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Lumbar Intervertebral Disc Herniation Following Experimental Intradiscal Pressure Increase*

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Summary

An experimental biomechanical model of overload and rupture of the annulus fibrosus (AF) and lumbar disc herniation was achieved by increasing intradiscal pressure while keeping disc height constant in 69 motion segments at the L4–L5 level excised from cadaveric spines. The experiments were made on 53 specimens in neutral posture and on 16 specimens in flexion posture.

The values found for the rupture intradiscal pressure (RIP) ranged from 750 to 1300 kPa for neutral posture and the maximum RIP in anterior flexion was 1177 kPa.

The degree of disc degeneration was assessed by vertebral transcorporeal discography (previous to experiment) and by sectioning the intervertebral disc after the experiment.

The herniated lumbar intervertebral disc model by intradiscal pressure increase makes possible these assertions:

- The correlation between the degree of AF degeneration and the RIP is significant: the maximum RIP corresponds to a non-degenerated AF and the less RIP can tear only a degenerated AF; so disc herniation only occurs to discs with torn AF.
- AF breaking is more often paramedian, left or right. The place of AF breaking was paramedian in 70.3% cases, median in 9.45% cases and posterolateral in 20.25% cases.

Keywords: Rupture intradiscal pressure; transcorporeal discography; disc herniation.

Introduction

Disc degeneration affects the biomechanical behaviour of all vertebral components and induces spinal segment changes with the deterioration of general spinal behaviour.

In 1959 Nachemson was the first to report results concerning the determination of intradiscal pressure on fresh spinal specimens. Subsequently, the intradiscal pressure was measured in vivo with a special transducer (Nachemson and Morris, 1964) and afterwards the lumbar intradiscal pressure was determined for different types of loading (Nachemson and Elfstrom, 1970).

In order to understand the disc degeneration by tears showing up, followed by annulus ruptures and herniation of the nucleus pulposus, it is important to know the intradiscal pressure at failure of the annulus fibrosus.

Such a measurement can not be performed in living humans and for this reason we conceived an experimental model allowing the measurement of the rupture intradiscal pressure in the AF. We isolated the L4–L5 spinal segments, which were subjected to measurement.

Earlier experimental studies on disc herniation were performed with different combined loading modes, resulting in intradiscal pressure increases as one of the parameters. Therefore we decided to design an experimental study with intradiscal pressure increases as the only experimental parameter.

Materials and Methods

From the L1–L5 lumbar segments, removed from 113 cadavers between 21 and 71 years old without spinal deformities, 69 motion segments of the L4–L5 level were used. The distribution was:

- 16 cases in the 21 to 30 year age group
- 15 cases in the 31 to 40 year age group
- 21 cases in the 41 to 50 year age group
- 9 cases in the 51 to 60 year age group
- 8 cases in the 61 to 70 year age group

The device used for fixing the motion segment, increasing intradiscal pressure and measuring the value producing the annular failure is shown in Fig. 1.

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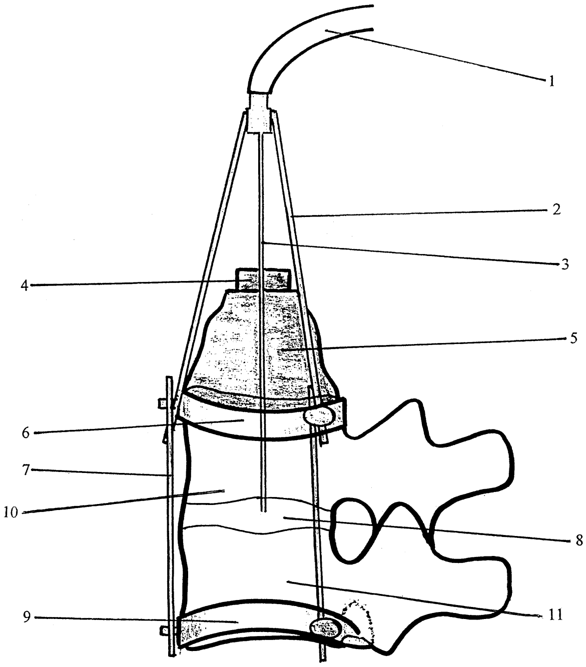

Fig. 1. The device for measuring the RIP of the annulus fibrosus in an isolated lumbar spinal segment: *(1)* connecting metal tube; *(2)* stabilising rod; *(3)* transcorporeal intradiscal metal tube; *(4)* rubber gasket; *(5)* molded rubber sleeve; *(6)* tightening collar; *(7)* tightening rod; *(8)* intervertebral disc; *(9)* tightening collar with jaws; *(10)* L5 vertebral body *(11)* L4 vertebral body

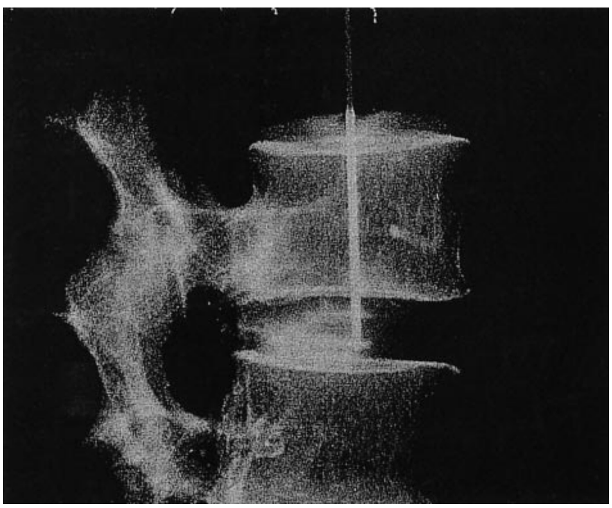

Fig. 2. Transcorporeal discography of the isolated spinal segment

After measuring the pressure at which the AF fails, the disc was sectioned transversally and:

- The circumferences and the outer and inner diameters of the AF were measured.
- The location of annulus tears was shown.
- The aspect of the nucleus pulposus and the degree of annular degeneration were macroscopically assessed, by identifying the annular circumferential and/or radial tears.

In view of the RIP found in the experiment and the discal dimensions measured, the following parameters were worked out:

- the maximum tangential stress withstood by the AF
- the force that produces the failure of the AF.

Specimen Preparation

After removing the vertebral segments L1–L5 from cadaveric spines, the motion segment L4 vertebra/L4–L5 intervertebral disc/ L5 vertebra was used in the experiment. The procedure was performed on motion segments with intact neural arches.

The degree of the disc degeneration was assessed by transcorporeal discography previous to the experiment (Fig. 2) and after the experiment the disc is sectioned and the annular tears and the failure are evaluated.

The discography was performed after drilling the L5 vertebra through the inferior end-plate and before setting the device for increasing intradiscal pressure and was performed in all cases in the neutral position. The exploration was achieved with omnipaque 300 mg/ml, using 0.5–1 ml for each disc. The nuclear, central space of the disc, considered as an extended nuclear cavity, was denoted NC and the radial tears occuring in approximately half the annular width are denoted RT (Tables 1 and 2).

Some motion segments were excluded:

- discs with annular tears up to the periphery were excluded from the analysis – the RIP was so small that AF broke immediately;
- the great narrowing discs were excluded from the experiment because they became homogenous fibrosus and very hard (RIP was over 14.75 atm).

Device for Measuring the Rupture Intradiscal Pressure (RIP)

The device is relatively simple and can be used for fixing the motion segment, increasing and measuring the intradiscal pressure.

The device consists of a source of pressure, with a manometer graduated in kgf/cm^2 up to 16 atm and connected to a tube with 2 mm diameter and 1.5 mm width of the outer wall, which is introduced into the DIV through a tunnel drilled in the body of the subjacent vertebra.

The system intradiscal tube-vertebra is tightened between the tunnel drilled through the vertebra and the tubular rod; at the level of the vertebral cartilage end-plate, tight rubber gaskets and a rubber sleeve are applied; everything is then fixed with a metal collar around the vertebral body through which the rod is introduced. The other vertebral body is also fixed posterolaterally to the pedicles with a metal collar, without injuring them; three vertical fastening rods (one placed anteriorly and two posterolaterally) attach this vertebral body to the first collar.

To exemplify the procedure: the motion segment is reversed; at the geometrical center of the inferior plate of L5 vertebra a tunnel with a diameter of approximately 4.5 mm is drilled up to the discal space, then the rod is introduced and tightened inside. Rapid adhesive and dental cement are applied, then the rubber gasket, fastened by a ring with a screw and finally the rubber sleeve, which is tightened to the vertebral body by the metallic collar. The second collar (incomplete and with fastening pedicular jaws, for attachment inside of the spinal canal) is fixed on the L4 vertebral body and tightened with the three rods: the anterior medial one and the two lateral ones.

The increase in pressure was achieved by means of an electric compressor, which can theoretically increase the air pressure up to 16 atm within 5.5 min; practically one can obtain 14.75 atm within 5 min; the connection between the experimental device and the compressor was made by copper tubes of 10 mm diameter.

Table 1. *RIP for the L4–L5 level, Neutral Position*

Nr.	Age	Sex	RIP kPa	σ kPa	Faf kN	Disc degeneration	
						Discography	Maroscopic assessment
1	21	M	950	2533	5.344	N	CT
2	22	F	900	2569	5.13	NC	CT
3	22	M	925	2530	5.146	NC	CT
4	23	F	882	2511	5.202	NC	CT
5	25	M	980	2937	5.753	N	CT
6	26	F	775	2343	4.854	RT	ERT
7	27	M	900	2698	5.285	NC	RT
8	28	M	1177	3405	6.925	N	N
9	28	M	1000	2969	6.264	NC	CT + RT
10	29	F	950	2664	5.621	NC	RT
11	31	F	950	3009	6.348	NC	CT
12	32	M	800	2465	5.013	NC	ERT
13	34	F	800	2398	4.697	NC	RT + CT
14	35	F	775	2568	5.223	RT	MRT
15	35	M	1177	3138	6.621	NC	CT
16	36	M	1025	3318	6.876	NC	CT
17	36	M	950	2664	5.621	NC	MRT
18	38	M	875	2771	5.846	NC	CT
19	39	F	882	3175	6.457	RT	CT
20	40	F	800	2553	5.194	NC	CT
21	41	M	800	2650	5.616	RT	MRT
22	41	M	750	2375	5.153	RT	ERT
23	42	F	850	2524	5.522	NC	ERT
24	42	M	1025	2875	6.066	NC	CT + RT
25	43	F	1050	2948	6.22	N	CT
26	44	M	850	2692	5.68	NC	ERT
27	44	M	900	2968	5.417	NC	MRT
28	45	M	1000	2735	5.795	NC	CT
29	46	M	850	2459	5.21	RT	CT + MRT
30	47	M	1100	2864	6.07	NC	CT
31	47	F	1300	3314	7.022	N	N
32	48	F	1100	3009	6.376	NC	CT
33	49	F	850	2586	5.355	RT	ERT
34	50	F	785	2486	5.270	RT	CT + MRT
35	50	M	950	2748	5.823	NC	MRT
36	50	F	950	2748	5.589	NC	ERT
37	51	M	1100	2969	6.151	NC	CT
38	51	F	1000	2969	6.264	RT	CT
39	52	M	900	2774	5.633	RT	CT
40	53	F	1000	2805	5.921	NC	MRT
41	54	M	980	3020	6.139	NC	MRT
42	56	M	850	2816	5.725	RT	CT + MRT
43	58	F	1275	3576	7.552	NC	CT
44	58	M	1100	3266	6.896	NC	CT
45	59	M	925	2851	5.788	RT	RT
46	61	M	1100	3182	6.464	NC	CT + RT
47	62	M	800	2650	5.392	RT	ERT + CT
48	63	F	1100	3085	6.540	NC	CT
49	64	M	980	2910	6.172	RT	RT
50	65	M	850	3029	6.179	RT	ERT
51	66	F	1250	3506	7.506	NC	CT
52	68	M	1000	3082	6.284	RT	MRT
53	68	F	1100	3390	6.908	RT	RT

Table 2. *RIP for L4–L5 Level in Anteflexion*

Nr.	Age	Sex	RIP kPa	σ kPa	Faf kN	Flexion angle	Disc degeneration	
							Discography	Macroscopic assessment
1	22	M	800	2465	5.013	5°	NC	CT
2	23	M	850	2816	5.716	4°	NC	CT
3	24	F	800	2465	5.016	3°	NC	CT
4	25	M	900	2672	5.645	4°	NC	N
5	26	M	1050	2872	5.847	3°	N	N
6	29	M	950	2664	5.626	3°	NC	CT
7	32	F	750	2485	5.056	5°	RT	ERT
8	34	F	1100	3085	6.514	4°	NC	CT
9	35	M	950	2928	5.954	4°	NC	RT
10	37	F	1177	3301	6.971	5°	NC	CT
11	39	M	800	2650	5.403	6°	RT	RT
12	42	M	825	2543	5.180	5°	NC	RT
13	44	F	950	3009	6.358	5°	RT	CT
14	44	M	850	2816	5.726	5°	RT	RT
15	45	F	980	2910	6.166	4°	RT	CT
16	49	F	850	2690	5.705	4°	RT	ERT

Experimental Procedure

The lumbar motion segment was turned upside down in order to permit the assembling of the rubber gasket and the molded rubber sleeve through a collar, so that no pressure loss occurred.

The vertical tunnel was drilled through the inferior vertebral body of the motion segment, the rod was introduced up to the disc center and then tightened inside and the discographic control was performed. The discography could indicate the presence of some radial tears up to the periphery of the AF (the identification of smaller tears was uncertain) and the discs with such tears were discarded.

The vertical assembly was then tightened, the two collars and the tightened rods were applied and the device was connected to the source of pressure.

The intradiscal pressure was increased, verifying the tightness of the system in the mean time. The mechanical connection of the two vertebrae did not allow for the height of the disc to increase, permitting only transverse expansion (bulging) of the AF.

The increase in pressure, read on the manometer, reaches 10 atm (1000 kPa) within 3.5 min; in other words the system undergoes an increase in pressure of approximately 100 kPa/20 seconds.

The failure of AF is identified by the sudden decrease in pressure indicated by the manometer (accompanied by a specific cracking sound).

After recording the RIP, the system is dismantled; then the posterior arch is excised, trying to identify the location of the rupture in the annular circumference.

The discal diameters and the circumference are measured and the maximum discal height, corresponding to the nucleus pulposus, is assessed. Then the rest of AF was removed from the intact vertebra and the aspect of the cartilage end-plate and the presence of tears were recorded.

In 53 cases the experiments were performed in normal position and during anterior flexion in 16 L4–L5 segments.

The anterior flexion of the motion segment was obtained by changing the length of the anterior rod and modifying the tightening angles of the two posterolateral rods making up the fastening system; the flexion angles were between 3°–5°, (the values are in Table 2).

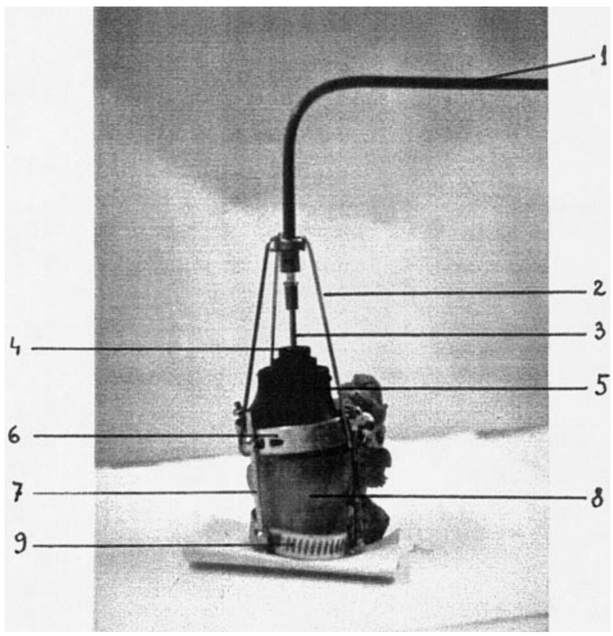

Fig. 3. The device for measuring the rupture intradiscal pressure of the normal annulus fibrosus in an isolated lumbar spinal segment. *(1)* connecting metal tube; *(2)* stabilizing rod; *(3)* transcorporeal intradiscal metal tube; *(4)* rubber gasket; *(5)* molded rubber sleeve; *(6)* tightening collar; *(7)* tightening rod; *(8)* IVD; *(9)* tightening collar with jaws

Annular Stress Calculation

From a physical point of view, the intervertebral disc can be considered as a distorted cylindrical tube with a thick wall and small height.

This biomechanical approximation of the disc, as a thick-walled cylindrical pressure container was used in order to assess the stress that appears in collagen fibres of the AF during axial compression (Adams & Hutton, 1989).

The maximum tangential stress that the AF can withstand at its exterior surface, until it fails, was worked out with the formula:

$$\sigma = 2 \times p \times \frac{R^2}{R^2 - r^2}$$

where p is the rupture intradiscal pressure (RIP) of the AF, measured experimentally; R and r are the values of the disc's radius, after the measurement of the circumferences and the outer and inner anteroposterior and transverse diameters; the measurements were performed after the horizontal dissection of each disc.

Results

Rupture Intradiscal Pressure (RIP)

The RIPs measured in the experiment described above, for neutral and flexion posture are given in the Tables 1 and 2.

Initially, the AF bulges up and then it fails, sometimes, the failure happens as an "eruption", but usually a quasi-punctual tear appears, growing as the pressure increases. This tear might appear anywhere, but more frequently it occurs posteriorly or posterolaterally.

The RIP varies dramatically: it ranges from 750 to 1300 kPa in neutral posture and in anterior flexion from 750 to 1177 kPa.

The change of intradiscal pressure versus time rises gradually, followed by a steep slope, which represents the sudden decrease in pressure when annular failure occurs (Fig. 4).

The transcorporeal discography performed before the experiment allowed the assessment of the degree of annular degeneration, manifested as radial tears, but it did not completely exclude discal degradation (the smaller tears can not be identified by discography).

It could estimate that the different values of the RIP, within the same age group and for subjects of the same size (or approximately the same size), depending on the degenerative lesions identified discographically or by sectioning the disc. However, the maximum values of the RIP did not show a clear dependency in all cases on the normal aspect of discs. Individual factors could also be involved here.

It was appreciated that the maximum values measured in the experiment represent the real biological (biomechanical) values of the RIP, all lower values being influenced (diminished) by the degree of discal degeneration.

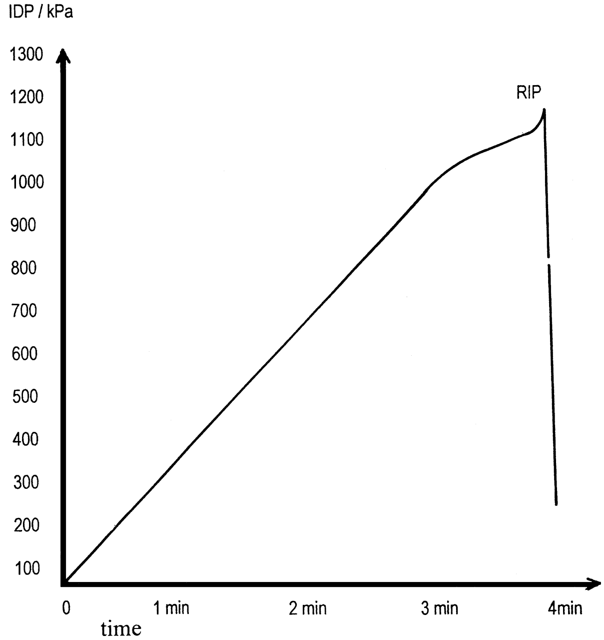

Fig. 4. Intradiscal pressure *(IDP)* versus time when testing the L4–L5 disc to failure; *RIP* the rupture intradiscal pressure

The Maximum Tangential Stress σ at the Outer Surface of AF

σ is calculated for the moment when the intradiscal pressure attains its limit value and the AF collapses. The maximum tangential stress appears as a very specific characteristic, because it depends on the annular dimensions. Its values range from 2.3 MPa to 3.5 MPa for neutral posture and during flexion from 2.1 to 3.3 MPa.

The Annular Failure Force

This force, denoted Faf, corresponds to the maximum peripheral loading producing the annular failure and can be worked out in view of the maximum stress the AF can withstand during the experimental increase in intradiscal pressure.

The values calculated are 4.69 to 7.55 kN for neutral posture and during flexion 5.01 to 6.97 kN. These variations are significantly related to the degree of disc degeneration.

Degenerative Discal Changes

The degeneration of discs subjected to the experiment was proven discographically and by horizontal dissection of the discs.

In the 69 discographies the following aspects were found:

- 23 cases with radial tears in internal half of AF, denoted RT
- 40 cases with extended nuclear space on the profile radiography, denoted NC
- 6 normal discographies, denoted N

The identification of smaller tears of AF by discography was difficult or uncertain.

The horizontal sectioning of DIV fissured during the increase in intradiscal pressure, was performed immediately after the experiment in each case, with a surgical blade.

The discal diameters and circumference were:

- The outer anteroposterior diameters had these values: 28–36 mm
- The outer transversal diameters: 43–57 mm
- The circumferences of AF: 112–139 mm
- The inner diameters had values of 18–23 mm, on an average 20.4 mm
- The height of discs: 8–13 mm

The elements of interest were the aspect of the nucleus pulposus, the occurrence of a central cavity, the fibrous fringes, the inhomogeneous fibrosis, the homogeneous (rare) aspect and the aspect of AF, which was usually not clearly delimited from the nucleus pulposus (NP).

At annular level, the tears were denoted as follows:

- MRT for multiple radial tears;
- ERT for extended radial tears;
- CT for circumferential tears.

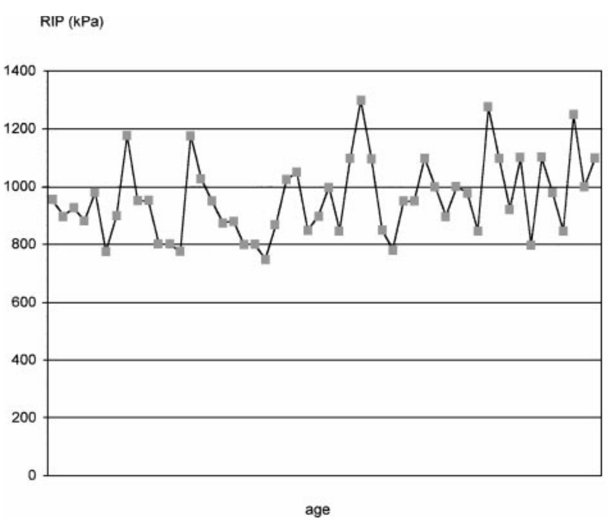

Fig. 5. RIP for the L4–L5 level in neutral position

Also end-plate lesions were found in the inferior end-plate aspect of the L4 vertebra (21 cases with disruptures, fractures etc., an aleatory variation by RIP. Their age can not be established).

The comparison between the discography and horizontal dissection shows: 4 discs with normal aspects, 55 discs with aspects of moderate degeneration and a minor involvement of AF and 10 discs with signs of marked degeneration (with old radial tears, extended into the AF).

According to Nachemson's scheme of classification and to the macroscopic aspect found in the experiment, the discs were grouped as follows:

- First degree: 8 discs
- Second degree: 19 discs
- Third degree: 32 discs
- Fourth degree: 10 discs

Discussion

In this study intradiscal pressure at which failure of the AF occurs was measured and attemps were made to correlate this pressure with the degree of discal degeneration.

The motion segment, isolated and subjected to the experiment, was static from the biomechanical point of view.

The annular failure can be considered a true biomechanical catastrophe for the disc and for the motion segment in general; however there are situations when the failure of the AF does not entail major biomechanical changes, if disc herniation with clinical symptomatology is excluded.

In case of an old and quasi-homogeneously fibrotic disc (when the disc herniation does not occur) the axial transmission of the load is archieved less by the fibrotic NP, whose elasticity is not signifiant, and more by the whole fibrous elastico-plastic structure, occupying the entire disc.

In general, in the studies on axial compression, researchers have not reported disc herniation as a result of increasing pressure during the compression of functional spinal units (Evans, Lissner, 1960; Jayson, 1983).

The more recent researches done in this field reconsider the biomechanical aspect of the occurrence of disc herniation; in 1982 Adams and Hutton demonstrated a possible herniation mechanism, studying spinal specimens free of the neural arches during hyperflexion and axial compression.

In our study intradiscal pressure was increased while keeping disc height stationary. This has the advantage of testing AF strength only on pressure load, without additional compressive stress which occurs under axial spinal loading with decrease of disc height.

In our experiments the RIP varied between 750 and 1300 kPa for the L4–L5 level in neutral position.

The great variability of RIP does not permit one to establish a relationship with age. The correlation with the degenerative aspect permits one to assert that the minimum values of RIP are correlated with the increased degree of annular degeneration. The maximum RIP values were found for the less degenerated discs, irrespective of age.

The maximum values of RIP corresponded to the discs showing no signs of degeneration.

If the cases with RIP higher than a certain value are selected there are:

– 22 cases with $980 < \text{RIP} < 1300$ kPa, 41.5%, in normal position,
– 7 cases with $950 < \text{RIP} < 1177$ kPa, 43.75%, in anteflexion.

These cases with maximum RIP, with a small degree of disc degeneration which was demonstrated by discography and confirmed macroscopically, correspond to normal discs.

A percentage of 59% of the specimens showed some degree of disc degeneration at the annular level, irrespective of age, which affected the annular strength: for those cases the RIP had low values.

In view of the RIP value, characteristic for each disc and disc dimensions, other discal characteristics were calculated: the maximum tangential annular stress, σ and annular failure force, Faf.

The maximum values of σ and Faf correspond to the smallest degree of annular degeneration.

According to this experiment for which the specimens had not been selected (only those with known lumbar disturbances and marked degeneration had been previously discarded) and extrapolating the results, it could be asserted that approximately one third of the population, belongs to a group which shows normal discs.

The assessment of the disc degeneration holds only for a single lumbar disc level. Therefore, the results can not be extrapolated to a whole individual spine or an entire population.

Experimental findings (Markolf, 1970; Farfan, 1973) have shown that not mere axial compression, but flexion and torsion are the first to affect the AF. The first structure affected by axial compression is the extremely thin cartilage end-plate, which is fractured, so diminishing the force that can attain values capable of rupturing the AF.

Due to the lesion of the cartilage end-plate, without annular rupture, axial spinal load can attain high values capable of injuring the vertebral body. The fracture of the cartilage end-plate leads to a decrease in annular loading by the intraspongy herniation.

There are two visible ways in which the discs responded to the increase in intradiscal pressure:

– due to the increase in intradiscal pressure, a “bulge” of the AF occured, followed by its failure; this aspect was found in younger than 35–36 years, revealing an elastic behaviour;
– the increase in intradiscal pressure did not visibly change the exterior aspect of the AF until it failed; it is assumed that this behaviour is due to a rigid AF.

Consequently, the elastic AF is specific for younger ages; it is less degenerated with less tears and theoreticaly the pressure producing the failure of this AF should be higher.

The great variation of RIP, irrespective of age, can be ascribed to other individual variable factors as well: the annular width, the state of discal hydration and the AF–NP continuity. These individual variable factors are difficult to identify and quantify, despite of their influence seeming important.

Taking into account the visco-elastic load-dependent behaviour of the AF, the relationship between the intradiscal pressure and the annular response has the following stages:

1. The intradiscal pressure increases up to a certain limit, without producing annular lesions; the situation corresponds to an elastic behaviour of AF. The intradiscal pressure attempts to stretch the wall, while the elastic force in the stretched annulus fibrosus counteracts the intradiscal pressure. An equilibrium is attained, consisting of the maintenance of the DIV deformation and stresses that appear in the AF, as a response to the internal pressure acting on it.
2. The increase in intradiscal pressure above the elastic limit produces lesions of the AF, manifested as tears that weaken the annular structure, without yet rupturing the AF. The tension variation withstood by the AF destroys the elastic equilibrium state,

causing structural changes and irreversible deformation. These permanent deformations make it impossible for the force acting in the stretched walls of the AF to counteract intradiscal pressure. The intradiscal pressure determining this behaviour is below a critical value, close to the RIP. If the intradiscal pressure does not exceed the critical value and the loading ceases, the integer parts of the AF, not completely destroyed, will ensure the partial return to the previous state.

3. When the critical intradiscal pressure is exceeded, the pre-existent lesions turn into complete rupture. A slip/dislocation of the lamellar layers of the AF occurs (resembling the torsion situation); a further increase in intradiscal pressure determines intralamellar ruptures, with the occurrence of circumferential tears resulting in dislocations of the lamelar fibres, leading to radial tears that propagate up to the annular periphery.

In view of the variations of the RIP values, measured in this study, it seems that the critical intradiscal pressure is an individual characteristic, probably depending on constitutional factors and a range of factors appearing later in life.

Conclusions

– The RIP is directly related to the degree of intervertebral disc degeneration.
– The maximum value of the RIP is correlated with the most reduced degree of disc degeneration, implying that the value of 1177 kPa up to 1300 kPa represents the RIP for a healthy disc for respectively anteflexion and normal position.
– The low values of RIP (between 750–800 kPa) are correlated with the highest degree of disc degeneration. The less RIP can tear only a degenerated annulus fibrosus.
– Minimum values of failure load hold for the anteflexion position which demonstrates decrease of annular strength produced by additional stress on the annular fibres in flexion.
– The AF breaking by intradiscal pressure increase is more often paramedian, left or right: paramedian in 70.3% cases, median in 9.45% cases and posterolateral in 20.25% cases. This has a correlation with clinical findings.
– Disc herniation can occur at low values of intradiscal pressure in discs with a high degree of degeneration.

In other words: the increase in intradiscal pressure selects the degenerated discs with fissured annulus fibrosus for herniation at low RIP.

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