'STRESS' DISTRIBUTIONS INSIDE INTERVERTEBRAL DISCS

THE EFFECTS OF AGE AND DEGENERATION

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We investigated the distribution of compressive 'stress' within cadaver intervertebral discs, using a pressure transducer mounted in a 1.3 mm diameter needle. The needle was pulled along the midsagittal diameter of a lumbar disc with the face of the transducer either vertical or horizontal while the disc was subjected to a constant compressive force. The resulting 'stress profiles' were analysed in order to characterise the distribution of vertical and horizontal compressive stress within each disc. A total of 87 discs from subjects aged between 16 and 87 years was examined.

Our results showed that age-related degenerative changes reduced the diameter of the central hydrostatic region of each disc (the 'functional nucleus') by approximately 50%, and the pressure within this region fell by 30%. The width of the functional annulus increased by 80% and the height of compressive 'stress peaks' within it by 160%. The effects of age and degeneration were greater at L4/L5 than at L2/L3, and the posterior annulus was affected more than the anterior. Age and degeneration were themselves closely related, but the stage of degeneration had the greater effect on stress distributions.

We suggest that structural changes within the annulus and endplate lead to a transfer of load from the nucleus to the posterior annulus. High 'stress' concentrations within the annulus may cause pain, and lead to further disruption.

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Intervertebral discs are probably the most common source of chronic low back pain (Kuslich, Ulstrom and Michael 1991). The outer annulus fibrosus has a nerve supply (Bogduk and Twomey 1991) and pain may arise from abnormal mechanical stimulation after posterior herniation of nuclear material, or internal disruption of the disc structure (Crock 1986; Schwarzer et al 1995). Alternatively, pain may arise from cell-mediated changes in disc biochemistry, possibly involving inflammation of innervated tissues. These processes are likely to be interdependent because chondrocyte metabolism depends on mechanical stresses acting in the surrounding tissue (Ohshima, Urban and Bergel 1995), and animal experiments have shown that structural damage, in the form of a scalpel cut, gives rise to cell-mediated degenerative changes throughout the disc (Osti, Vernon-Roberts and Fraser 1990). It seems likely therefore that intervertebral disc pain arises from the combined effects of mechanical damage and a biological response to that damage.

The mechanical stresses acting within intervertebral discs are therefore relevant to pain. Many investigators have measured the hydrostatic pressure in the nucleus pulposus (Nachemson 1965, 1981; Quinnett, Stockdale and Willis 1983; Brinckmann and Grootenboer 1991) and the compressive stress acting between the disc and the endplate of the adjacent vertebrae (Horst and Brinckmann 1981). These studies, however, have given little information about the annulus, although this contains the nerve endings of the disc and also the most active cells (Bayliss, Johnstone and O'Brien 1988), and were incapable of detecting any localised concentrations of stress. These may be particularly important in the initiation of structural damage and the production of pain.

This lack of information led us to develop a technique for measuring intradiscal stress directly in loaded cadaver discs. We used a transducer capable of responding to compressive stress in soft tissues (McNally, Adams and Goodship 1992) and mounted it in the side of a 1.3 mm diameter needle (Fig. 1). When this needle was pulled through a disc it provided a complete profile of compressive 'stress' in one plane across the anteroposterior diameter (McNally and Adams 1992). The transducer output is proportional to the average compressive stress acting on it, and the constant of proportionality (the calibration coefficient) obtained when the transducer is calibrated in a bath of saline is also applicable to the disc (McMillan et al

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Fig. 1

The apparatus used to apply compressive forces to a motion segment during stress profilometry. Inset is a diagram of the side-mounting of a transducer in a needle of 1.3 mm diameter.

1996). This finding implies that, when disc material deforms into the recess of the needle to press on the transducer, the restoring forces within the disc material are negligible. This would not be the case in harder materials, and in order to differentiate our measurements from the theoretical concept of stress in solid materials, we will refer to the transducer output as 'stress', using inverted commas.

Our initial results indicated that there were large 'stress' peaks in the annulus (McNally and Adams 1992). Later experiments showed that 'stress' distributions are affected by prior creep loading (Adams et al 1996), by the angulation of adjacent vertebrae (McNally, Adams and Goodship 1993; Adams et al 1994) and by prior damage to the adjacent vertebral bodies (Adams et al 1993).

In our present study, we examined the effects of age and degeneration. Our aim was to identify changes in the internal mechanical functioning of lumbar discs which may be responsible for structural disruption and low back pain.

MATERIALS AND METHODS

Cadaver material. We collected 53 human lumbar spines from cadaver donors aged between 16 and 87 years, and

stored them in sealed plastic bags at -20°C . Specimens were thawed at 3°C for 12 hours before being dissected into 'motion segments' consisting of two vertebrae with the intervening intervertebral disc and ligaments. A total of 87 motion segments was tested. Tissue dehydration was minimised by wrapping specimens in thin PVC film whenever possible. Death and frozen storage have little effect on the mechanical properties of the spine (Adams 1995).

'Stress profilometry'. Each motion segment was secured in two cups of a mildly-exothermic dental stone and loaded on a computer-controlled materials-testing machine (Dartec Ltd, Stourbridge, UK; Fig. 1). Compressive load was applied by two low-friction rollers which held the motion segment in a neutral position (neither flexed nor extended), without inhibiting any horizontal 'settling' movements of the vertebrae. A compressive load of 300 N was applied for 15 minutes to counter the possibility that the disc had become superhydrated after death.

The instrumented 1.3 mm needle was then pulled through the midsagittal diameter of the disc as described previously (McNally and Adams 1992). The transducer output was sampled at 25 Hz and plotted against the transducer position to obtain a 'stress profile'. During the measurements a 2 kN compressive force was applied to the disc to simulate the normal spinal loading during moderate manual labour (Nachemson 1981). A few small or osteoporotic specimens were tested at 1 kN. Profiles were repeated with the needle rotated by 90° giving 'profiles' for a 12 o'clock and a 3 o'clock position as discussed later.

Sectioning and grading of discs. After testing, each motion segment was removed from the dental stone and refrozen at -17°C . Most were later sectioned in the sagittal plane, using a fine saw for bone and a sharp knife for the frozen disc. Several parallel sections were obtained from many of the specimens, and were thawed and photographed. A few test discs were defrosted and then cut through in a plane parallel to the vertebral endplates. Disc dimensions were measured and the degree of disc degeneration assessed according to the following criteria, based on previous work (Galante 1967; Adams, Dolan and Hutton 1986; Vernon-Roberts 1988; Buckwalter 1995).

Grade 1. The disc was white, and usually showed no signs of structural disruption to the annulus or vertebral body endplates. The distinction between the annulus and nucleus was obvious only on thin sagittal sections; in these the nucleus appeared to be gelatinous or even translucent (Fig. 2a).

Grade 2. The disc was cream-coloured and usually showed no signs of structural disruption. The nucleus appeared to be fibrous and rather yellow, but was still soft. The concentric lamellae of the annulus were distinct and intact (Fig. 2b).

Grade 3. There were signs of disruption of the annulus or adjacent endplates. The nucleus was fibrous, dry and often discoloured. The annulus usually contained fissures or splits, and small marginal osteophytes were often present

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Macroscopic appearance of the four grades of disc degeneration, from grade 1 (a) to grade 4 (d) as described in the text.

around the rim of the vertebral body. The vertebral endplates were usually concave on the disc side (Fig. 2c). *Grade 4.* Severe disruption made it difficult to distinguish between annulus and nucleus. The disc was usually narrowed. The nucleus was often brown and fibrous and the annulus contained gross radial or circumferential fissures. The endplate was often damaged or depressed in the centre and marginal osteophytes were usually present (Fig. 2d).

The grade of each disc was assessed by one of the authors (MAA) without reference to the 'stress profiles'.

RESULTS

Typical 'stress profiles'. Most discs showed a large central region or volume in which the vertical and horizontal 'stresses' measured with the transducer at 12 o'clock and at 3 o'clock respectively were equal and unvarying with location (Fig. 3). This region represents the functional nucleus pulposus; a significant finding was that the apparent fluid behaviour of this region extended well into the anatomical inner annulus in which there was a well-defined lamellar structure. In front and behind this functional nucleus the transducer showed areas in which the horizontal and vertical readings differed from one another, and varied with

Fig. 3

Distribution of horizontal and vertical compressive stress along the mid-sagittal plane of a typical non-degenerated intervertebral disc loaded to 2 kN (male, 40 yr, L2/L3). The central region between the broken lines shows hydrostatic pressure in which stress does not vary with direction or location. The height (h) of a 'stress peak' in the annulus is measured relative to nuclear pressure (P = posterior; A = anterior).

Fig. 4a

Fig. 4b

Typical stress profile for a grade-1 disc (a): female, 27 yr, L1/L2 and for a grade-4 disc (b): female, 82 yr, L4/L5.

distance. This represents the solid behaviour of the middle and outer annulus. Figure 4 shows 'stress profiles' for typical grade-1 and grade-4 discs.

Analysis of the 'stress profiles'. We quantified the width of the three regions (anterior annulus, nucleus, posterior annulus) by superimposing the vertical and horizontal profiles on a computer screen. A cursor was used to indicate the boundaries of the functional nucleus within which the horizontal and vertical readings did not differ from each other or from their values in the centre of the disc by more than 5%. Some discs from older subjects showed local variation of up to 10% within a central region which otherwise showed hydrostatic features; in such cases, the whole region was considered to be nucleus. The computer was then used to calculate the width of each region, and the mean and maximum vertical and horizontal 'stress' within it. We expressed widths as percentages of the full sagittal width of the profile. The whole analysis was undertaken by a colleague who had no preconceived ideas concerning the results of the investigation.

The measured values in the 'stress profile' were generally in proportion to the applied load, and we therefore adjusted the measurements which we obtained at 1 kN by the following equation:

Normalised 'stress' = $I + ((\text{measured 'stress'} - I) \times 2)$ where

I = intrinsic stress (the measured 'stress' at zero applied load). On the basis of previous work, we assumed a value of 0.1 MPa for I .

Finally, we defined 'stress peaks' as localised concentrations in which the maximum value exceeded those on either side of it by more than 10% of the pressure in the nucleus. We counted the number of such peaks within the region of the posterior and the anterior annulus of each profile, recording the height of the largest peak in any one region *over and above the pressure in the nucleus*, as the size of the 'stress peak'. Table I gives the mean results of this analysis.

The effects of age, degeneration, lumbar level and gender. We used multiple linear regression to assess the influence of these factors on various features of 'stress profiles'. The results are summarised in Table II. They show that degeneration had the greatest effect: compared with normal discs, degenerated discs (grade 3 or 4) had a smaller nucleus with a smaller hydrostatic pressure and a wider posterior annulus which contained more and higher 'stress peaks'. The age of the subject correlated significantly with the degree of degeneration (Fig. 5), but it had very little *additional* effect on the 'stress profiles' when the influence of degeneration had been accounted for.

The effect of lumbar level on the 'stress' distributions is

Table I. Mean ($\pm$ SD) results from stress profiles grouped for each lumbar level

Lumbar level	No	Age (yr)	Disc degeneration	Posterior annulus			Anterior annulus			Nucleus	
				Width (%)	Vertical stress peak		Width (%)	Vertical stress peak		Width (%)	Pressure (MPa)
					Height (MPa)	Number		Height (MPa)	Number		
L1/L2	6	59.7 $\pm$ 20.9	2.17 $\pm$ 1.17	25 $\pm$ 12	0.36 $\pm$ 0.49	0.83 $\pm$ 0.75	33 $\pm$ 12	0.47 $\pm$ 0.76	0.83 $\pm$ 0.75	42 $\pm$ 23	2.13 $\pm$ 0.66
L2/L3	30	46.3 $\pm$ 16.2	2.23 $\pm$ 0.82	23 $\pm$ 10	0.51 $\pm$ 0.56	0.63 $\pm$ 0.56	25 $\pm$ 9	0.35 $\pm$ 0.71	0.60 $\pm$ 0.77	52 $\pm$ 16	1.94 $\pm$ 0.66
L3/L4	6	54.5 $\pm$ 17.2	2.33 $\pm$ 0.82	27 $\pm$ 11	0.88 $\pm$ 0.38	1.33 $\pm$ 0.82	27 $\pm$ 7	0.29 $\pm$ 0.40	1.00 $\pm$ 0.00	45 $\pm$ 16	1.59 $\pm$ 0.68
L4/L5	43	46.5 $\pm$ 15.5	2.42 $\pm$ 0.91	28 $\pm$ 12	0.79 $\pm$ 0.66	0.98 $\pm$ 0.56	24 $\pm$ 11	0.31 $\pm$ 0.41	0.65 $\pm$ 0.48	48 $\pm$ 17	1.74 $\pm$ 0.52
L5/S1	2	44.0	2.50	21	0.41	1.00	27	0.50	1.00	52	1.83

Fig. 5

The relationship between disc degeneration and age for L4/L5 discs ($R_{sq} = 0.58$). This was greater than that for the L2/L3 discs ($R_{sq} = 0.35$).

shown in Table I and Figure 6. We studied relatively large numbers of discs from the L2/L3 and L4/L5 levels and data for each of these levels were approximately normally distributed. We therefore compared the average values at these levels using two sample *t*-tests. At L4/L5, the posterior annulus was wider than at L2/L3 ($p = 0.05$) and the height of the 'stress peaks' within it were greater ($p < 0.05$). Nuclear pressure was decreased at L4/L5, but this difference just failed to reach statistical significance. Female specimens were associated with an increased nucleus pressure, probably because they were smaller, but no other gender differences were noted.

Fig. 6

The stresses in the anterior annulus and the nucleus varied with lumbar level. The bars show the maximum stress recorded in each region of the annulus and the mean pressure in the nucleus, with error bars showing the SEM. The maximum stresses in the annulus exceed the mean pressure in the nucleus.

To assess the effect of degeneration, we compared the mean data from grade-1 discs and grade-4 discs at the L4/L5 level (Table III), using only one level to minimise variations due to lumbar level. Similar results were obtained when we compared discs aged 30 years or under

Table II. Each row refers to a different feature of the 'stress profiles', and the columns indicate the influence of gender, age, etc on each feature, as indicated by multiple linear regression. The usefulness of this table is indicated by the following example: the width of the nucleus for a male, 50 years old, grade 2, L4/L5 disc would be given by the equation: Width (%) = $75.6 + 2.5 \times 1 - 0.079 \times 50 - 11.2 \times 2 + 0.6 \times 4 = 62.1\%$. The value of R_{sq} expresses the % of the variation in each feature of the profiles which is attributable to the combined effects of gender, age, degeneration and lumbar level

	Constant	Sex ($m = 1, f = 0$)	Age (yr)	Degeneration (scale 1 to 4)	Lumbar level (scale 1 (L1/L2) to 5 (L5/S1))	R_{sq} (%)
Width of nucleus (%)	75.6***	2.5	-0.079	-11.2***	0.6	38
Width of posterior annulus (%)	6.6	-0.6	-0.027	8.0***	0.7	34
Width of anterior annulus (%)	17.6***	-1.9	0.107	3.3*	-1.3	20
Pressure in nucleus (MPa)	3.06***	-0.40**	-0.0040	-0.203*	-0.095	26
Stress peak in posterior annulus (MPa)	-0.36	0.04	-0.0020	0.336***	0.097(*)	24
Stress peak in anterior annulus (MPa)	0.26	0.15	0.0072	-0.152	-0.005	5
Number of peaks of vertical stress in posterior annulus	-0.07	0.02	0.0001	0.260**	0.103(*)	18
Number of peaks of vertical stress in anterior annulus	0.37	0.08	0.0024	0.051	0.006	2

Significant influences are as follows:

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Trends are shown by (*) $p < 0.1$

Table III. Comparison of stress distributions (mean $\pm$ SD) in grade-1 and grade-4 discs (all L4/L5). The mean age of grade-1 discs was 27 years and of grade-4 discs 70 years

	Grade 1 (n = 6)	Grade 4 (n = 6)	Difference (%)	p value of difference
Nucleus width (% of disc width)	63.0 $\pm$ 17.5	32.1 $\pm$ 18.0	-49	<0.01
Intra-discal pressure (MPa)	1.94 $\pm$ 0.19	1.34 $\pm$ 0.30	-30	<0.005
Posterior annulus width (%)	20.3 $\pm$ 9.8	37.5 $\pm$ 11.6	84	<0.01
Height of posterior annulus peaks (MPa)	0.51 $\pm$ 0.46	1.34 $\pm$ 0.86	162	<0.05
Anterior annulus width (%)	16.7 $\pm$ 8.5	30.4 $\pm$ 12.6	82	<0.05
Height of anterior annulus peaks (MPa)	0.29 $\pm$ 0.38	0.06 $\pm$ 0.09	-79	=0.09

with discs aged 60 years or over with the same grade of degeneration.

Number of 'stress peaks'. The number of peaks of vertical compressive 'stress' within the annulus usually equalled or exceeded the number of peaks of horizontal 'stress', and were usually larger. Peaks of vertical 'stress' were more common in the posterior than in the anterior annulus ($p < 0.05$). The number recorded in the posterior annulus showed an interesting variation with degeneration: discs with no 'stress' peaks were mostly from young subjects with no degeneration (grade 1) and a large nucleus (Fig. 4a). Discs which showed one 'stress peak' in the posterior annulus were older and more degenerated; this group included the oldest and most degenerated discs tested (Fig. 4b). Of the nine discs which displayed two or more peaks in the posterior annulus (Fig. 7), however, only one was severely degenerated (grade 4) and only two were from subjects older than 58 years. Six of these discs were at the L4/L5 level: they tended to have a particularly wide posterior annulus and a particularly low nuclear pressure.

DISCUSSION

'Stress profiles' provide new insights into the mechanical function of intervertebral discs. The intradiscal stresses which we measured were not highest in the nucleus pulposus, as is commonly believed (Keller et al 1989) but in the inner and middle annulus fibrosus, especially posterior to the nucleus. The outermost 2 to 4 mm of annulus has practically no resistance to compressive stress; for this reason the pressure in the nucleus has been found to exceed the nominal 'applied stress' (applied load divided by cross-sectional area) in the annulus. Our results have also shown that the functional anterior annulus is no wider than the functional posterior annulus (Table I). This is because the inner anterior annulus shows a hydrostatic resistance to pressure and thus behaves as part of the nucleus, despite its distinctly lamellar structure.

Our results also show how ageing and degeneration affect these 'stress' distributions. They are themselves closely associated, but degeneration has a much greater effect than ageing *per se* on the 'stress profiles'. Many discs were found from subjects in the sixth and seventh decades which did not show macroscopic signs of severe

Fig. 7

Stress profiles showing multiple stress peaks in the posterior annulus. These were most commonly seen in L4/L5 discs, but were particularly obvious in this L3/L4 disc from a 47-year-old man.

degeneration, and had relatively normal 'stress profiles'.

Many of our results are unsurprising. Nachemson (1965) predicted that degeneration would result in a transfer of compressive stress from the nucleus to the annulus, and result in a 34% fall in nuclear pressure. His simple model could not predict how stress would be redistributed in the annulus, or indeed whether it was transferred to the annulus or to the apophyseal joints.

Age-related changes in the internal mechanics of discs can be partly explained by biochemical changes in disc composition. With increasing age, disc collagens and proteoglycans undergo quantitative and qualitative changes which may be related to nutritional compromise, or to the action of degradative enzymes (Buckwalter 1995), and the water content of the nucleus pulposus falls by 10% to 15% (Adams and Hutton 1983). A 10% loss in disc height (about 10% water loss) reduces nuclear pressure by less than 15%, however, and has no effect on the width of the hydrostatic region (Adams et al 1996). This modest fall in nuclear pressure may be attributable to increased loading of the apophyseal joints after the 10% loss in disc height (Adams

and Hutton 1980). When severe creep loading is used to drive 20% of the water from all regions of the disc, the nuclear pressure falls by 36% and the height of the 'stress peaks' in the posterior annulus increases by 35%, but the width of the hydrostatic region remains largely unaffected (Adams et al 1996). Comparison between these percentages and the data in Table III suggests that a 10% to 15% age-related fall in the water content of the nucleus cannot fully explain the large changes in 'stress' seen in degenerated discs.

This suggests that the degenerative changes which most affect intradiscal stress distributions are not merely biochemical in origin. Structural defects, which featured in our system of grading and which increase in severity with increasing age, may be more important. The presence of damage to a vertebral body endplate reduces the pressure in the nucleus of adjacent discs by up to 57%, and doubles the size of 'stress peaks' in the posterior annulus (Adams et al 1993). Other structural changes in the disc which increase the space available for the nucleus, such as radial fissures, or posterior disc prolapse, have a similar effect (Adams and Dolan 1996).

Gross changes in intradiscal stress arising from structural defects may be the cause of the biological and cell-mediated changes which normally accompany such defects in life. Chondrocytes are sensitive to changes in the compressive stress in their matrix and would respond to decompression by producing less proteoglycan (Ohshima et al 1995). This would tend to reduce further the volume of nuclear material and accentuate the transfer of load from nucleus to annulus. High stress peaks in the annulus adjacent to a depressurised nucleus may then lead to collapse of the annulus into the nucleus, as is seen in old, degenerated discs (Tanaka, Nakahara and Inoue 1993). Thus, an initial structural defect in a vertebral endplate or annulus could result in a degenerative spiral involving biochemical changes and further structural disruption. This is a simplification of mechanisms which have previously been proposed to explain disc degeneration (Crock 1986; Bogduk and Twomey 1991) because it does not need to postulate inflammatory or autoimmune processes.

Our hypothesis can explain the age-related transfer of load from nucleus to annulus, but why should the posterior annulus be affected more than the anterior? One possible explanation is that the posterior annulus in the lumbar spine is shorter than the anterior, and is therefore less able to accommodate vertical deformation. Moderate flexion corrects this imbalance and equalises 'stresses' across the whole of the disc (Adams et al 1994). This may explain why the lumbar spine is normally flexed during lifting activities, when compressive forces on it are greatest (Dolan, Earley and Adams 1994; Dolan, Mannion and Adams 1994). The differences which we found between the posterior and anterior annulus in our experiment may then be attributed to the loading of the motion segments in the neutral position rather than in moderate flexion.

Changes in lumbar disc mechanics may have direct clinical consequences. High peaks of compressive 'stress' in the posterior annulus may elicit pain from the innervated annulus, or from the vertebral end plates upon which they press. In addition, symptoms may be produced indirectly when the outer lamellae are forced outwards, and the inner lamellae inwards, disrupting the lamellar structure of a region of the disc. This may explain the origin of *multiple* 'stress peaks' in the posterior annulus of middle-aged discs which showed only moderate degenerative changes (Fig. 7). Such multiple peaks were associated with a low nuclear pressure and a particularly wide posterior annulus; when a similar combination of features is seen clinically, it is often associated with severe back pain (McNally et al 1996). It seems possible that multiple 'stress peaks' may represent an early, painful, stage of disc degeneration, when the posterior annulus is failing, but is still load-bearing. The later stage of complete collapse to a very narrow disc would produce stress-shielding by the apophyseal joints (Dunlop, Adams and Hutton 1984), and may therefore not be as painful. The concept that discogenic pain is associated with only *partial* failure of the posterior annulus is consistent with the results of 'provocation discography'. In these studies, the worst pain is reported from fissured discs that nevertheless retain the injected contrast medium (Moneta et al 1994; Schwarzer et al 1995).

In theory, pain from a partially failed posterior annulus could be alleviated by using a spinal fixator to unload this part of the disc. In practice, however, fixators may be unable to do this effectively (Edwards et al 1997).

Conclusions

- 1) The central region of a lumbar intervertebral disc, including the inner annulus, behaves like a pressurised fluid. Compressive stresses within this 'functional nucleus' do not vary with the direction or location of a pressure transducer.
- 2) The highest compressive stresses are normally found in the annulus, with the exception of the outermost 2 to 4 mm, which behave like a tensile skin.
- 3) Age-related degenerative changes reduce the sagittal diameter of the functional nucleus by approximately 50%, and the pressure within it falls by 30%. The width of the functional annulus increases by 80%, and compressive stress peaks within the posterior annulus increase by 160%.
- 4) The effects of age and degeneration are greater at L4/L5 than at L2/L3, and the posterior annulus is affected more than the anterior.
- 5) Age and degeneration are closely related, but degeneration has the greater effect on intradiscal stresses.
- 6) Changes in disc mechanics are probably initiated by damage to the annulus or endplate, or by a cell-mediated reduction in proteoglycan content. Either of these would reduce the nuclear pressure, and transfer compressive stress from the nucleus pulposus to the posterior annulus.
- 7) High stress concentrations in the posterior annulus may

be a cause of pain, and of further structural disruption.

8) Complete collapse of the posterior annulus would transfer compressive load from the annulus to the apophyseal joints, and this may explain the spontaneous relief from discogenic pain which occurs in some patients.

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REFERENCES

- Adams MA.** Mechanical testing of the spine: an appraisal of methodology, results and conclusions. *Spine* 1995;20:2151-6.
- Adams MA, Dolan P.** Which comes first: disc degeneration or mechanical failure? Proc Spine Society Australia, Cairns, November 1996.
- Adams MA, Dolan P, Hutton WC.** The stages of disc degeneration as revealed by discograms. *J Bone Joint Surg [Br]* 1986;68-B:36-41.
- Adams MA, Hutton WC.** The effect of posture on the role of the apophysial joints in resisting intervertebral compressive forces. *J Bone Joint Surg [Br]* 1980;62-B:358-62.
- Adams MA, Hutton WC.** The effect of posture on the fluid content of lumbar intervertebral discs. *Spine* 1983;8:665-71.
- Adams MA, McMillan DW, Green TP, Dolan P.** Sustained loading generates stress concentrations in lumbar intervertebral discs. *Spine* 1996;21:434-8.
- Adams MA, McNally DM, Chinn H, Dolan P.** Posture and the compressive strength of the lumbar spine. 1994;9:5-14.
- Adams MA, McNally DS, Wagstaff J, Goodship AE.** Abnormal stress concentrations in lumbar intervertebral discs following damage to the vertebral body: a cause of disc failure. *Eur Spine J* 1993;1:214-21.
- Bayliss MT, Johnstone B, O'Brien JP.** Proteoglycan synthesis in the human intervertebral disc: variation with age, region and pathology. *Spine* 1988;13:972-81.
- Bogduk N, Twomey LT.** *Clinical anatomy of the lumbar spine*. UK, Churchill Livingstone, 1991.
- Brinckmann P, Grootenboer H.** Change of disc height, radial disc bulge and intradiscal pressure from discectomy: an in-vitro investigation on human lumbar discs. *Spine* 1991;16:641-6.
- Buckwalter JA.** Aging and degeneration of the human intervertebral disc. *Spine* 1995;20:1307-14.
- Crock HV.** Internal disc disruption: a challenge to disc prolapse 50 years on. *Spine* 1986;11:650-3.
- Dolan P, Earley M, Adams MA.** Bending and compressive stresses acting on the lumbar spine during lifting activities. *J Biomech* 1994;27: 1237-48.
- Dolan P, Mannion AF, Adams MA.** Passive tissues help the back muscles to generate extensor moments during lifting. *J Biomech* 1994;27: 1077-85.
- Dunlop RB, Adams MA, Hutton WC.** Disc space narrowing and the lumbar facet joints. *J Bone Joint Surg [Br]* 1984;66-B:706-10.
- Edwards AG, McNally DS, Mulholland RC, Goodship AE.** The effects of posterior fixation on internal intervertebral disc mechanics. *J Bone Joint Surg [Br]* 1997; in press.
- Galante JO.** Tensile properties of the human lumbar annulus fibrosus. *Acta Orthop Scand* 1967:Suppl 100.
- Horst S, Brinckmann P.** Measurement of the distribution of axial stress on the end-plate of the vertebral body. *Spine* 1981;6:217-32.
- Keller TS, Hansson TH, Abram AC, Spengler DM, Panjabi MM.** Regional variations in the compressive properties of lumbar vertebral trabeculae: effects of disc degeneration. *Spine* 1989;14:1012-9.
- Kuslich SD, Ulstrom CL, Michael CJ.** The tissue origin of low back pain and sciatica: a report of pain response to tissue stimulation during operations on the lumbar spine using local anesthesia. *Orthop Clin North Am* 1991;22:181-7.
- McMillan DW, McNally DS, Garbutt G, Adams MA.** Stress distributions inside intervertebral discs: the validity of experimental 'stress profilometry'. *Engn in Medicine* 1996;210:81-7.
- McNally DS, Adams MA.** Internal intervertebral disc mechanics as revealed by stress profilometry. *Spine* 1992;17:66-73.
- McNally DS, Adams MA, Goodship AE.** Development and validation of a new transducer for intradiscal pressure measurement. *J Biomed Eng* 1992;14:495-8.
- McNally DS, Adams MA, Goodship AE.** Can intervertebral disc prolapse be predicted by disc mechanics? *Spine* 1993;18:1525-30.
- McNally DS, Shackelford IM, Goodship AE, Mulholland RC.** In-vivo stress measurements can predict pain on discography. *Spine* 1996; in press.
- Moneta GB, Videman T, Kaivanto K, et al.** Reported pain during lumbar discography as a function of annular ruptures and disc degeneration: a re-analysis of 833 discograms. *Spine* 1994;19:1968-74.
- Nachemson A.** In vivo discometry in lumbar discs with irregular nucleograms. *Acta Orthop Scand* 1965;36:418-34.
- Nachemson AL.** Disc pressure measurements. *Spine* 1981;6:93-7.
- Ohshima H, Urban JP, Bergel DH.** Effect of static load on matrix synthesis rates in the intervertebral disc measured in-vitro by a new perfusion technique. *J Orthop Res* 1995;13:22-9.
- Osti OL, Vernon-Roberts B, Fraser RD.** Annulus tears and intervertebral disc degeneration: an experimental study using an animal model. *Spine* 1990;15:762-7.
- Quinnell RC, Stockdale HR, Willis DS.** Observations of pressures within normal discs in the lumbar spine. *Spine* 1983;8:166-9.
- Schwarzer AC, Aprill CN, Derby R, et al.** The prevalence and clinical features of internal disc disruption in patients with chronic low back pain. *Spine* 1995;20:1878-83.
- Tanaka M, Nakahara S, Inoue H.** A pathologic study of discs in the elderly: separation between the cartilaginous endplate and the vertebral body. *Spine* 1993;18:1456-62.
- Vernon-Roberts B.** Disc pathology and disease states. In: Ghosh P, ed. *The biology of the intervertebral disc*. Volume II. Boca Raton, Florida: CRC Press Inc, 1988:73-119.