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MEASUREMENT OF INTRADISCAL PRESSURE

By

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The nucleus pulposus consists of a three dimensional network of collagen fibres, enmeshed in a mucoprotein gel which contains various mucopolysaccharides (Hirsch, Paulson, Sylvén & Snellman; Bernardi, Happey & Naylor). The water content of the nucleus pulposus diminishes with increasing age (Püschel; Keyes & Compere; Hirsch et al.) while the polysaccharides complex decreases and is replaced by collagen (Sylvén).

The nucleus pulposus has been regarded as an osmotic system, capable of varying both its water content and the inner pressure. Göcke observed that absorption of fluid made the nucleus swell and that specimens from young people absorbed fluid to a considerably greater extent than those of old people. Naylor and Smare suggested that the breaking down of large complex molecules into smaller ones would increase the osmotic pressure and consequently increase the intradiscal pressure to such extent that the annulus ruptured. They have, both in 1951 and in 1956, published results of intradiscal pressure measurements on lumbar spines made with a Bordon gauge pressure indicator to which pressure was transmitted via an open needle filled with mercury. 137 discs were measured after immersion in distilled water. Most discs developed a pressure of 2.1–3.2 Kg. per cm^2. after 48 hours in water. According to these authors the pressure in the nucleus could be influenced by 1) the amount of polysaccharide, 2) the concentration of protein gel in the nucleus, 3) the presence of cavities of various sizes in the nucleus, 4) variations in the elasticity of the annulus fibrosus. There was a tendency to find lower pressures with increasing age. In 30 per cent of the cases, however, no pressure was produced, a phenomenon

The author is indebted to Prof. B. J. Andersson, Dept. of Technical Hydromechanics, Stockholm, for his generous technical advice.

for which they could offer no explanation. The hydrophilic properties were said to depend on a process regulated by two factors, viz. osmotic pressure variation, in the protein gel, and the cohesive forces of the tissue.

Using a specially constructed plethysmograph, Charnley exposed nuclear fragments to isotonic saline solution. He recorded pressures of 100–200 mm. mercury and inferred from this that the disc under certain conditions could absorb an excess of fluid, causing it to swell and develop an abnormally high pressure. Charnley was of the opinion that sudden intradiscal hypertension could cause acute low back pain.

Ott has performed swelling tests on nuclear substance obtained through surgical removal of discs. He found an increase in volume of more than 100 per cent if the specimen was put in physiological saline. In addition he found that the swollen nuclear fragments were practically incompressible with loading up to 15 Kg.

Hendry on the other hand tends to consider the imbibition pressure, i.e. the pressure required to separate a gel's disperse phase, the protein-polysaccharide complex of nucleus pulposus, from its dispersion medium of tissue fluid, of primary importance for the water content of the nucleus. The affinity between the two constituents causes them to exhibit the phenomenon known as hydration, solvation or imbibition and is such that a pressure, known as the imbibition pressure, is required to force them apart. He has demonstrated that a degenerated disc retains less fluid than a normal one by removing pieces of the nucleus and weighing the fresh specimens; they were weighed again after 24 hours immersion in physiological saline and again after having been dried over dehydrated calcium chloride under reduced pressure. Hendry's attempt to measure the imbibition pressure using an open needle inserted in the nucleus failed. On the other hand, he was able to measure this pressure by placing the disc in a syringe, weighting the piston and reading the volume changes on the syringe graduations. In the syringe the specimens could be loaded. The tests he made on specimens obtained from surgical cases were in principle identical with those made by Charnley. From his experiments Hendry concluded that the gel loses the ability with increasing age to retain its water content under conditions of stress. He furthermore proved that what Charnley and Naylor believed to be hyperhydration actually is an undue susceptibility to changes in environment. The large amount that is absorbed on removal from the body results from the inability to retain a normal amount when in the body. Far from generating an unusually high

pressure, it reacts to increased pressure by losing an abnormally large volume of fluid. He also pointed out that stress transmitted through the vertebral body should be seen as 1. a force balanced by the imbibition pressure of the nucleus, and 2. a remaining force which must be transmitted by the annulus. A reduction of he nuclear imbibition pressure causes the greater part of the total stress to be transferred to the annulus, while the character of the stress may be altered from alternating tension and compression to constant compression.

Disturbances in the water-binding properties of the mucoprotein gel affect the physical and physiological properties (Hirsch, 1951; Hirsch, Paulson, Sylvén & Snellman; Hendry).

Several attempts have been made to study the mechanical behaviour of lumbar discs. Göcke demonstrated by loading tests that the "elasticity" on the whole was independent of the macroscopic appearance. Virgin concluded from his elasticity tests that the intervertebral disc is an organic viscoelastic structure capable of bearing very heavy weights without changing. He observed that drying-up of the nucleus did not affect the elasticity to any great extent. With loading up to 150 Kg. Hirsch and Nachemson found no significant difference between the deformation of normal and degenerated discs. They pointed out the disc's ability to adapt itself to mechanical stresses. Perey has shown that the disc actually tolerates a greater amount of stress than the vertebral body.

It is generally thought that the nucleus is always subjected to a certain amount of pressure. Using a spring dynamometer fixed to metal pins projecting from the vertebrae, Petter measured this pressure and found it to be about 15 kp. The arches were removed and the annulus was dissected before the pressure was recorded.

Up to now no measurements have been made of the pressure variations in the nucleus resulting from different conditions of stress. Neither do we possess any knowledge to the proportions in which an applied load is transmitted by annulus and nucleus in normal and degenerated interspaces.

In technology it is a well known fact that "to find the inner strains occurring in a loaded body the physical properties of the body must be known and this can only be achieved by experiments" (Odquist). Inversely, it can be said that if the inner pressure of a disc can be measured, it should provide some information as to its physical properties.

METHODS OF PRESSURE RECORDING

Measurement of the pressure in the various air or fluid-filled cavities of the human organism has long been a point of interest. Various manometers have been used. In particular the study of pressure conditions in the circulatory system has been instrumental in the development of sensitive manometers. Tybjaerg Hansen gives in his monograph a detailed description of the available constructions, of which the electric ones have come into the most general use in the past few years.

An electric manometer may be based on one of the following principles:

1. Compression of electrolytes or ionized gases changes their electric resistance. Gurdijan and Lissner have used this principle to study the increase of intracranial pressure in skull injuries.
2. If a crystal such as quartz or tourmaline is subjected to mechanical strain, its potential changes. This is known as the piezoelectrical effect. Sjövall used this method to prove his theory concerning the effect of skull injuries on the cerebral substance.
3. Changes in the magnetic field of a coil containing an iron core induces a current. Wetterer built his manometer on this principle.
4. The capacitance between two electric condensators changes in a ratio to their relative distance. Frommer and Hansen have developed manometers of this type.
5. A fine metal wire which is subjected to stresses which produce changes in its original length, exhibits at the same time a change in electrical resistance. Very slight variations can be electrically measured in this way. This so-called "strain-gauge" principle is widely used in medical research. Gurdijan and Lissner, Evans, Hirsch and Brodetti have applied it to bone, while Darcus et al. and Tuttle et al. have constructed various dynamometers for the measurement of muscle strength. Strain gauge manometers are common and are available in many different models.

PRESENT INVESTIGATIONS

Experimental devices.

a. *Compression apparatus.*

The disc is placed vertically in a pneumatic clamp (Fig. 1). The width of the jaws is 100 mm. which limits the size of the specimen. One disc with part of the two adjacent vertebral bodies was tested after

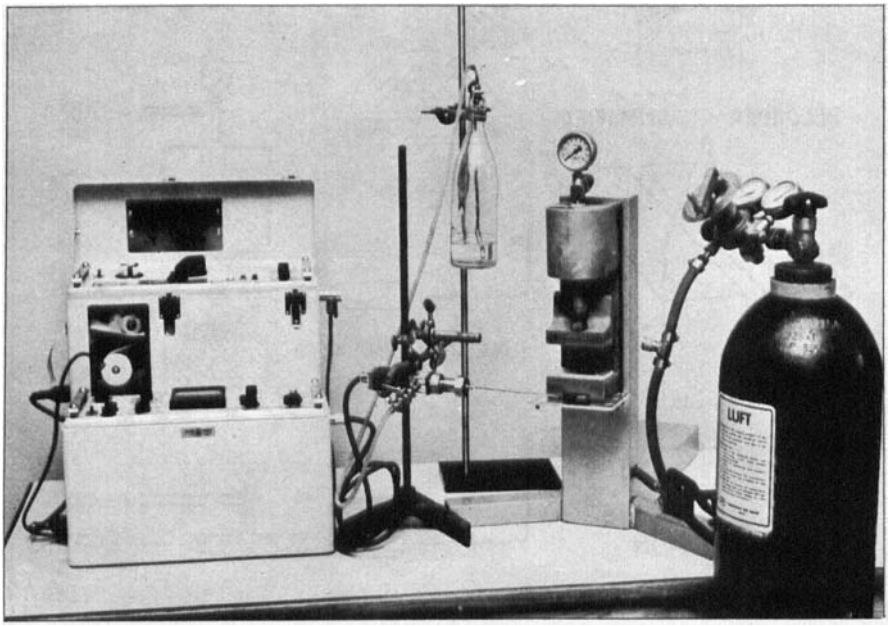


Fig. 1.
Close up view of experimental devices. On the right the pneumatic clamp, on the left the "jet recorder" and the amplifier.

laminectomy. The clamp gives compressive forces of 350 Kg. per cm^2. pressure. Readings were made for loads of 40, 80, 125, 175 and 220 Kg.

b. *Apparatus for measurement of intradiscal pressure.*

In the preliminary experiments the open end of a needle was inserted directly into the nucleus, glycerin was injected and the needle was then connected with the manometer. Earlier authors as Naylor et al. and Hendry have tried to measure the pressure in a similar way. Our results confirm that this it not feasible. In several experiments highly varying results were obtained. This makes it impossible to draw any conclusions. An additional disadvantage is that the experiments cannot be repeated.

In 37 experiments a polyethylene 60 tubing attached to a Luer-Lok needle was used. Both needle and tubing were filled with distilled water while the end of the tubing was plugged with a piece of steel of suitable dimensions. (Fig. 2). With this arrangement it was possible to measure the pressures acting inside the disc at right angles to the surface of the

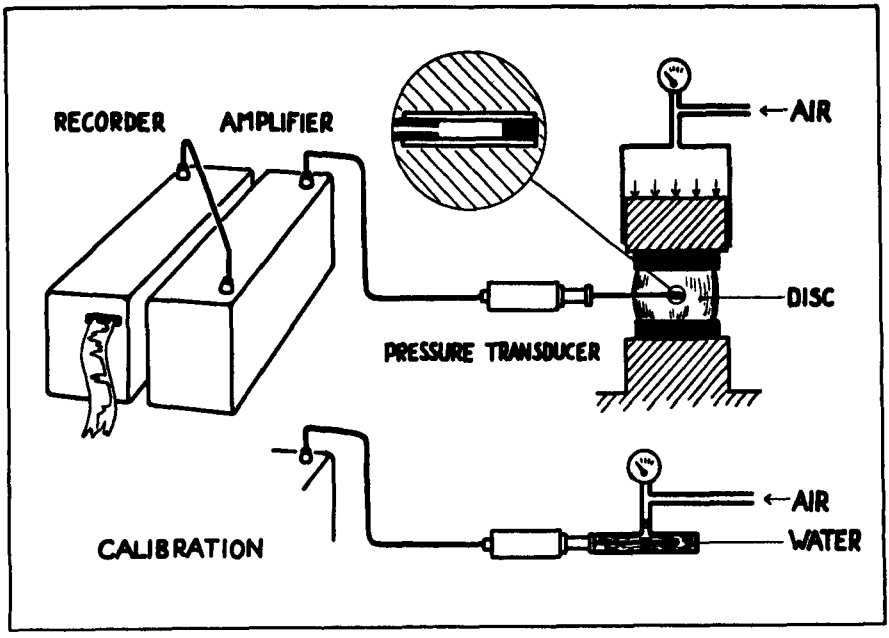


Fig. 2.
Schematic drawing of the experimental devices. The inset shows a magnification of the pressure recording instrument.

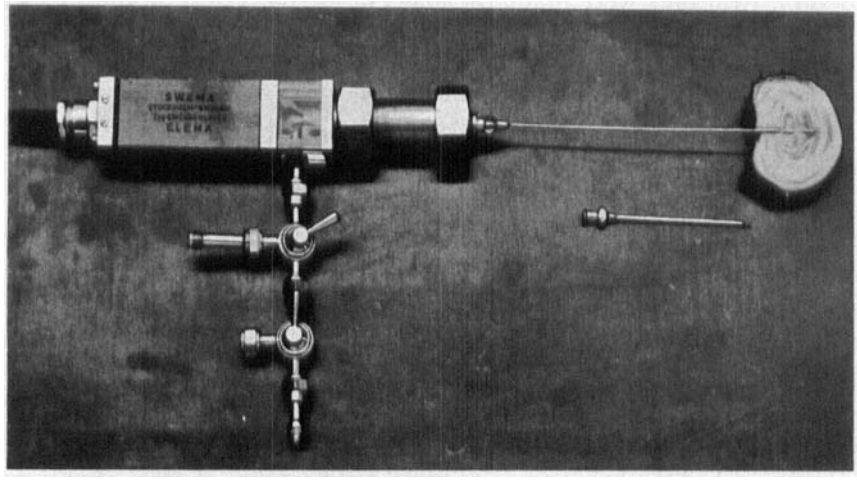


Fig. 3.
The mechano-electrical pressure transducer with attached needle and plastic tubing. Its position is demonstrated on a cross-sectioned disc.

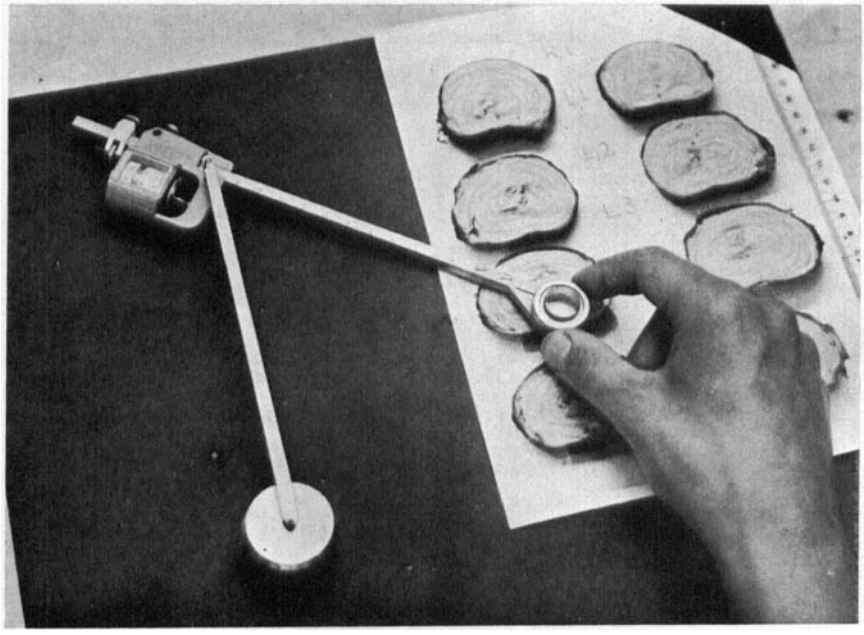


Fig. 4.
The Amsler planimeter in use.

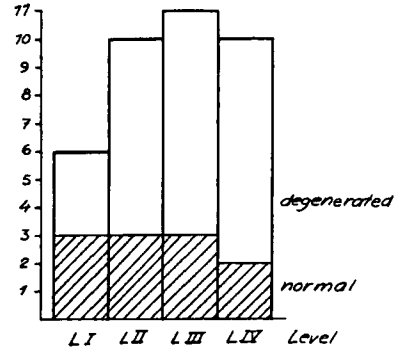


Diagram 1.
Distribution of specimens with regard to level in the lumbar spine and macroscopic appearance.

catheter. The needle was inserted into the disc via a graded record cannula which was then withdrawn (Fig. 3).

Roentgen plates were taken in two planes before the specimen was loaded. When under maximum load, a new roentgen plate was taken to ensure that the catheter had not changed its position or shape.

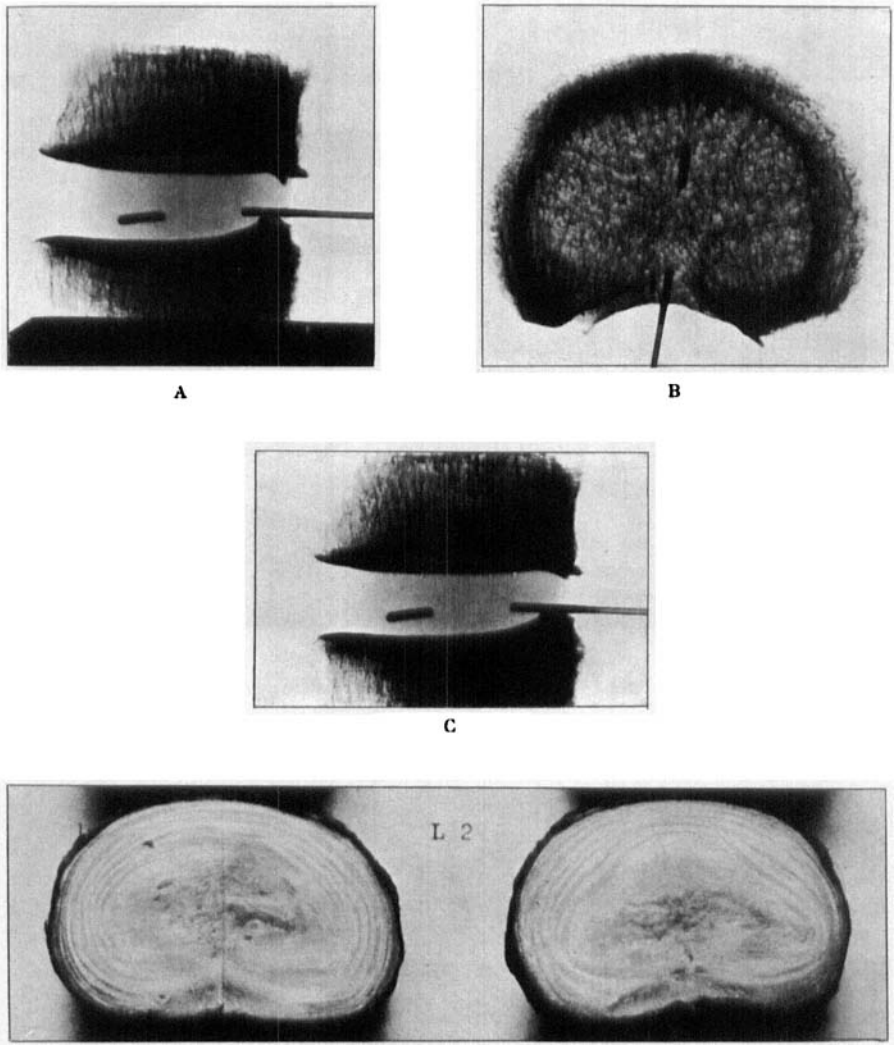


Fig. 5.

Roentgen plates and macroscopic appearance of a normal disc. The corresponding results are shown in table 1. A and B before loading. C under maximum load.

Before and after each experiment the catheter was calibrated against known pressures in a compression chamber. Different types of plastic were tested, but only a few were found to possess elastic properties equal to repeated pressure tests.

The needle with its attached plastic catheter was connected to the mechano-electrical pressure transducer. This transducer is of the

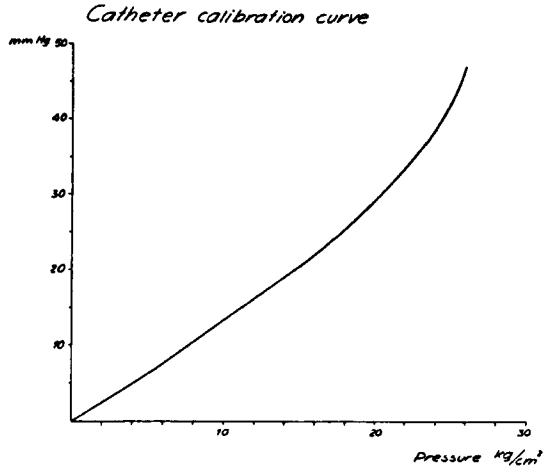


Fig. 6.
Calibration results from the plastic catheter used in experiments on the disc shown in fig. 5.

TABLE 1

Results obtained from specimen 252/L2. Surface area 14.8 cm². Fig. 5.

Load kg	Recorded pressure mm Hg		
	1.	2.	$\bar{m}$
40	5.0	5.0	5.0
80	11.2	11.8	11.5
125	17.5	18.8	18.2
175	26.3	25.0	25.7
220	35.6	34.4	35.0

Load kg	Calibrated intradiscal pressure kp/cm²		Index
40	4.0	$\frac{4.0 \cdot 14.8}{40}$	1.48
80	8.7	$\frac{8.7 \cdot 14.8}{80}$	1.61
125	13.5	$\frac{13.5 \cdot 14.8}{125}$	1.60
175	18.2	$\frac{18.2 \cdot 14.8}{175}$	1.54
220	22.7	$\frac{22.7 \cdot 14.8}{220}$	1.53
			$\bar{m}$ 1.55

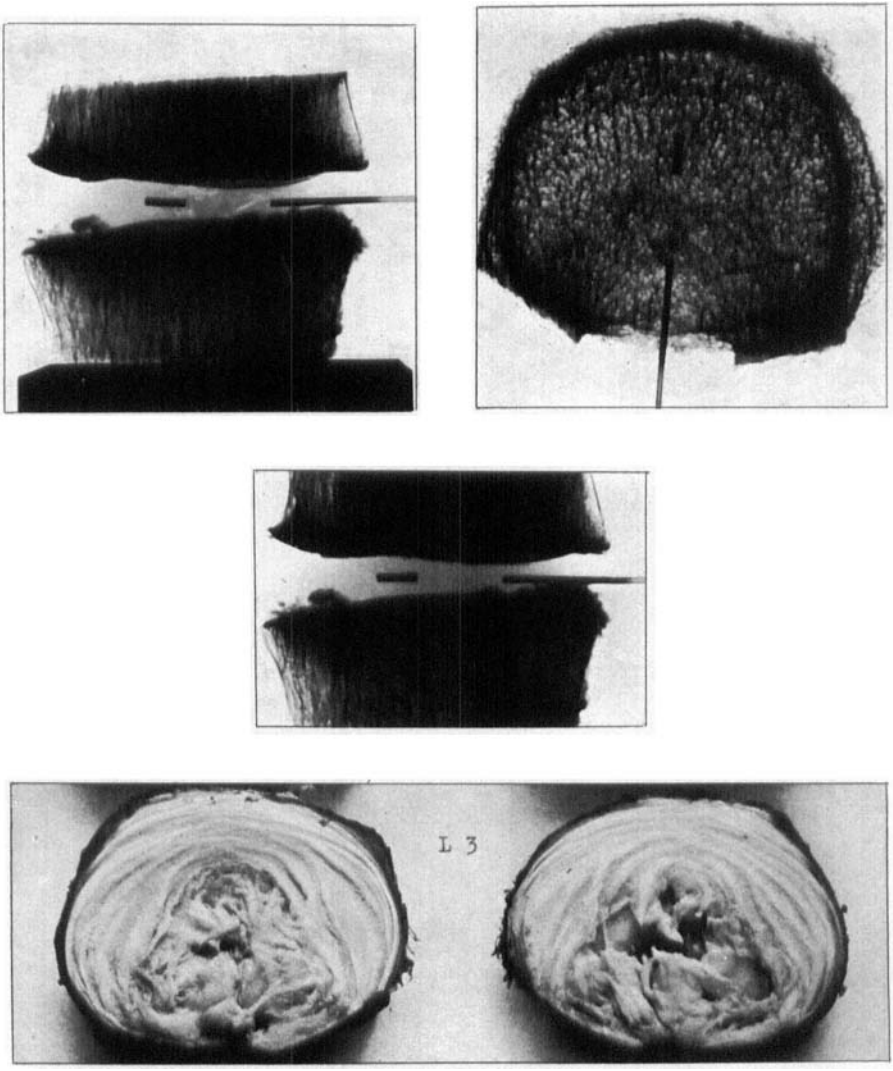


Fig. 7.
Roentgen plates and macroscopic appearance of a degenerated disc.
The corresponding results are shown in table 3.

Statham type modified by KIFA-Elema and built on the strain-gauge principle. The sensitive element is of the variable resistance type and consists of 4 strain threads. The threads will increase in electrical resistance by elongation, while the resistance will decrease by shortening. The threads form a Wheatstone bridge to which the membrane of the

transducer is mechanically coupled. The pressure chamber of the transducer is made of transparent plastic material through which any air bubbles remaining after filling can be discovered immediately. The transducer is connected to an amplifier from which direct readings can be made. The measured values were recorded with a direct-writing Jet Recorder (mingograph) which impells an extremely fine jet of liquid at high speed at a rotating paper from a fine nozzle fixed to the galvanometer suspension system.

TABLE 2

Calibration of catheter used in specimen 252/L2. Fig. 5.

Pressure kp/cm²	Recorded mm Hg			
	1.	2.	3.	$\bar{m}$
2	2.4	2.6	2.3	2.4
4	5.1	5.0	5.0	5.0
6	7.5	7.4	7.2	7.4
8	10.5	10.5	10.5	10.5
10	13.4	13.4	13.4	13.4
12	16.1	16.0	16.1	16.1
14	19.1	19.3	19.1	19.2
16	21.5	21.5	22.0	21.7
18	25.0	25.4	25.5	25.3
20	29.1	29.0	29.0	29.0
22	33.3	33.5	33.0	33.3
24			38.5	38.5
26			47.0	47.0

TABLE 3

Results obtained from specimen 296/L3. Surface area 25.3 cm². Fig. 7.

Load kp	Recorded pressure mm Hg		
	1.	2.	$\bar{m}$
40	0.7	0.5	0.6
80	0.9	1.0	1.0
125	1.4	1.5	1.5
175	2.0	2.0	2.0
220	2.9	2.7	2.8

Load kp	Calibrated intradiscal pressure kp/cm²	Index
40	1.3	0.82
80	2.2	0.70
125	3.3	0.67
175	4.3	0.64
220	5.8	0.67
		$\bar{m}$ *0.70*

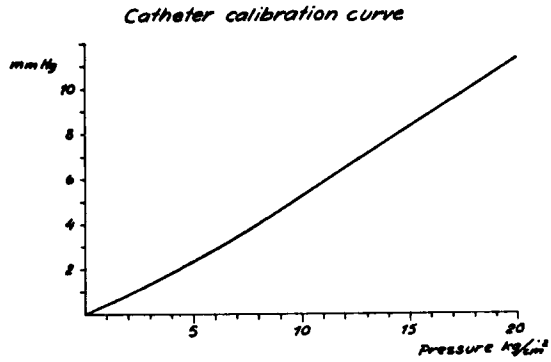


Fig. 8.
Calibration results from the plastic catheter used in experiments on the disc shown in fig. 7.

For a clear picture of the intradiscal pressure as well as for comparison of the results obtained with different specimens, careful consideration of the area of the disc is a prerequisite. After cross-sectioning of the discs the area was determined with an Amsler planimeter (Fig. 4).

RESULTS

Experiments were made on 37 discs from 13 lumbar spines. The specimens were divided into normal and degenerated discs. The latter category included all specimens showing annulus ruptures on macroscopic examination. Diagram 1 shows the distribution of the examined specimens with regard to level in the lumbar spine and macroscopic appearance.

TABLE 4
Calibration of catheter used in specimen 296/L3. Fig. 7.

Pressure kp/cm²	Recorded mm Hg		
	1.	2.	$\bar{m}$
2	0.9	0.9	0.9
4	1.9	1.9	1.9
6	2.8	2.8	2.8
8	3.9	3.9	3.9
10	5.2	5.2	5.2
12	6.3	6.4	6.4
14	7.6	7.5	7.6
16	8.7	8.5	8.6
18	10.0	10.2	10.1
20	11.4		11.4

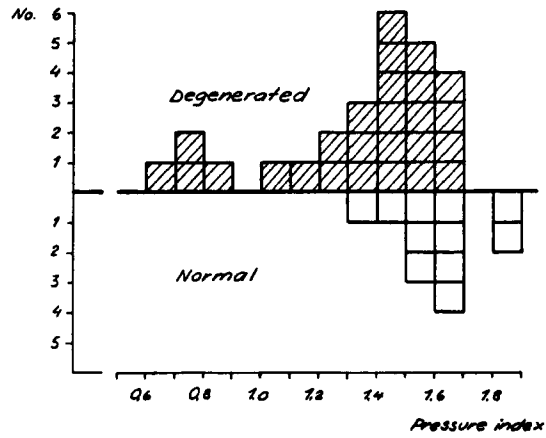


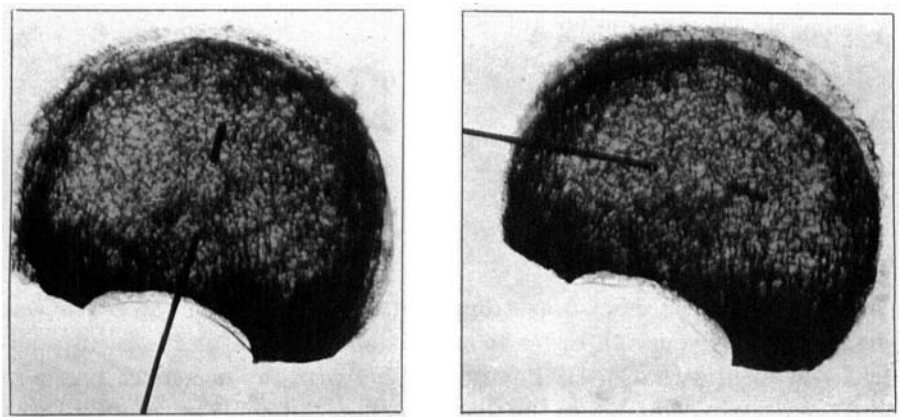
Diagram 2.

Distribution of pressure indices in normal and degenerated discs. Each square represents one disc.

TABLE 5

Pressure indices tabulated by interspace and state of discs.

	Normal	Degenerated
L 1	1.6	1.5
L 2	1.7	1.4
L 3	1.5	1.3
L 4	1.7	1.2



A B

Fig. 9.

Position of the needle and catheter when inserted A. dorsally, B. laterally.

TABLE 6

Results obtained from specimen 310/L2. Surface area 21.5 cm². The intradiscal pressure was measured from different sides of the disc.

Load kp	Recorded pressure mm Hg	Calibrated intradiscal pressure kp/cm²	Index	
1. *Catheter inserted dorsally.*				
40	2.9	2.7	1.45	
80	5.8	5.4	1.45	
125	8.9	8.2	1.41	
175	12.7	11.6	1.42	
220	16.1	14.5	1.42	
				$\bar{m}$ 1.43
2. *Catheter inserted laterally.*				
40	2.8	2.6	1.40	
80	5.9	5.5	1.48	
125	9.0	8.3	1.43	
175	12.4	11.3	1.39	
220	15.8	14.2	1.39	
				$\bar{m}$ 1.42

TABLE 7

Decrease of pressure index after end plate fracture.

Load kp	Recorded pressure mm Hg	Calibrated intradiscal pressure kp/cm²	Index	
1. *Before fracture.*				
40	2.5	4.0	1.41	
80	5.3	8.0	1.41	
125	8.1	12.2	1.38	
175	11.6	16.6	1.34	
				$\bar{m}$ 1.39
220 – end plate fracture at this load.				
2. *After fracture.*				
40	2.0	3.2	1.13	
80	3.5	5.5	0.96	
125	5.5	8.6	0.97	
175	7.9	12.0	0.97	
				$\bar{m}$ 1.01

The area of the discs was computed. The intradiscal pressure was measured in kp/cm². In order to permit comparison of the results obtained with different discs the quotient between the measured pressure and the pressure applied to the discs was determined. This quotient was called the pressure index. At the same time the calculation supplied a measure of the weightbearing capacity of the nucleus. Tables 1 and 2

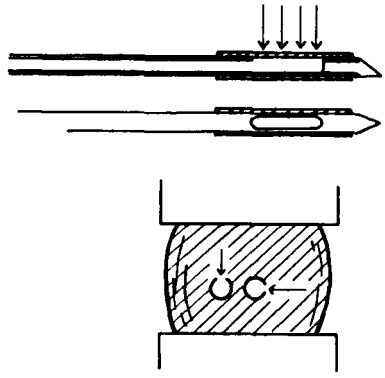


Fig. 10.
Schematic drawing of catheter used for measuring intradiscal pressure in different directions.

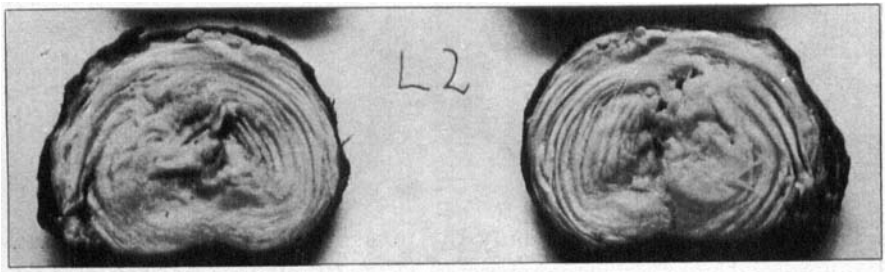


Fig. 11.
Macroscopic appearance of one of the discs in which both horizontal and vertical pressures were measured. The corresponding results are shown in table 8.

and Fig. 6 show how the results were obtained in a normal specimen (Fig. 5). Results in a degenerated specimen are shown in tables 3 and 4 and Figs. 7 and 8. Diagram 2 illustrates the index distribution for normal and degenerated discs. The index averages for normal and degenerated discs at different levels are found in table 5.

In all experiments the pressure-recording catheter was inserted dorsally. Roentgen plates were taken to ensure its accurate position in the nucleus. As a further check on the method three discs were subjected to a second experiment in which the catheter was inserted laterally.

Fig. 9 illustrates the position of the catheter in one of these experiments. The results of these measurements appear to be identical with those of the first experiment, as is illustrated in table 6.

In two cases fracture of the endplates occurred at a load of 220 Kg. Renewed loading of these specimens caused a 30–40 per cent drop of the index (Table 7).

TABLE 8

Results of measuring intradiscal pressure in vertical and horizontal directions with the catheter as shown in fig. 10.

Load kp	Recorded pressure mm Hg			Calibrated intradiscal pressure kp/cm²	Index
	1.	2.	$\bar{m}$		
1. *Catheter opening vertical.*					
40	4.0	4.0	4.0	3.4	1.61
80	10.0	10.0	10.0	6.8	1.61
125	16.6	16.8	16.7	10.2	1.55
175	22.8	23.2	23.0	13.5	1.46
220	29.0	29.6	29.6	16.7	1.44
					$\bar{m}$ *1.53*
2. *Catheter opening horizontal.*					
40	4.6	4.0	4.3	3.6	1.70
80	10.0	9.4	9.7	6.7	1.58
125	15.8	15.8	15.8	9.8	1.48
175	22.0	22.2	22.1	13.0	1.40
220	27.6	28.6	28.1	16.1	1.38
					$\bar{m}$ *1.51*

To allow measurement of only the pressure acting in a given direction a special needle was constructed (Fig. 10). It was used in 4 specimens. The vertical pressure was measured by directing the needle-opening upwards. The needle was then turned 90° and the horizontal pressure was measured. The results from one of these experiments (Fig. 11) are found in table 8.

DISCUSSION

Average intradiscal pressure values are lower for degenerated discs, i.e. discs showing annulus ruptures and gross anatomical nuclear changes, than for normal discs. Discs L1–L4 were tested. The greatest variation in pressure indices between normal and degenerated discs was found at the L4 level. The weightbearing capacity of the nucleus in a normal L4 disc is 50 per cent greater that that of a degenerated disc.

Fracture of the endplate decreases the intradiscal pressure by 30–40 per cent.

The proportional distribution of nucleus and annulus was calculated by planimetry. The nucleus occupies on an average 60 per cent of the cross-sectional area of the disc. A lowering of the index from 1.5 to 1.0 means, therefore, that the strain on the annulus in a degenerated disc is roughly four times that of a normal disc. The relation between the total pressure transmitted by the annulus and that transmitted by the nucleus may be calculated for various indices and different surface areas of the nucleus, according to the following formula:

P = force applied to whole disc
P_n = force transmitted by nucleus
P_a = force transmitted by annulus
A_d = disc area
A_n = nucleus area
A_a = annulus area

$$\text{Index} = I = \frac{P_n}{P/A_d} =$$

$$\frac{P_n}{P_n \frac{A_n}{A_d} + P_a \frac{A_a}{A_d}} = \frac{1}{\frac{A_n}{A_d} + \frac{P_a}{P_n} \frac{A_a}{A_d}}$$

since $P = P_n A_n + P_a A_a$

$$\therefore I = \frac{1}{\frac{A_n}{A_d} + \left(1 - \frac{A_n}{A_d}\right) \frac{P_a}{P_n}}$$

$$\frac{A_n}{A_d} + \left(1 - \frac{A_n}{A_d}\right) \frac{P_a}{P_n} = \frac{1}{I}$$

$$\left(1 - \frac{A_n}{A_d}\right) \frac{P_a}{P_n} = \frac{1}{I} - \frac{A_n}{A_d}$$

$$\frac{P_a}{P_n} = \frac{1 - \frac{A_n}{A_d} I}{I\left(1 - \frac{A_n}{A_d}\right)}$$

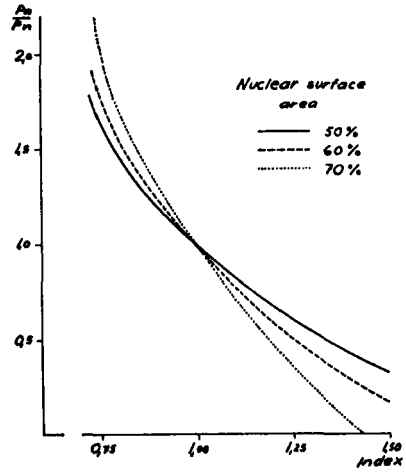


Fig. 12.

The relation between the total force transmitted by the annulus (p_a) and that transmitted by the nucleus (p_n) for various pressure indices and different nuclear surface areas. The curves are calculated from the formula given in the text.—With decreasing pressure index the ratio p_a/p_n increases. The stress taken up by the annulus increases.—The relation between the nuclear and annular surface areas may affect the stress-distribution.

SUMMARY

1. Experimental devices are presented through which it is possible to study intradiscal pressure.
2. Specimens from the first to fourth lumbar interspace have been tested and results from 11 normal and 26 degenerated discs are presented.
3. Under vertical load the intradiscal pressure is lower in degenerated discs than in normal.
4. When the nucleus loses part of its weightbearing capacity because of degenerative changes, the annulus will suffer from an increased pressure.
5. This increase of stress on the annulus in a degenerated disc can be calculated with the method described. In experiments on the fourth lumbar disc the annulus had to take four times as much pressure in a degenerated disc as in a normal disc.
6. A fractured vertebral end-plate seems to bring about a two to three times greater stress on the annulus in a disc subjected to vertical load.

RESUME

1. Des méthodes expérimentales grâce auxquelles il est possible d'étudier les pressions intradiscales sont présentées.
2. Des spécimens des ménisques entre les 1ère et 4ème vertèbres lombaires ont été examinés et les résultats obtenus pour 11 disques normaux et 26 dégénérés sont présentés.
3. Sous une charge verticale, la pression intradiscale est plus faible dans les disques dégénérés que dans les disques normaux.
4. Lorsque le nucleus perd une partie de sa capacité portative c'est en raison des altérations dégénératives, l'annulus souffrant sous une pression accrue.
5. L'augmentation de l'effort de l'annulus dans un disque dégénéré peut être calculé au moyen de la méthode décrite. Les essais pratiqués ont montré que l'annulus du 4ème disque lombaire doit supporter une pression quatre fois plus élevée lorsque le disque est dégénéré que lorsqu'il est normal.
6. Une fracture de la plaque terminale paraît exiger de l'annulus d'un disque soumis à une charge verticale un effort deux à trois fois supérieur.

ZUSAMMENFASSUNG

1. Experimentelle Vorrichtungen werden gezeigt, mittels welcher es möglich ist den Druck innerhalb der Zwischenwirbelscheiben zu studieren.
2. Scheiben vom ersten bis zum vierten Lendenzwischenraum wurden geprüft und die Ergebnisse von 11 normalen und 26 degenerierten Zwischenwirbelscheiben werden mitgeteilt.
3. Während vertikaler Belastung ist der intradiskale Druck in degenerierten Scheiben niedriger als in normalen.
4. Wenn der Nucleus einen Teil seiner gewichtstragenden Fähigkeit wegen degenerativer Veränderungen verliert, dann wird der Annulus bei zunehmenden Druck { chädigt werden.
5. Diese Zunahme der Beanspruchung des Annulus in einer degenerierten Scheibe kann mittels der beschriebenen Methode bestimmt werden. In Versuchen an der vierten Lendenscheibe musste der Annulus das Vierfache an Druck in einer degenerierten als in einer normalen Scheibe auf sich nehmen.
6. Eine gebrochene Wirbelendplatte scheint eine ungefähr zwei bis dreimal so grosse Beanspruchung auf den Annulus einer Scheibe, die vertikaler Belastung unterworfen wird, zu übertragen.

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