were thoroughly analyzed (Figure 8), and this was verified by a multimodal approach.

DOCUMENTATION OF ENDPLATE JUNCTION FAILURES

Our study shows that the incidence of EPJ failure has been grossly underrated probably because of the difficulty of documentation.[22,37–39] Plain radiographical identification has

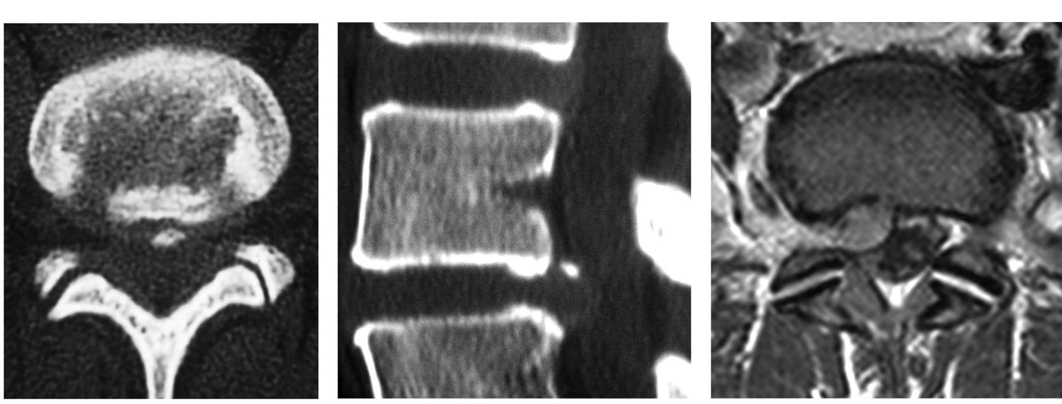

Figure 6. The end plate junction avulsion was most common in the central zone (**A, B**) but however the herniation was more common in the paracentral region (**C**). This indicates that there are interlamellar migration of the disc herniation from the central to the paracentral region.

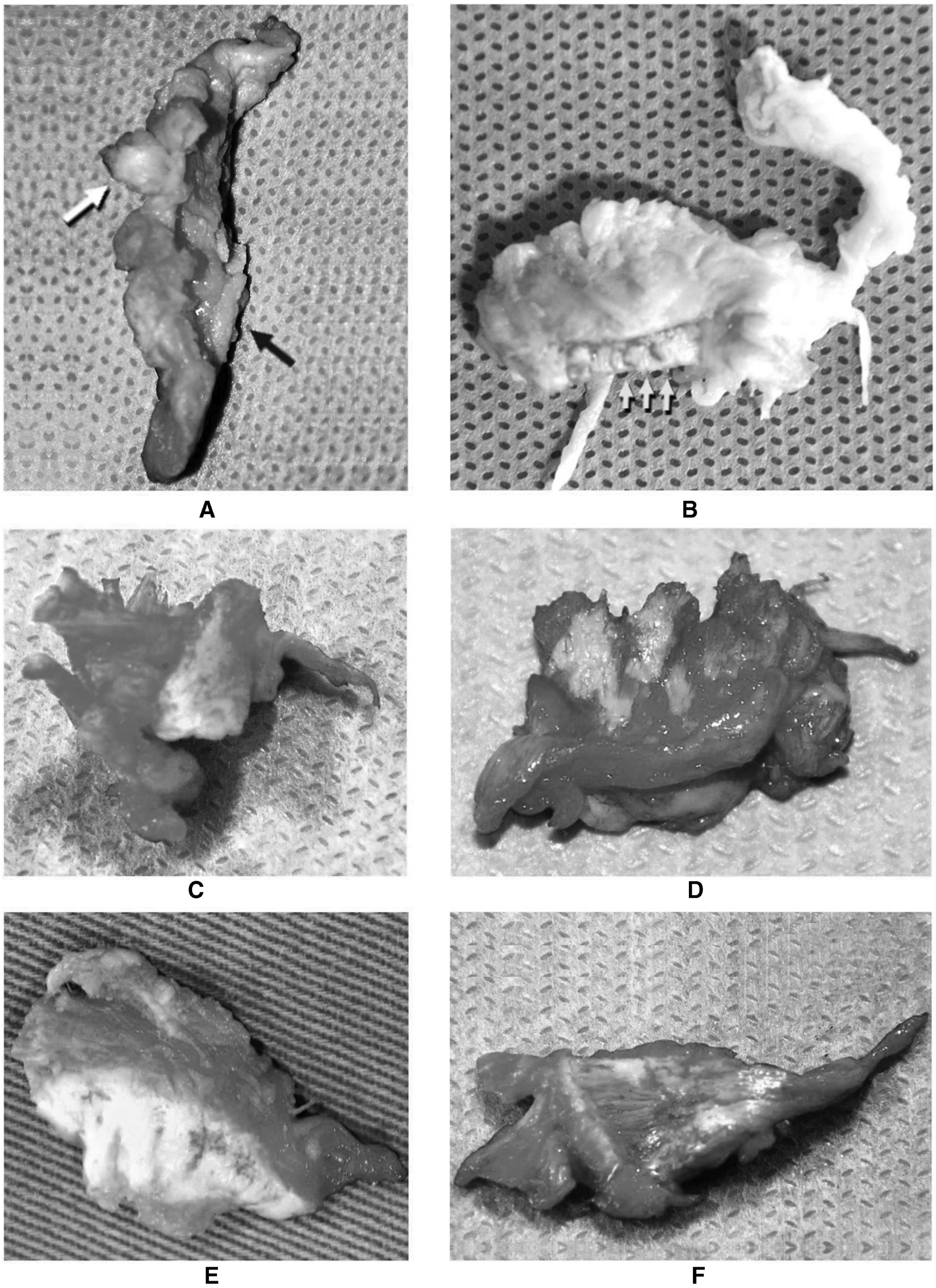

Figure 7. Macroscopic evidence of endplate in the herniated material. Disc herniations often contained attached pieces of the endplate which could be either as a thin rim of cartilage (black arrow in **A** and yellow arrow in **B**) or bone (white arrow in **A**). The endplate cartilages could also be easily visualized as large pieces of cartilage attached to the annulus (**C** and **D**). In few cases, large pieces of endplate cartilage were found to be loosely lying in the herniated material (**E** and **F**).

been quoted in 29% of patients,[41] but in our series we could firmly establish a plain radiographical diagnosis only in 12% of herniated discs. When CT evaluation of the EPJ was used, the incidence increased to 104 (58% of discs). It is critical that the thin CT cuts are executed through the vertebral endplate rather than at the disc level so that these endplate avulsions are not missed.

MRI is not very useful for revealing bony fragments in the herniated mass (Figure 9). Fragments are more conspicuous on proton density or gradient echo sequences than the usually performed T1 or T2 weighted images that show only larger fractures containing some marrow.[42] So, we identified EP fractures by indirect findings as shown in Figure 3. Multimodal imaging protocol and focused evaluation revealed the incidence of EP defect to be as high as 65% in our series.

STRUCTURAL CLASSIFICATION OF LDH

We also found several distinct patterns for failure, which led us to postulate a CT based classification depending upon the nature, location, and size of the fragment.

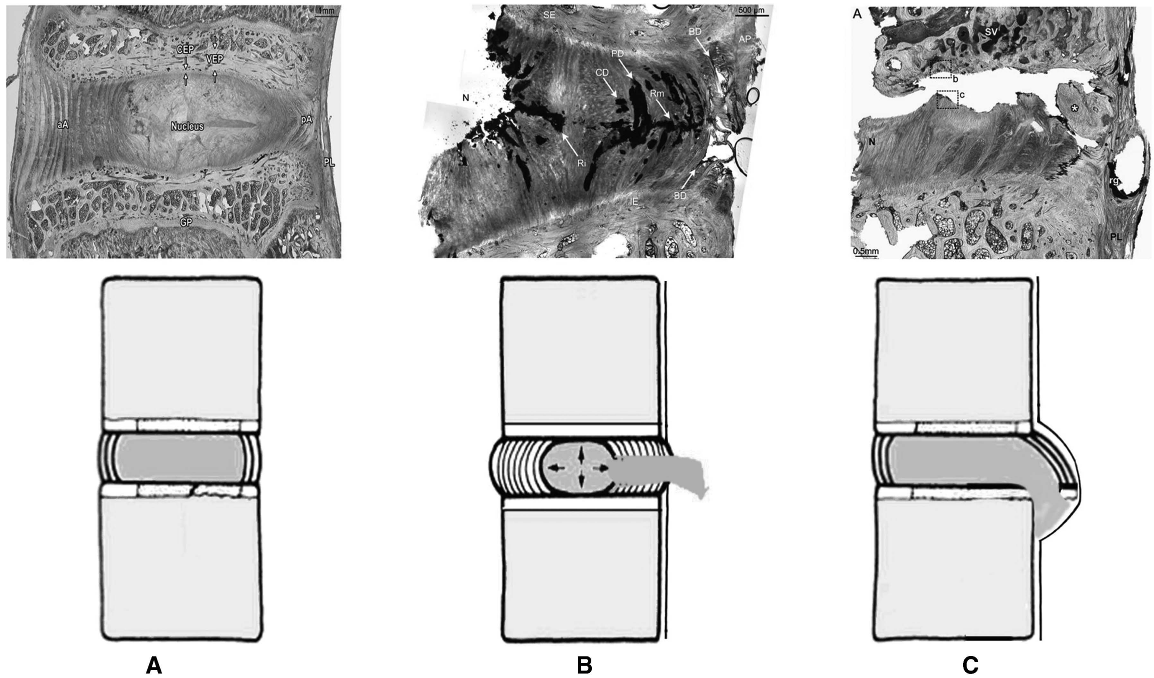

Figure 8. Histological sections from the work of Samuel Peter Veres and our line diagram depicting the disc in normal and states of failure. Studies of the disc clearly shows the disc in normal state with contained nucleus (**A**). The disc can fail either by the rupture of the annulus fibrosis (**B**) or by the avulsion of the endplate (**C**) depending upon the nature of force applied and the posture of the disc. Our line diagram depicts the three situations of normality (**A**), failure through the annulus fibrosus (**B**), and failure through avulsion of the endplate junction (**C**).

Type I Herniation

Failure of the disc due to avulsion of the EP junction was termed as type I herniation and was seen in 117 (65%) of discs. Various patterns of failure were noted ranging from occult avulsions (see Supplemental Digital Content Figure 5 available at http://links.lww.com/BRS/A783) to frank bony avulsions (Figure 1).

Rim fracture was the most common type of EPJ failure and was noticed in 25% of all discs studied and 50% of discs showing EPJ failure. All rim failures were mainly observed in the center of the EP and could vary from a tiny avulsion to a complete avulsion.

The size of the rim plate avulsion was not correlated to the size of the herniation as even small avulsions could lead to a large herniation (see Supplemental Digital Content Figure 15 available at http://links.lww.com/BRS/A784). Although the rim avulsions were central, the herniations were most often paracentral, indicating that the discs could have interlamellar migration laterally to rest on the paracentral zone (see Supplemental Digital Content Figure 16 available at http://links.lww.com/BRS/A785). Experimental studies have proved that nuclear material may readily move circumferentially within the outer posterior annulus which may possess weak interlaminar cohesion and thus allowing lateral migration.[14] Also, larger avulsions led to frequent irregular bony impingement into the canal and canal stenosis (Figure 5).

Large bony avulsions were seen in 24 (13%) of all discs studied and 26% of type I discs. The bony avulsion was central in 20 and paracentral in only 4 (see Supplemental Digital Content Figure 17 available at http://links.lww.com/BRS/A786). The finding that bony defects were more common in the posterolateral region than rim avulsions probably corroborates with the study of Veres *et al*[17] where torsion was found to increase the incidence of defects in the posterolateral corner often with avulsion of a bone fragment.

The observation that more than 50% of LDH is due to a bony endplate fracture can have clinical relevance and practical implications during the acute rehabilitation phase. Several questions arise whether to have an extended period of rest in these patients, to provide a lumbar support or to have a delayed return to heavy physical work, *etc*.

The failure was predominantly in the lower EPJ in 89 (86%) as the inferior endplate is less thicker and supported by less denser trabecular bone resulting in lesser ultimate compressive strength.[43,44]

Type II Herniation

Sixty-four (35%) of the discs had no radiological and intraoperative evidence of damage to the EP and were termed as type II herniation. Evidence of AF failure observed through the presence of HIZ was however present only in 11% of discs. Thirteen patients had intraoperative evidence of EPJF without any radiological evidence of endplate avulsion (Figure 10).

Serial Postcontrast MRI

Evidence of EPJF was provided by postcontrast MRI studies which in 8 patients with type I failure and 5 with type II showed a definite leak of the contrast through the EP junction,

Figure 9. The images shows that MRI does not clearly show even large bony avulsions. There is a large bony fragment clearly seen in both axial and sagital cuts of CT scan (**A** and **B**). MRI however does not show clear evidence of a fragment neither in the sagital (**C**) or two different axial cuts of herniation (**D** and **E**).

proving that the site of failure to be the EPJ (see Supplemental Digital Content Figures 2 and 3 available at http://links.lww.com/BRS/A780 and http://links.lww.com/BRS/A781). In none of the discs was there a clear leak through the AF. Our study is the first *in vivo* study that has confirmed that EPJ failure by avulsion is the main cause for LDH. The incidence of EPJ failure was 58% when only preoperative radiological assessment was considered but in fact increased to 65% when intraoperative findings of cartilage avulsion was added.

Is LDH Purely a Phenomenon of "Mechanical Failure"? Our findings by demonstrating similar sites of failure for LDH as shown in previous mechanical disc failure stud-ies indicate that the etiology of LDH is more likely to be mechanical. However, the strength of the AF and the robust-ness of the EPJ depend upon the nature of collagen, carti-lage, and other matrix proteins that may all be determined genetically. It can be presumed that the site and pattern of failure is determined by the nature of mechanical forces, but

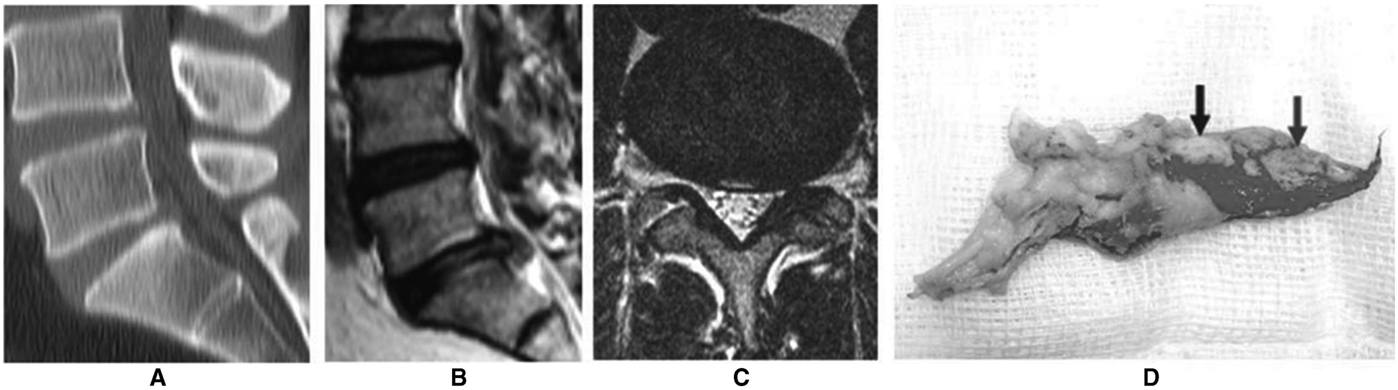

Figure 10. The above case demonstrates that many discs with Type II herniation may in fact be Type I as EPJF through cartilaginous avulsions may not be always well seen by radiology. In this patient, the endplate appeared normal in CT scan (**A**) and MRI (**B**). There was evidence of HIZ in the centre in axial cut of MRI (**C**). However intraoperatively herniated material showed both cartilage (blue arrow) and bone (black arrow) attached to the nucleus (**D**).

the individual susceptibility to failure may be biological and genetic.

Does EPJ Avulsion Lead to Precipitous LDH?

Many discs with EPJF showed chronicity of the lesions either by absorption of the fragment or sclerosis of the bone at the region of avulsion. This suggests that the entire sequence may occur through a series of subclinical failure episodes that ultimately lead to a clinically relevant herniation.

Is Preventive Intervention Possible?

In clinical practice, a traumatic event directly preceding the onset of symptoms is more often absent than present.[45–47] It has been also shown that after fracture of the vertebral rim, the process of LDH could take many months of normal loading.[14,16] This observation offers a potential window of opportunity for intervention which can prevent progression and an ultimate herniation.

LIMITATIONS OF THE STUDY

Although the study documented the predominance of EPJF in LDH *in vivo*, it has not studied if there are any differences in the pattern of presentation, clinical progress, and prognosis between the 2 groups of type I and type II herniation. We have also not studied the incidence of type I and type II herniation in patients who have responded to conservative treatment and did not require surgery. The study also involved a detailed radiographical and histological evaluation that may not be feasible in the day-to-day clinical practice. The intra- and interobserver reliability of the observations made in CT, MRI, naked eye assessment, and histopathological assessment also needs to be validated. These aspects will be important avenues for future studies.

CONCLUSION

Our study provides the first *in vivo* evidence that LDH in humans is the failure of the EPJ more commonly than AF rupture. The findings also provide the first clinical validation of the previous *in vitro* mechanical disruption studies of discs in human and ovine spines. A focus toward repair or prevention involves identifying the anatomical structure that failed and the knowledge of how and why it failed. Our study advises refocus of research into the critical area of EPJ.

➢ Key Points

- ❑ This multimodal *in vivo* study has proved that the mode of failure of LDH is more often by endplate junction avulsion than by AF rupture.
- ❑ Our study results validate the findings of biomechanical and FEM studies that predict EPJ as an important area of failure in LDH.
- ❑ A new classification of LDH has been proposed based on the "anatomy of failure" that will help to understand the eitiopathology of LDH.
- ❑ The evidence of endplate junction failure opens up opportunities for prevention, repair, and biological treatment strategies that may prevent progression of LDH after the initial event of EPJ avulsion.
- ❑ Future research in LDH must focus on EPJ in addition to AF.

Supplemental Digital Content is available for this article. Direct URL citations appearing in the printed text are provided in the HTML and PDF version of this article on the journal's web site (www.spinejournal.com).

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