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ALF NACHEMSON

Lumbar Intradiscal Pressure

Experimental studies on post-mortem material

EJNAR MUNKSGAARD · COPENHAGEN 1960

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To my parents

and my wife

Contents

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Uppsala, March 1960.

Alf Nachemson.

CHAPTER 1

Historical introduction

The patho-physiological background of low-back pain has been discussed in the orthopaedic literature for the past 30 years. The problem has been reviewed partly in terms of morphological changes in the intervertebral discs,[1] partly as a possible sequel to a pathological state in the intervertebral joints,[2] the ligaments,[3] and the neuro-muscular system.[4]

Since a prolapsed disc could be shown to be the cause of sciatica in the large majority of cases,[5] and because the patient with sciatica usually has low-back pain as a preliminary stage, many have considered the intervertebral disc to be the cause of low-back pain.[6] The extensive research on intervertebral discs has now clearly defined the structural, roentgenographic, and chemical changes which occur.[7]

At the present time, the prevailing opinion is that morphological disturbances in the intervertebral disc are the underlying cause of low-back pain.[8] It has not,

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[1] Schmorl 1927, Andrae 1929, Keyes and Compere 1932, Barr 1937, Saunders and Inman 1940, Coventry, Ghormley and Kernohan 1945, Friberg and Hirsch 1949, Lindblom 1951, Hansen 1952, Hirsch and Schajowicz 1952, Schmorl and Junghanns 1953, Hirsch 1959, and others.

[2] Ghormley 1933, Badgley 1941, Cyriax 1945, Güntz 1956, and others.

[3] Walsh 1939, Headley 1939, Malmros 1942, Lindblom 1951, Junghanns 1951, Spurling 1953, Schönbauer and Allmer 1957, and others.

[4] Jung and Brunschwig 1932, Roofe 1940, Heyman 1941, Hirsch 1948, Wiberg 1949, Lindahl and Rexed 1950, Charnley 1951, Smyth and Right 1958, and others.

[5] Mixter and Barr 1934, Deucher and Love 1939, Eckert and Decker 1947, and others.

[6] Charnley 1945, 1952, Waris 1948, Naylor and Smare 1951, Hult 1954, Hendry 1958, Leikkonen 1959.

[7] Structural studies: Schmorl 1927, Böhmig 1929, Keyes and Compere 1932, Güntz 1941, Coventry, Ghormley and Kernohan 1945, Bradford and Spurling 1947, Sylvén 1950, Lindblom and Hultquist 1950, Hansen 1952, Hirsch and Schajowicz 1952, Peacock 1952, Happey, Mac Rae and Naylor 1953. Chemical studies: Püschel 1930, Paulsson, Sylvén, Hirsch and Snellman 1951, Sylvén, Paulsson, Hirsch and Snellman 1951, Hirsch, Paulsson, Sylvén and Snellman 1952, Ott 1954, Happey, Horton, Mac Rae and Naylor 1955, Naylor, Happey and Mac Rae 1955, Hall, Lloyd, Happey, Horton and Naylor 1957, Bernardi, Happey and Naylor 1957, Gardell 1957, Gardell and Hansen 1959, Hallén 1958. Roentgenographic studies: Schmorl 1927, Calvé and Galland 1930, Love 1939, Bromer 1939, Knutsson 1942, 1944, 1957, Friberg and Hirsch 1949, Hagelstam 1949, Hult 1954, Söderberg and Andrén 1955, Fernström 1957, Schalimtzek 1958, Griffiths 1958.

[8] Keyes and Compere 1932, Joplin 1935, Headley 1939, Coventry, Ghormley and Kernohan 1945, Bradford and Spurling 1947, Steindler 1947, Inman and Saunders 1947, Hirsch 1950, Junghanns 1951, Cloward and Buzaid 1952, Schmorl and Junghanns 1953, Spurling 1953, Perey 1957, and others.

however, been possible to define exactly in which way structural changes disturb the function of the intervertebral disc so that clinical symptoms appear. The mechanism of production of low-back pain is still unknown.

Many have tried, either theoretically or experimentally, to ascertain which mechanical disturbances arise as a result of structural changes in the disc.[9]

Stated in very simple terms, it was thought that when the nucleus pulposus underwent degenerative changes with consequent ruptures in the annulus fibrosus, the stability of the disc lessened. This would result in the disc being more easily deformed, thus producing a greater or lesser intermittent pressure on the adjoining nervous structures, in particular on the longitudinal ligaments and nerve roots.

Attempts have also been made to measure the degree of instability as well as to record the deformation of the disc under various mechanical strains.[10] The information obtained in this way has not given a clear picture of the mechanical conditions. Seen against the background of known morphological data, the mechanical argument has provided inadequate support for the acceptance of a purely mechanical concept of the causation of low-back pain and sciatica.

As the disc consists of different parts and the experiments so far performed have only aimed at studying the behaviour of the more superficial elements, it was thought worthwhile to elucidate the mechanical conditions inside the intervertebral discs.

There has been much discussion about pressure disturbances inside the intervertebral disc, resulting from abnormal structural conditions, but this controversy has lacked information about the real pressures and their variations in different degrees of degeneration.[11]

The purpose of the investigation

The author, in the present work, set out to introduce a method for measuring intradiscal pressure and to record in post-mortem specimens the pressures in

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[9] Fick 1904, Strasser 1908, Keyes and Compere 1932, Joplin 1935, Friberg 1941, Barr and Mixter 1941, Severin 1943, Robberts 1944, Knutsson 1944, Coventry, Ghormley and Kernohan 1945, Key and Ford 1948, Hagelstam 1949, Hansen 1950, 1956, Junghanns 1951, Lindblom 1951, 1957, Virgin 1951, 1958, Ingelmark and Ekholm 1952, Charnley 1952, Lindemann and Kuhlendahl 1953, Hirsch and Nachemson 1954, Hansen and Olsson 1954, Hirsch 1955, 1956, 1959, Perey 1957, Roaf 1958, Naylor 1958, Hendry 1958, Putschar 1959, Hansen 1959, Nachemson 1959, and others.

[10] Göcke 1931, 1932, Knutsson 1944, Friberg 1947, Hagelstam 1949, Virgin 1951, 1958, Ingelmark and Ekholm 1952, Hirsch and Nachemson 1954, Hansen and Olsson 1954, 1958, Hirsch 1955, Evans 1957, Bartelink 1957, Brown, Hansen and Yorra 1957, Hardy, Lissner, Webster and Gurdjian 1958, Decoulx and Rieunau 1958, Evans and Lissner 1959.

[11] Petter 1933, Malmros 1942, Lindblom 1947, Hirsch 1948, Unander-Scharin 1950, Naylor and Smare 1951, Charnley 1952, 1958, Krayenbühl and Zander 1953, Ott 1954, Naylor and Horton 1955, Brush, Horton, Smare and Naylor 1956, Naylor 1958, Hendry 1958, and others.

relation to the age, level of the intervertebral space and degree of structural changes. By studying the way in which the nucleus pulposus distributed pressure, it might be possible to clarify the mechanism by which force is transmitted through the lumbar interspace. In addition, the disturbances in intradiscal pressures occurring after certain forms of spinal fractures have been discussed, as well as the influence of the intervertebral joints on the pressure in the nucleus pulposus.

CHAPTER 2

Earlier measurements of the reaction to compression of lumbar vertebrae and discs

Rauber (1876), Messerer (1880), Lange (1902), Göcke (1931), and Perey (1957) have measured the compressive strength in the bodies of the lumbar vertebrae. In the experiments of these authors the fracture load was between 300 and 700 kp[1] for lumbar vertebrae. The compressive strength decreases with increase in age (Perey 1957). Furthermore, it has been possible to establish that the vertebral body has a certain elasticity (Rauber 1876, Messerer 1880, Göcke 1931, Perey 1957). Rauber has also shown that the modulus of elasticity for the femoral diaphysis varies with the temperature and the amount of moisture in the bone. Messerer found no great difference between living and dead bony tissue with static loading.

In compression experiments on sections of the lumbar spine, it has been established that the strength of the intervertebral disc is greater than that of the vertebral body. On compression of the intervertebral discs with adjacent slices of bone, the fracture begins most often at the bony endplate, which is the weakest part of the system (Perey 1957, Brown, Hansen and Yorra 1957, Decoulx and Rieunau 1958, Hardy, Lissner, Webster and Gurdjian 1958). Table 1 shows the results of the various authors. Certain authors (Bradford and Spurling 1947, Hoag and Rosenberg 1953, Mattiash 1956, Perey 1957) have tried to estimate the loading of the lower lumbar discs on standing or when lifting objects in the stooping position. The figures given by these authors are all considerably higher than the fracture loads established experimentally.

Göcke (1932) and Virgin (1951) in experiments on the lumbar intervertebral discs have shown that they possess elastic properties and that these properties are retained even in later life (Virgin 1958). The latter author also showed that the capacity for recovery in a disc with degenerative changes of the nucleus, was at

[1] A kilopond (kp) is defined as the force that gives a mass of 1 kg an acceleration of 9.80665 $m/sec.^2$

Since acceleration due to gravity varies only between 9.78 and 9.83 $m/sec.^2$, the value for the gravity force in kiloponds may be regarded, for practical purposes, as equivalent to that for the mass in kilograms. In British and American writings, force is sometimes given in kilograms or pounds. Regardless of the system employed, the comparative figure for kilograms and kiloponds will nevertheless be, in practical use, 1.0.

TABLE 1.

Fracture load for lumbar spine specimens.

The values are widely scattered in the series of the different authors.

Author	Preparation	Number of specimens tested	Fracture load, mean value
Bartelink 1957	One disc + parts of adj.vert.	10	320 kp
Evans 1957	One disc + parts of adj.vert.	96	390 kp
Perey 1957	One disc + parts of adj.vert.	40	560 kp
Brown-Hansen-Yorra 1957	One disc + parts of adj.vert.	5	550 kp
Decoulx-Rieunau 1958	Two discs + 3 adj. vert.	9	700 kp
Evans-Lissner 1959	Pelvis + 5 lumb.vert. and intervert.discs	7 3	400 kp (embalmed) 250 kp (fresh)

least as good as when the nucleus was intact. Ingelmark and Ekholm (1952) and Hirsch and Nachemson (1954) have compressed single lumbar discs and adjacent bone, and were able to establish that healthy discs are somewhat less compressible than degenerated ones. The values given by Hirsch and Nachemson agree well with those of Fessler (cited by Fick) described during the last century. Hirsch and Nachemson (1954) also measured the dorsal and ventral expansion and found that a healthy L 4-disc expands about 30% less than one which has degenerated. The authors were unable, on vertical loading, to find that the removal of posterior bony elements had any great effect on the ability of the disc to tolerate vertical mechanical forces. They also studied the effects of dynamic forces on the discs and found that very small and fast acting forces could increase the deformation of the disc to a very great extent. By using the results on lateral expansion obtained by Hirsch and Nachemson, Horton in 1958 was able to show that the increase in the angle between the axis of the collagen fibrils of the annulus fibrosus is probably associated with the elasticity of the disc. A change of only 1° between adjacent sheets of the annulus fibrosus should give the necessary increase in radius. He was also able to show that the properties of the annulus in this respect did not change with age. His findings were partly based on the observations made in 1954 by Naylor, Happey and Mac Rae. These authors suggested from their roentgen-crystallographic studies that the elasticity of the disc was due to the change in orientation of the sheets of the annulus fibrosus. Horton (1958) observed that this property did not change greatly with age.

CHAPTER 3 Earlier experiments on the pressure of the nucleus pulposus

Fick (1904) noticed that the nucleus pulposus was able to swell to two hundred times its size, and Göcke (1932) observed that absorption of fluid occurred to a considerably greater extent in discs from young people than in those from old. It has been shown that the water content of the nucleus pulposus diminishes with increasing age (Püschel 1930, Keyes and Compere 1932 and Hirsch, Paulsson, Sylvén and Snellman 1952). The nucleus pulposus consists of a three-dimensional network of collagen fibrils enmeshed in a mucoprotein gel which contains various mucopolysaccharides (Sylvén 1950, Hirsch, Paulsson, Sylvén and Snellman 1952, Bernardi, Happey and Naylor 1957). The nucleus pulposus has been regarded as an osmotic system capable of varying both its water content and the inner pressure (Keyes and Compere 1932, Naylor and Smare 1951, Charnley 1952, 1955).

Attempts have been made to explain the diurnal variations in length of the spine with a similar mechanism (Keyes and Compere 1932, de Puky 1935).

Fick (1904), as well as later authors, e.g. Schmorl (1927), Calvé and Galland (1930), Petter (1933) and Junghanns (1951) claimed that the nucleus pulposus possessed an inner pressure or "turgor" of its own. This would explain why the nucleus protrudes when a disc is sectioned in a vertical direction. It is furthermore known that if one separates the entire column of the posterior bony elements from the entire column of the vertebral bodies, the former at once will shrink (Fick 1904, Malmros 1942). The ligamentous tension which produces this shrinking causes the disc to be under a certain amount of pressure even when unloaded (Steindler 1955).

Harris and Mac Nab (1954) stated on the basis of their experimental investigation that the observation that the nucleus pulposus does not protrude when an intervertebral disc is divided horizontally, suggested that the protrusion seen in vertical division may in part be due to the unopposed contraction of the remaining annulus fibrosus. This opinion is shared by other authors (Roberts 1944, Spurling 1953, Lindemann and Kuhlendahl 1953, Kelly 1958).

Naylor and Smare (1951) published results of intradiscal pressure measurement on lumbar spines made with a Bourdon gauge pressure indicator to which pressure was transmitted via an open needle filled with mercury. Human lumbar discs were measured after immersion in distilled water. Most discs developed a pressure of 2–3 kp/cm^2 after 48 hours in water. According to these authors the pressure in the nucleus could be influenced by:

1. The amount of the 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.

They found a tendency to lower pressure with increasing age. Regardless of age and degree of degeneration they found no pressure in 30% of their discs, a phenomenon which they explained by the probable presence of cavities in the nucleus.

Charnley (1952) and Ott (1954) have exposed nuclear fragments to isotonic saline solution and noticed that they were able to swell and generate pressure. Hendry (1958) has established that a degenerated lumbar disc retains less fluid than a normal one. He claims that the isolated observation that the nucleus pulposus increases in weight or builds up pressure in contact with saline or water indicates only that it was originally less than fully hydrated. It provides no information on the actual capacity of imbibition of the nucleus and is no basis for the comparison of one nucleus with another. He tried to measure the imbibition pressure through an open needle in the nucleus, but failed. He concluded that with increasing age the nucleus pulposus loses the ability to retain its water content under conditions of stress. Furthermore he proved that what Charnley and Naylor *et al.* believed to be hyperhydration actually is an "undue susceptibility to changes in the environment".

CHAPTER 4

Development of a method for intradiscal pressure measurements

In this work the word pressure is used for the excess-pressure, i.e. the absolute pressure minus the atmospheric pressure.

Available methods for measuring pressure in the human subject

1. *Different types of gauges for measuring pressure*

Measurements can be made using open or closed systems. Among the *open* systems, mention can be made of the purely mechanical one used by, e.g. Carldeyro, Alvarez and Reynolds 1950, who measured the intra-uterine pressures with an ordinary mercury manometer and a needle directly inserted into the uterus. Naylor and Smare (1951) used a Bourdon gauge pressure indicator to measure the pressure inside the disc. Liévre and Boaro (1958), using a water manometer, measured the epidural negative pressure in normal subjects and in patients operated for herniated discs, without succeeding in showing any practical, clinical differences.

Among the types of *closed* gauges, suitable for pressure measurement in biological material, mention can be made of the so-called membrane gauges, which according to the pressure, produce a movement, mechanically, which is later recorded. Another type consists of piezo-electrical crystals, whose use is however limited by the difficulty in obtaining a leakage resistance sufficiently large for static measurements. In dynamic experiments they have been used by Sjövall (1943) who studied brain injuries after trauma.

Because of the unreliability of the piezo-electric gauges in static experiments, one of the membrane type was considered to be more suitable for the purpose of this investigation.

2. *Different methods of recording*

Membrane movements can be recorded by mechanical, optical, electrical or combined methods.

A. The *mechanical recording* is suitable only for the open systems, since the movements obtained with the closed systems are too small to make accurate recording possible.

B. *Optical system.* Hamilton's (1934) membrane manometer is an example of a purely optical system, used mainly in research on the circulation (Werkö 1947). A variant of this is the optico-electrical manometer, where the light is recorded electrically.

C. *Electrical system.* The electrical systems are based on the principle that mechanical movements or pressures from the organ in question are transformed into electrical quantities, which can be transferred to a suitable recorder. Transformation of the membrane movements into electrical quantities can be made according to the following principles:

(*a*) *Change in resistance.* One type of instrument is based on the change of resistance occurring in an electrolytic solution when the length or the cross-sectional area of the path of the current is changed. In this kind of instrument the part sensitive to pressure is placed at one end of a rod which is inserted into the organism. Gurdjian and Lissner (1944) have measured the intracranial pressure with "pressure plugs" built on this principle. An increase in intracranial pressure in the vicinity of these pressure plugs decreases the electrical resistance in the cerebrospinal fluid between two platinum electrodes placed in these plugs through the skull.

The strain gauge system, where the strain-sensitive parts consist of a wire system of a special metal alloy, is built on the same principle, viz. a change in resistance with change in length. Thus strains obtained by small mechanical movements can be transformed into a change of electric resistance. This principle is probably the one most commonly used at the present time. Bloomenthal, Olsen and Necheles (1952) and Stein, Morgan and Reynolds (1957) have measured the pressure in the bone marrow of dogs, while Dahlström (1959) with a differential manometer based on the same principle studied the mechanics of breathing. Embrey (1955) has measured the uterine pressure, as have Ingelman–Sundberg, Lindgren and Ljungström (1953) and Lindgren (1955) who were especially interested in the first stage of labour. This electromanometer, however, has been used mainly in conjunction with measurements of pressure in connection with catheterisation of the heart (Holmgren 1956).

(*b*) *Change of inductance.* This method is based on the fact that changes in a magnetic field containing an iron core induce a current. A change in pressure which displaces the iron core produces a change in the continuous current through the coil. Wetterer's (1943) instrument can be mentioned as an example of these inductance manometers. They cannot be used for static measurements.

(*c*) *Other electro-magnetic principles* such as the Thomson effect, i.e. changes of resistance in a magnetic field of bismuth and similar substances, are possible but less often used manometric methods.

(*d*) *Change in capacitance.* The capacitance between two electric condensor plates changes in inverse proportion to their relative distance. If one of them consists of an electric membrane which is affected by pressure, it is possible to transform pressure into electrical voltage. The principles of such a manometer have been fully developed by Hansen and Warburg (1949, 1950) in Denmark.

Preliminary experiments

For practical reasons the author chose to use a manometer built on the strain-gauge principle (Kifa-Elema electromanometer), which has a comparatively high degree of accuracy. During the experiments it has been found suitable for measuring the pressures in question. However, the design of the gauge had to be changed during the course of the experiments.

Since it has been previously generally accepted that the pressures in the nucleus pulposus behave hydrostatically, no attempt was made in the beginning to verify this postulate.

In the first series of experiments consisting of 10 discs, a needle was inserted into the nucleus and connected to the electromanometer by a piece of plastic tubing. The system was filled with water. The discs were exposed to repeated vertical loads in a compression apparatus. The results of pressures obtained in the nucleus were extremely varied and irregular, and appeared to depend partly on the nucleus imbibing some of the water from the pressure recording system, and partly on a blockage of the needle by fragments of nucleus which impeded pressure measurement. To avoid the former error, glycerine was substituted for water in the manometer system. In 21 lumbar discs from 10 backs the pressure was then measured in a loaded disc after a little glycerine had been injected. Variable and non-reproduceable results were also obtained by this method. Leakage of glycerine through annulus ruptures was seen in some specimens. The plastic catheter connecting the needle to the pressure transducer was in some specimens seen to contain

TABLE 2.

This table shows that the measurements can be reproduced.

Load kp	30	60	90	120	150	180
			Scale units			
Experiment 1	5	12	22	33	48	66
Experiment 2	6	12	22	33	47	65
Experiment 3	6	13	22	33	46	65
Experiment 4	6	13	22	33	47	65

TABLE 3.

Increase in intradiscal pressure on static loading (150 kp) per unit of time.

Values recorded on the Mingograph-paper moving at 25 mm/sec. The duration of load application was not evaluated. Gauge "PE 60". Amplification 1.

cm	1	2	3	4	5	6	7	8	9	10	12	14	16
sec.	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.2	3.6	4.0	4.8	5.6	6.4
Rel. pressure units	7.5	10.8	13.3	15.0	15.8	16.7	17.6	18.3	19.3	19.9	20.8	21.7	22.5

cm	18	22	27	35	40	45	50	55	60	65	70	75
sec.	7.2	8.8	10.8	14.0	16.0	18.0	20.0	22.0	24.0	26.0	28.0	30.0
Rel. pressure units	23.3	24.1	25.0	25.8	26.3	26.3	26.6	26.6	26.6	26.6	26.6	26.6

small fragments of nuclear substance. Thus it was shown that the experimental conditions were not suitable.

The difficulties which developed could be avoided if the nucleus was allowed to act on a membrane, which in its turn transferred the pressure to a receptor, i.e. a closed system. This membrane must be elastic and allow such changes in shape with pressure from the nucleus, that the amount of the displacement is

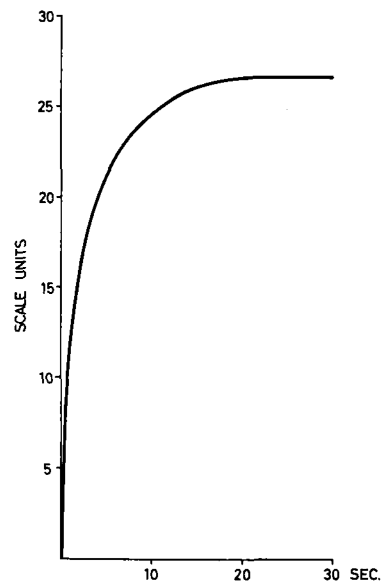


FIG. 1. Curve showing that the intradiscal pressure measured with the "PE 60"-gauge reaches a stable value after a relatively short time. The time needed for applying the load is not considered separately.

measurable with the given pressure transducer. The electromanometer used in this experiment showed a full deflection for a displacement of 0.9 mm^3.

Using discs from calves and 24 human discs from 15 subjects, different kinds of plastic, latex rubber, and thin silver membranes were investigated to see if they satisfied these requirements. In a small area the thickness of the wall of some ordinary needles was reduced to 0.17 mm. The ends of the needles were closed. Even with this arrangement no deflection was obtained. It was, however, established that certain kinds of polyethylene tubing satisfied the desired criteria. A piece of Polyethylene Tubing 60 (Clay–Adams) attached to a Luer–Lok needle was used (Nachemson 1959). Both needle and tubing were filled with distilled water while the end of the tube was plugged with a piece of steel (Fig. 9 p. 29). With this arrangement it was possible to measure the pressure inside the disc, acting at right angles to the surface of the tubing. The needle was inserted into the disc through a graded Record cannula which was then withdrawn. With this device, preliminary experiments were performed on a number of discs. These showed that the measurements were easily reproduceable (Table 2). In less than half a minute, the pressure of the nucleus, measured with this catheter reached a stable value for a given load (Table 3, Fig. 1). The amonut of fluid which is enclosed in the Luer–Lok needle and the receptor head, is very small in comparison with the system used in heart catheterization. This increases the sensitivity of the pressure transducer to temperature. By switching on the apparatus about three hours before the experiment so that it can warm-up and by avoiding temperature changes during the course of the experiment, it was largely possible to avoid the drift that was observed on the amplifier during the first experiments. Even moving the stop-cocks for zero-setting produced temperature disturbances.

By testing two different pieces of "PE 60" on the same disc, with conditions otherwise the same, it was found that the elasticity of the plastic tubing could vary in different sections. Because of this, it was necessary to calibrate every piece of tubing used as a pressure sensitive membrane before the experiments could be begun. For calibration it had to be exposed to a known outer pressure. For this purpose, a special pressure chamber was constructed (Fig. 2). This could be connected to the electromanometer by a specially constructed holder. It was important for the holder not to convey the pressure to the receptor's plastic cover or to its membrane. Calibrations with ink-coloured water in the chamber showed that there did not seem to be any leakage of dye into the water of the pressure receptor system even after repeated loadings (Table 4, Fig. 3).

In order to check the reliability of the calibration further, a completely closed needle was mounted onto the receptor. This needle was of the same dimensions as that on which the plastic catheter was fixed. The needle was placed into the calibration chamber and loaded. The deflections were very small, hardly measurable, as when a soldered Luer–Lok connection alone was tested (1–2 scale divisions

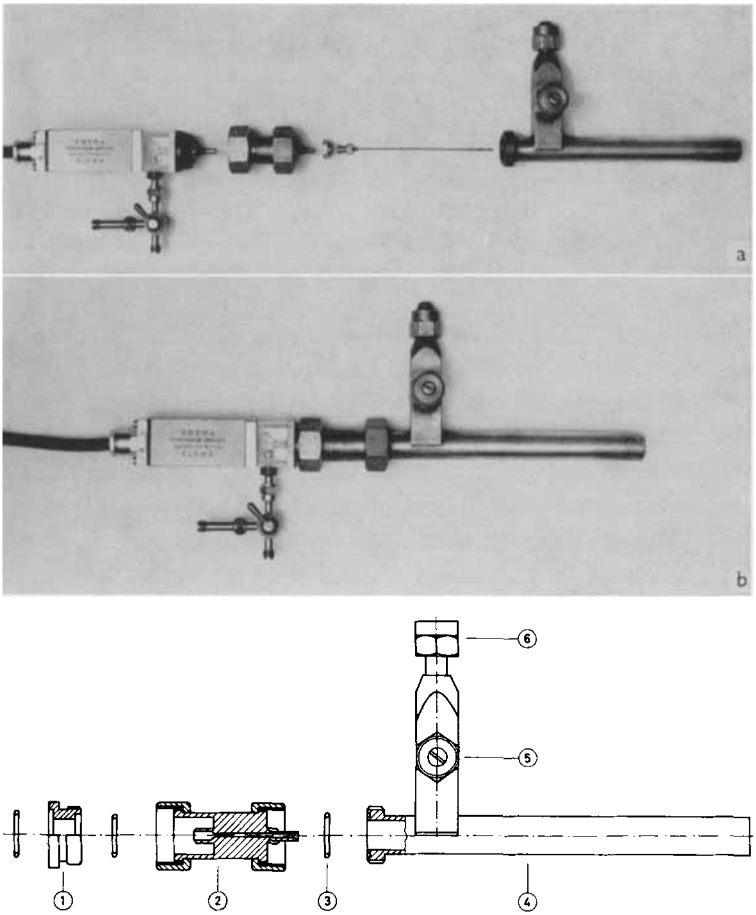


FIG. 2. The pressure transducer and the calibration chamber. a. The constituent parts. b. Assembled. c. Plan of the calibration chamber: *1. attachment to pressure-transducer. 2. intermediate piece with* a female Luer-Lok attachment. 3. washer. 4. the pressure chamber. 5. vacuum valve. 6. attachment to pressure regulator.

for 20 kp/cm^2 load with the strongest amplification). These small deflections probably depend on pressure conveyed directly from the pressure chamber against the receptor via the specially constructed holder, and could thus not be completely avoided.

During these preliminary experiments a certain doubt arose as to whether the nucleus pulposus would behave purely hydrostatically. For example, it was obvious that in severely degenerated discs there was no hydrostatic behaviour. It was therefore considered necessary to find out whether the discs behaved hydrostatically.

The nucleus pulposus has a fluid matrix containing a fibril network of ex-

TABLE 4.

Calibration of the gauge "PE 60".

Pressure kp/cm²		2	4	6	8	10	12	14	16	18	20
Recorded values from		0.9	1.9	2.8	3.9	5.2	6.3	7.6	8.7	10.0	11.4
the Mingograph		0.9	1.9	2.8	3.9	5.2	6.4	7.5	8.5	10.2	
(Scale units)	mean	0.9	1.9	2.8	3.9	5.2	6.4	7.6	8.6	10.1	11.4

ceedingly fine mesh (Schmorl 1927). This matrix is believed to be structurally a collagen-polysaccharide complex and its form is maintained by collagen fibrils emanating from the annulus and the end-plates (Sylvén 1951, Happey, Mac Rae and Naylor 1953).

The conditions necessary for a gauge to be able to measure the compressive stress in a given direction are that the gauge should have a small volume in comparison with the object to be studied, and that the sensitive area of the gauge is large in comparison with possible irregularities in the object. These irregularities can be either inclusions of harder material or lacunae. It has been estimated that these conditions are fulfilled for measurements in all but the most degenerated discs.

In a Luer–Lok needle 115 mm × 1.1 mm in size a hole 4 × 0.5 mm² was made in the side, 7 mm from the soldered tip. Polyethylene tubing "PE 90" was threaded over this and in repeated experiments showed itself to be elastic and to otherwise fulfil the previously specified requirements (p. 19) Table 5, Fig. 4). A needle with the same dimensions, but without a hole, when loaded up to 20 kp/cm² gave a deflection of 2–3 scale units with the highest amplification. This needle without a hole was put into a specimen which was loaded up to 220 kp. On maximum loading a deflection was obtained of 1 scale division with maximum amplifica-

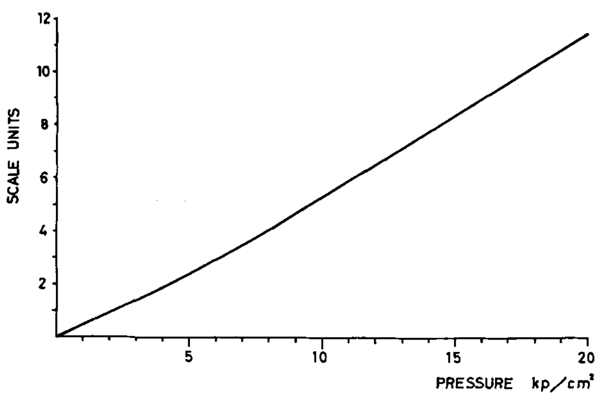


FIG. 3. Gauge calibration curve ("PE 60"). (Table 4.)

TABLE 5.

Calibration of the gauge "PE 90".

Table showing the elasticity of the polyethylene tubing "PE 90" threaded over the Luer-Lok needle 1.1 mm × 115 mm, with a hole 0.5 × 4 mm² in its side. Between the third and fourth calibration 1 hour has elapsed.

Pressure kp/cm²	2	4	6	8	10	12	14	16	18	20	22
Scale units	6	13	19	26	32	38	44	49	54	58	62
	6	12	19	26	32	39	44	49	54	58	63
	6	13	19	26	32	38	44	49	54	58	63
	6	13	19	26	33	39	45	49	54	58	62

tion. This also showed that the rise in temperature of the nucleus by compression is not of such a magnitude that it affected the result of the measurement. If the same needle was bent more than 20° in different directions no deflection was obtained. This check was carried out while the specimen was compressed, during which the pressure-sensitive needle was bent 5–10° downwards. This clearly did not affect the results.

The needle with the membrane was usually inserted 25 mm into the disc. Its diameter was 1.1 mm. Adding the extra volume of the threaded catheter produced a volume of about 30 mm³. Cloward and Buzaid (1952) found in their discograms that the nucleus pulposus had a diameter of 1–2.5 cm and Calvé and Galland (1930) mentioned that the gelatinous mass was irregularly egg-shaped. With a disc-height of 1.5 cm this implies an approximate nucleus pulposus volume of

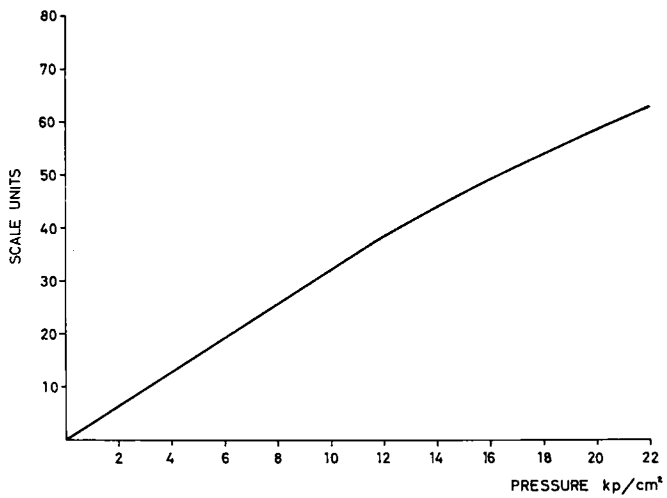


FIG. 4. Gauge calibration curve ("PE 90"). (Table 5.)

1–6.000 mm^3. Thus the volume of the needle used was of the order of 1% of the volume of the nucleus.

During the preliminary experiments with this needle it was found that the limit of elasticity of the tubing "PE 90" was exceeded if it was subjected to excess loads with pressures up to 15 kp/cm^2 or more. When experimenting with catheter "PE 60" it was noted that its elasticity was not the same in all parts. This was also the case with "PE 90". These facts make it necessary to calibrate the piece of plastic used before as well as after each series of measurements. If large differences then appear, the experiment must of course be rejected.

In order to measure the compressive stresses in different directions inside the disc, the needle must be released from its attachment to the pressure transducer, removed from the disc and turned in the required direction. For technical reasons, the position of the pressure transducer cannot be changed. During such a readjustment of the needle, it is possible that a small amount of air was forced into the closed system. It has also been difficult to attach the needle in the same way as previously, i.e. so that one gets the same internal pressure of the water inside the pressure transducer. For this reason a new calibration was carried out before and after every readjustment of the needle. The known outer pressures for which the catheters were calibrated have been 2-4-6-8-10-12-14-16-18-20 and in certain cases 22 kp/cm^2 pressure.

In a number of cases the observed values, on calibration before the intradiscal pressure measurements, have been slightly different from those observed after the experiments. In these cases the calibration curve has been drawn according to the mean of these two observations. The error arising from this procedure has been calculated as being less than 2% (the absolute mean of the % deviations of the first observed values in comparison with the mean between the two observations was for: 4 kp/cm^2: 1.7%, 8 kp/cm^2: 1.5%, and 12 kp/cm^2: 1.5%).

CHAPTER 5

Technique for the measurement of intradiscal pressure

Using the results of the experience gained from the preliminary experiments, equipment for the measurement of intradiscal pressures was assembled (Figs. 5 and 6). Detailed data concerning all the apparatus used in this study are given below.

Experimental Devices

In the investigations the following apparatus has been used.

1. *The compression apparatus* (Fig. 7)

The compression apparatus worked by compressed air. It was made of cast iron with jaws 100 mm in width. The maximum compressive force was 350 kp when the pressure was 7 kp/cm^2. The compressed air came from a cylinder and the pressure entering the compression apparatus was measured with an ordinary gas manometer. An excess pressure of 1–5 kp/cm^2 was used.

2. *The dynamometer* (Fig. 8)

The loads opposing the excess pressure of the compression apparatus were measured with a CEJ dynamometer no. 585.

The relationship of the excess pressure and the load in the compression apparatus can be seen in Table 6. The values of the compression apparatus were checked before and after every series of experiments. The above values were not changed while the series of experiments was in progress.

3. *Manometers for air pressure* (seen in Fig. 7)

Readings of pressures in the compression apparatus were made on a manometer, intended to measure pressures up to 10 kp/cm^2, the diameter of which was 10 cm. The reduced pressure, coming out of the cylinder of compressed air, was

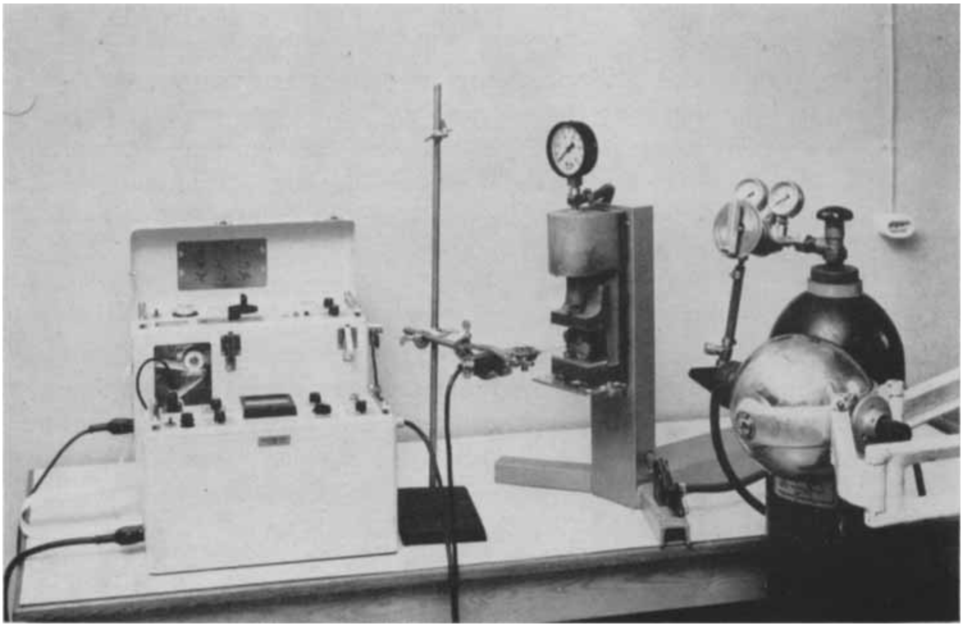


FIG. 5. Close-up view of experimental devices. On the right the compression apparatus, in the middle the pressure transducer and on the left the Mingograph and the amplifier.

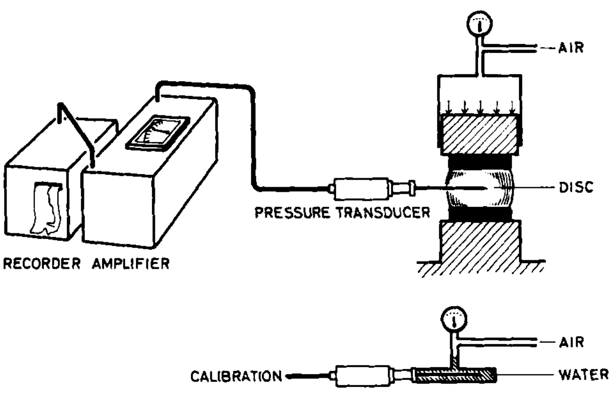


FIG. 6. Schematic drawing of the apparatus in use.

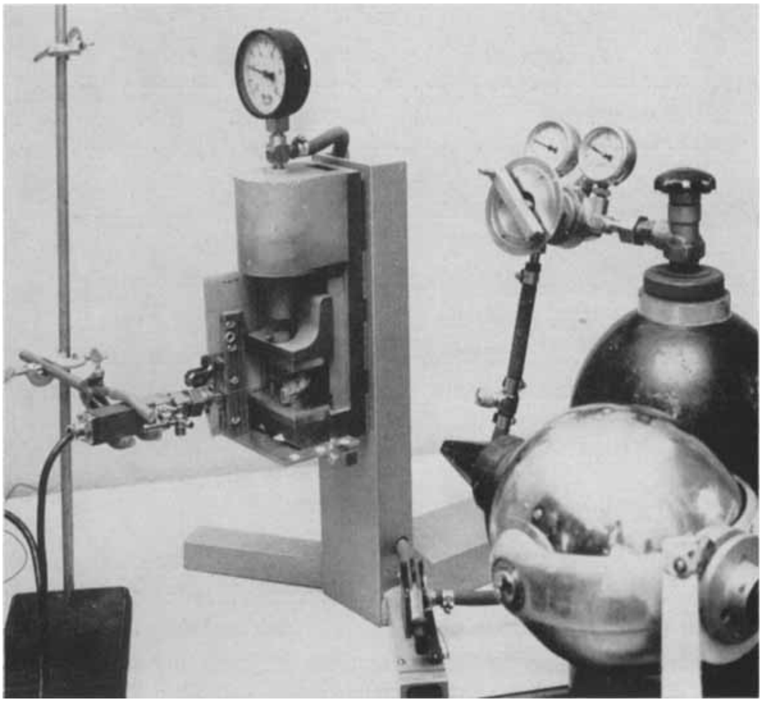


FIG. 7. The compression apparatus in use.

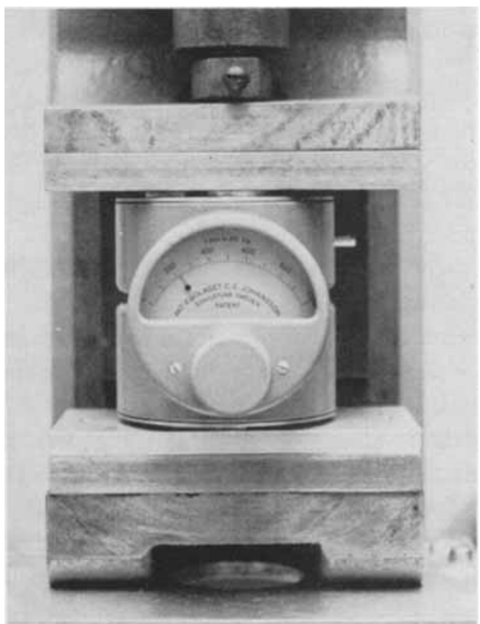


FIG. 8. The CEJ dynamometer in the compression apparatus.

TABLE 6.

Calibration of the compression apparatus.

Pressure kp/cm²	1	2	3	4	5
Load kp	40	85	125	175	220

measured with a manometer, 0–25 kp/cm² in range, and with a scale, the diameter of which was 15 cm. The accuracy of these manometers is given by the makers (Nordisk Armaturfabrik, Nos. 31422–100 and – 150, respectively) as ±1%, between 25 and 75% of the maximum values, and ±1.5%, above and below these limits.

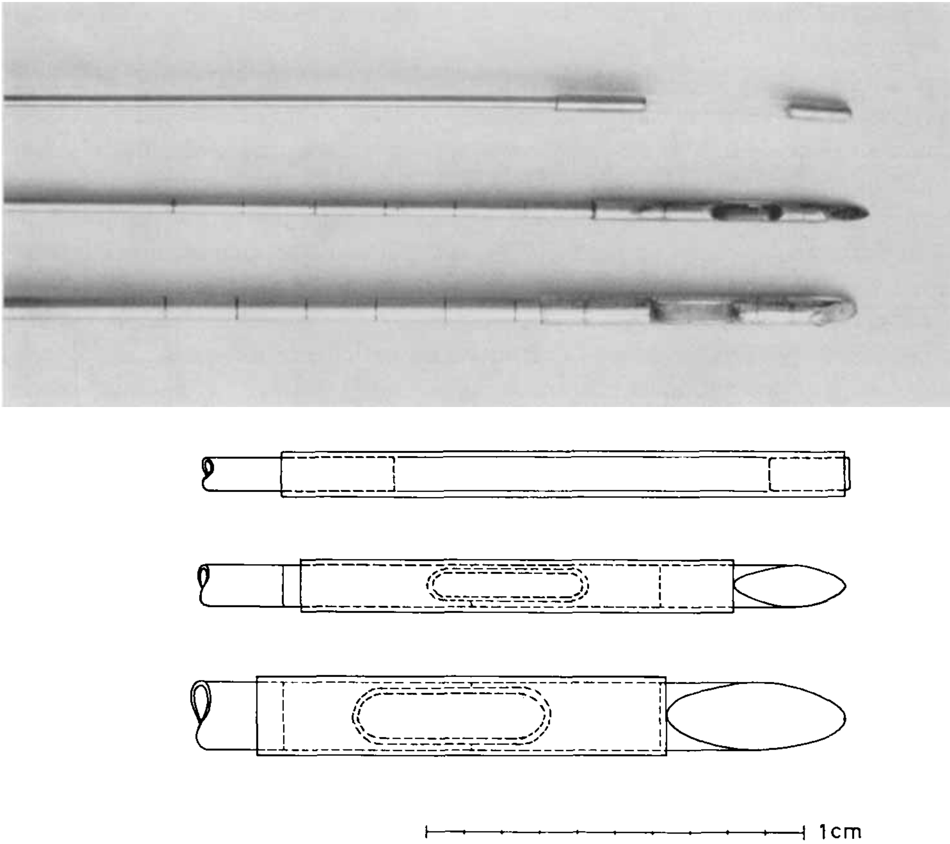
4. *The needles and polyethylene tubing* (Fig. 9)

(*a*) The specially constructed needle with the polyethylene tubing threaded over it, was a Luer–Lok needle, 115 mm long and with an outer diameter of 1.1 mm. It was sealed at the tip. The opening was 4 mm long and 0.5 mm wide. This was a suitable compromise between the desire for a small measuring surface and adequate sensitivity. Polyethylene tubing "PE 90", made by C. Adams, having an inner diameter of 0.86 mm and an outer diameter of 1.27 mm was threaded over its opening. This tubing was threaded on for a distance of about 2 cm, so that a good closure of the opening was obtained both proximally and distally. This was further checked by filling the needle with water, fixing it to a Luer–Lok syringe, and applying a high pressure to check that the system did not leak.

Thus, the polyethylene tubing came to lie over the opening in the needle like a membrane. The substance of the nucleus pulposus exerted its effect on this membrane. The polyethylene used was manufactured by the C. Adams Co., and is known as "Intramedic polyethylene tubing". It has been tested for absence of tissue reaction in animals. It can not be sterilized by boiling or autoclaving, but can be sterilized with special bactericidal solutions.

(*b*) In some specimens, a Luer–Lok needle was used with dimensions of 130 mm × 0.90 mm. The attached polyethylene tubing "PE 60" had an outer diameter of 1.22 mm and an inner diameter of 0.76 mm. The pressures in the nucleus pulposus measured with this gauge were those at right angles to the surface of the catheter.

(*c*) To test the validity of the method a third type of Luer–Lok needle was used. Its dimensions were 100 mm × 1.8 mm. The polyethylene tubing, threaded over its opening of 5 × 1.2 mm², had an inner diameter of 1.40 mm and an outer diameter of 1.90 mm ("PE 200").



a

b

FIG. 9. The different needles and the plastic tubing used in this study. a. Photo. b. Schematic drawing. At the top the "PE 60" needle, in the middle the "PE 90" needle, at the bottom the "PE 200" needle.

5. *The electromanometer* (Fig. 5)

(*a*) The Luer–Lok needle, filled with water, was joined to a mechano-electrical *pressure transducer,* the transparent plastic chamber of which was similarly filled with water. The pressure transducer converted pressure into its electrical equivalent which was then fed to the input of an amplifier. The mechano-electrical transducer was of the Statham type, modified by Svema-Elema, Sweden, and built on the strain-gauge principle, the sensitive element being of the variable resistance type. It consisted of a frame with a movable slide. Four sets of strain sensitive filaments were strung from the frame to the slide in such a way that when the slide was moved longitudinally two sets of filaments elongated and the other two shortened (push-pull arrangement). The change of resistance of a strain-sensitive wire is proportional to the change in length. These four resistances formed a balanced Wheatstone bridge.

The pressure variations in the nucleus were transmitted via the elastic polyethylene membrane to the copper membrane in the pressure head of the transducer. The movements in this membrane were conveyed to the pressure-sensitive elements in the transducer via a linkage pin, which was fastened to the centre of the copper membrane. The bridge was fed by an alternating current with a frequency of 1000 c/s. from a special oscillator. The movements of the membrane were transduced to electrical equivalence by altering the balance of the bridge which caused a current to flow to the input of the amplifier.

(*b*) The *amplifier* unit consisted of the oscillator, a three stage carrier frequency amplifier, a phase discriminator, an output circuit with filters, a cathode-follower output stage and a power supply part. The amplifier was supplied with two gain controls, one for continuous amplification and one for step control for selection of a suitable range. The ranges varied from 10 till 300 mm Hg. It was possible to switch from one range to another without repeating the standardization procedure. The amplifier has a scale, on which the pressure could be read directly.

6. *The Mingograph* (Fig. 5)

The values were recorded continuously with a one-channel jet-recorder of the type *Mingograph 12,* the recording principle of which was that a very fine jet of fluid was ejected at high speed through an extremely fine orifice. This system had certain advantages, e.g. there was no friction between the recording paper and the writing instrument. Consequently, even small changes could be recorded correctly.

Although designed originally for ECG the apparatus was also provided with a D-C input jack for registration of pressures. It had three paper speeds, 10, 25, 50 mm per second, which could be pre-set or changed during operation.

Greater accuracy, however, is obtained by direct readings of the scale on the amplifier. This was partly dependent on the avoidance of the inherent error of the Mingograph and partly on the small width of the paper in comparison with the ink line. Nevertheless, a recording was made in all the experiments.

7. *The calibration chamber* (Fig. 2, p. 21)

The calibration of the different plastic membranes was performed in a specially constructed copper chamber, which was filled with water and attached to the pressure transducer. The Luer–Lok needles could be exposed to known pressures by connecting to the reducing valve of a cylinder of compressed air. By attaching an intermediate piece to the needle attachment of the receptor, the pressure in the chamber could be prevented from influencing the transducer directly.

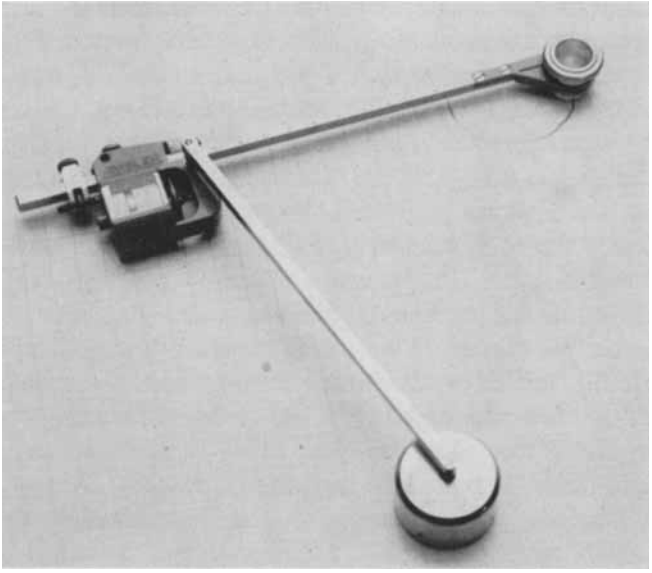


FIG. 10. The planimeter in use.

8. *The planimeter* (Fig 10)

The area of the discs was calculated with an Amsler planimeter. This was a compensation planimeter, i.e. a mechanical integrator, the appearance of which is seen in Fig. 10.

Its ocular was moved round the edges of the surface, so that the roller R turned N times. The area is thus $F = N \times A \times U$, where A is the length of the moving arm and U is the circumference of the roller. The scale of the Amsler planimeter was made in such a way that the area could be directly read in tenths of a cm^2.

Description of the method

In order not to damage the needle and its membrane, the annulus fibrosus was perforated by another needle of the same calibre. Then the pressure-sensitive needle was inserted into the nucleus pulposus to the required depth. It was inserted in the same way every time and its position checked with roentgenograms in two planes. To make assessment of the position of the membrane inside the disc easier, the needle was marked at every fifth millimeter. This made it possible to readjust the needle after turning, so that the membrane was in the same section of the disc.

On the basis of the theories proposed by earlier authors (Fick 1904, Schmorl 1927, Petter 1933 and others) it might be supposed that the nucleus pulposus is under a certain amount of pressure even when the disc is unloaded. Experiments were made to see if an increase in pressure occurred when the gauge was inserted in the nucleus pulposus. The deviations obtained in all cases were so small (1, or at the most, 2 scale units, with the actual amplification) that it was impossible to ascertain whether the deflection was due to a disturbance of the position of the plastic tubing on the needle when piercing the annulus fibrosus, or was due to any 'inherent' pressure of the nucleus pulposus. The experiments consequently led to the conclusion that any 'inherent' pressure in the nucleus pulposus was so small that it might be neglected in the continued experiments. The small scale deflection obtained could, to some extent, also be ascribed to a slight disturbance of the polyethylene tubing when the Luer–Lok needle pierced the annulus fibrosus. In all cases of pressure measurement inside the loaded disc, the readings started at the zero position on the scale of the amplifier.

The author also attempted to duplicate Petter's (1933) experiments, without being able to reproduce his observations.

The disc was loaded up to 220 kp in the specially constructed compression apparatus (Fig. 7, p. 27). Readings of the intradiscal pressure were usually taken with loads of 40, 85, 125, 175 and 220 kp. Higher loads were not applied to avoid fracturing the specimen. Occasionally, a load of 220 kp was found to be too great and produced a compression fracture. For this reason the highest load was not used on some of the smaller specimens, otherwise the load per unit area would have been too great.

It was also possible to establish that a pressure in the nucleus from e.g. 175 kp outer load was the same whether this load was derived from an increase from 125 kp, or a decrease from 220 kp. However, with direct decrease in load, rather a long time ensued (about 15 minutes) before this value was obtained. During this time, the drift in the electrical apparatus could have been significant, and it was necessary to correct for this drift by unloading to zero and then to measure this deflection on the amplifier.

The surface of the Luer–Lok needle with its membrane was $4 \times 0.5\ mm^2 =$

TABLE 7.

Calibration of the gauge "PE 200".

(Amplification 20).

Pressure kp/cm²	2	4	6	8	10	12	14	16	18	20	22
Scale readings											
before	6	13	20	26	32	37	41	46	49	53	57
after	7	15	25	32	36	41	46	49	54	57	61

Table 8.[1]

Comparison between measurements made with two different-sized needles.

The pressures were measured first with the "PE 90"-needle, then with the "PE 200"-needle. The differences between the values obtained are expressed as % deviations from the "PE 90"-values.

No.		607/59				500/59		606/59			
Discs tested		L 1	L 2	L 3	L 4	L 1	L 2	L 1	L 2	L 3	L 4
Degree of degeneration		2	2	2	3	2	2	2	2	2	2
Load kp	40	+9.1	− 1.3	+12.9	+12.9	−2.0	+10.7	+11.8	−1.6	±0	−2.7
	85	+1.5	− 5.0	− 3.8	− 0.8	−2.1	− 1.2	+ 4.1	+3.5	+2.4	+4.1
	125	±0	− 6.1	− 2.2	+ 2.2	−0.4	+ 3.8	+ 0.5	+3.0	+4.9	+4.9
	175	−5.9	− 5.6	− 3.9	− 0.9	−3.9	+ 1.6	+ 1.8	+6.3	+4.9	+7.1
	220	−5.5	−10.3	− 8.3	− 4.8	−1.1	− 0.7				

Mean +0.7 %. The mean of the absolute deviation: 4.2 %.

2 mm². To check the reliability of the method, a somewhat thicker needle with a larger opening was tested on six discs. Its area was $5 \times 1.2\ mm^2 = 6\ mm^2$. Over this opening, polyethylene tubing no. 200 was threaded, which largely fulfilled the requirements for membrane material. However, this plastic catheter was not completely elastic (Table 7).

Table 8 shows that the values for nucleus pressure obtained with this catheter were in good agreement with those obtained with "PE 90".

Table 9.[1]

Comparison between measurements made with two different-sized needles.

The pressures were measured first with the "PE 90"-needle and then with the "PE 60"-needle. The differences between the values obtained are expressed as % deviations from the "PE 90"-values.

No.		606/59				631/58		
Discs tested		L 1	L 2	L 3	L 4	L 1	L 2	L 3
Degree of degeneration		2	2	2	2	2	2	3
Load kp	40	−5.9	−1.6	−5.3	−2.7	+11.1	+12.3	+ 4.2
	85	−2.4	−1.4	−2.4	−7.3	+ 5.5	+ 4.5	+ 8.6
	125	−4.7	−0.3	−0.5	−6.0	+ 0.4	+ 2.3	+ 6.0
	175	+0.2	+3.8	+3.2	+3.7	+ 8.3	+ 6.0	+ 5.6
	220	+0.8	+4.1	+2.4	+1.2	+11.5	+ 8.4	+13.2

Mean +2.5 %. The mean of the absolute deviation: 4.8 %.

[1] For interpretation of the numbers given in this table, see chapter 6, p. 43 and table 10, p. 37.

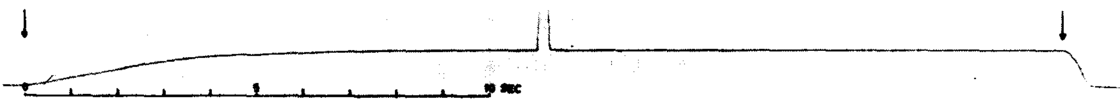


FIG. 11. Curve obtained by Mingographic registration, showing that the intradiscal pressure reaches a constant value after a short time (less than 20 sec.). At the first arrow the compression was begun, at the interruption of the line the applied load reached its final value (175 kp), and at the second arrow the load was relieved.

A similar comparison was also made between "PE 60" and "PE 90" (Table 9) with the same result, viz. that the pressures obtained with the different gauges were largely the same.

The discs were first loaded with 40 kp, and after one-half minute, the pressure was read on the amplifier. The load was then removed. The amplifier was checked with respect to zero position and then a load of 85 kp was applied. The pressure was again read and the load removed. This procedure was repeated for loads 125, 175 and 220 kp. It was established that the pressure in the nucleus on unloading always returned to zero (Fig. 11). By this means, a possible thermal drift which might have developed during the loading, could be corrected. This drift was small, which was also shown by the fact that the same result was obtained whether successive increase in loading occurred with or without unloading in between. It was not considered necessary to analyse this drift any further, since the measurements were carried out in such a way that the thermal drift could not distort the results. The readings were made after one-half minute of the load application. During this time the intradiscal pressure reached a stable value. This stability was checked on the amplifier scale, on which the readings were made. The deflection was also recorded with a Mingograph.

After the experiments, the specimens were cut through horizontally and the surface area of the discs measured (Table 11, p. 42). The disc was put on millimeter-paper and the outer margin carefully followed with a fine pen. The area drawn on the paper was calculated with the planimeter (Fig. 10, p. 31).

All the specimens were assessed macroscopically for degree of degeneration, were then photographed and stored in formalin.

With the procedure described above, a method was derived which can be considered to fulfil the conditions previously established for measuring the compressive stresses, which appear in the nucleus pulposus, when a vertical load is applied to an intervertebral disc.

Sources of error

The sources of error noticed by the author, in addition to those already mentioned in the text, were:

1. Faults in the apparatus (*a*) electrical equipment, (*b*) CEJ dynamometer, (*c*) Amsler planimeter, (*d*) compression apparatus, and (*e*) the air manometers.

2. Reading errors.

3. Possible changes in the elasticity of the plastic catheters during the loadings.

The safety measures, recommended by the manufacturers for the care of the electrical equipment, were taken, and checks carried out. The amplifier was compensated for fluctuations in line current.

According to the manufacturer, the CEJ dynamometer is a very accurate instrument and in addition to the ordinary measures for checking and care, it was also tested in an Amsler universal testing machine (see Fig. 55, p. 90).

The Amsler planimeter was checked by measuring known areas before and after every series of measurements.

The compression apparatus and its manometers were checked every day an experiment was carried out with the CEJ dynamometer. The manometers on which readings were made were provided with large and clear scales. The same air manometers were used for all the experiments. The error stated by the manufacturer amounted to ± 1–1.5%.

The reading error was not graded. The greatest possible care, with double readings and repeated experiments, however, can be said to limit the size of this factor. The author himself carried out all the observations.

Each piece of plastic tubing that was used was calibrated before and after the intradiscal pressure measurement. On comparing the values obtained before and after experiments in a certain direction, it was found that they sometimes deviated a little. The mean of the absolute deviation from zero in per cent of the value observed before and after a series of measurements, in comparison with the mean, was 1.6% (p. 24). This value also included a number of the other sources of error.

The increase in area, which occurred on loading the discs, amounted to about 5% of the area in the horizontally symmetrical plane in the unloaded state.

As shown by Hirsch and Nachemson (1954) the increase in area is rather similar for discs belonging to degeneration groups 1, 2 and 3 (p. 43). When calculating the load per unit of area, the load was divided by the original area (p. 62). This "engineering" load per unit of area is generally more convenient than the "true" load per unit of area (i.e. the load divided by the actual area). The fact that here the "engineering" and the "true" load per unit of area differed only about 5%, made it possible to use the "engineering" load per unit of area even for such approximate calculations, where, strictly, the "true" load per unit of area should be used (pp. 70–72).

CHAPTER 6 Material

The material used in this experimental study consisted of post-mortem specimens randomly collected from various departments of pathology. The lumbar spine specimens were always removed the same day as the post-mortem, which took place 1–6 days after the patient died, during which time the bodies were kept in cold storage. It was not always possible to carry out the experiments on the same day as the specimens were obtained. In these cases, they were stored either in a refrigerator (±0°C) until the next day, or put in deep-freeze (–25°C). They were stored in plastic bags to avoid dehydration as far as possible. Whether this method of storing affects the results or not has been investigated (see chapter 10). Table 10 shows the composition of the material with respect to age, sex, period of time and method of storage before the experiments were performed. In those cases where the main cause of death was cancer, the roentgenograms and the specimens were carefully studied in order to eliminate the specimens affected by metastases.

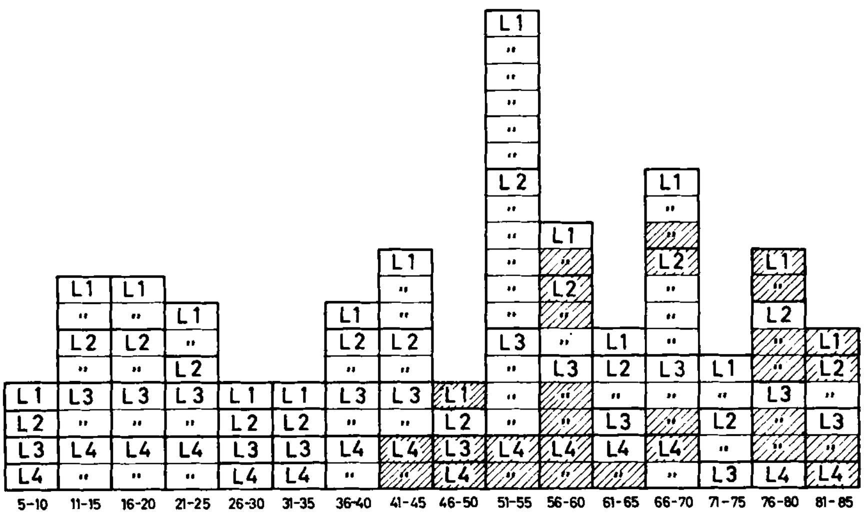


FIG. 12. Discs subjected to pressure measurements. The disc level and age group are seen. The most degenerated discs (group 4) are shown thus: ////

TABLE 10.

Specimens studied in this work.

The numbers refer to the classification system of the pathological department.

R = Refrigerator. D = Deep-freezer.

No.	Sex	Age in years	Main cause of death	Postmortem days after death	Expts. performed days after death	Discs tested				Stored in
614/59	♀	6	V.O.C. congen.	1	2	L1	L2	L3	L4	R
267/59	♀	11	Oedema cerebri	1	4	L1	L2	L3	L4	D
606/59	♂	12	V.O.C. congen.	1	1	L1	L2	L3	L4	R
286/58	♀	18	Colitis ulcerosa	2	5	L1	L2	L3	L4	D
552/59	♂	20	Fractura cranii	1	33	L1	L2	L3	L4	D
500/59	♂	22	Fractura costae I–VII	3	50	L1	L2	L3	L4	D
298/58	♂	25	Combustio ord. III	1	10	L1		L3	L4	D
617/58	♂	27	Intoxic. barbitur.	2	8	L1	L2	L3	L4	D
604/58	♂	35	Nephrit. chron. (uremia)	2	3	L1	L2	L3	L4	R
607/59	♂	36	Infarct. cordis	3	3	L1	L2	L3	L4	R
310/59	♀	38	Ca. ovarii	2	18		L2	L3	L4	D
288/58	♂	41	Sarcoidosis	3	6	L1	L2	L3	L4	D
296/58	♂	41	Fractura cranii	6	8	L1				R
292/58	♂	42	Infarct. renis (uremia)	2	4	L1	L2	L3	L4	R
303/59	♂	48	Ileus paralyticus	2	12	L1	L2	L3	L4	D
577/58	♀	51	Embolia pulm.	1	9	L1	L2			D
258/58	♀	53	Embolia pulm.	1	5	L1	L2	L3	L4	D
602/59	♀	53	Hemorr. cerebri	1	2	L1	L2	L3		R
262/58	♂	54	Hemorr. cerebri	2	9	L1	L2			D
470/58	♀	55	Infarct. cordis	1	55	L1	L2	L3		D
309/59	♂	55	Infarct. cordis	2	14	L1	L2	L3	L4	D
180/59	♂	58	V.O.C. congen. op.	2	5	L1	L2	L3		D
144/58	♂	60	Trombosis cerebri	0	7	L1	L2	L3	L4	D
573/58	♀	60	V.O.C. congen.	1	2		L2	L3	L4	D
580/58	♀	65	Nephrit. chron. (uremia)	1	10		L2		L4	D
631/58	♂	65	Hemorr. cerebri	1	2	L1	L2	L3	L4	R
310/58	♂	67	Ca. pancreatis	4	4		L2	L3		R
169/59	♂	68	Hypernephroma	1	4	L1	L2	L3	L4	D
572/58	♂	68	Infarct. cordis	1	3	L1	L2	L3	L4	R
467/58	♀	70	Cardioarterioscl. c. uremia	1	55	L1				D
248/58	♀	70	Infarct. cordis	2	7		L2			D
270/58	♀	71	Embolia pulm.	2	9	L1	L2	L3		D
311/58	♀	74	Pheochromocytoma	3	3	L1	L2			R
183/59	♂	77	Cholecystitis ac.	2	11	L1	L2	L3		D
593/59	♂	77	Embolia pulm.	1	3	L1	L2	L3		D
257/58	♀	77	Ca. choledochi	2	10		L2	L3	L4	D
259/58	♀	81	Infarct. cordis	1	13		L2	L3		D
592/59	♂	82	Insuff. cordis	3	3	L1	L2	L3	L4	R

Total number of indiv.: 38. Total number of discs: 121

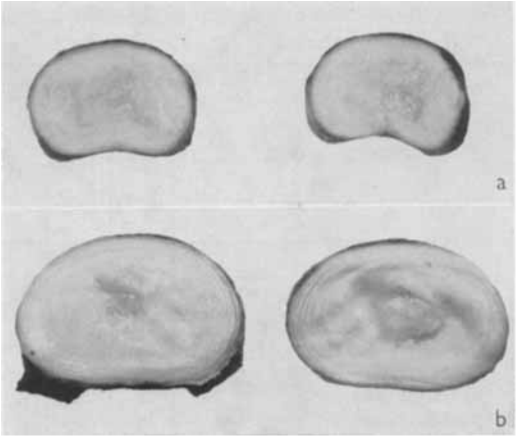


FIG. 13. Macroscopic view of two discs belonging to degeneration group 1. a. L 1 female, age 11 (267/59). b. L 4, male, age 35. (604/58). Scale 1:2.

The departments of pathology wished to preserve the sacrum. For this reason, the lumbar spine was removed, by sectioning through the lumbo-sacral disc. Only four lumbar discs were used during the experiments. The disc just above the lumbosacral has been called L 4, the one above that L 3 etc. In general, the discs were prepared so that they were cut out with slices of adjacent vertebral bodies, 1–1 $^{1}/_{2}$ cm thick. The pedicles and joint processes were removed. The cut surfaces

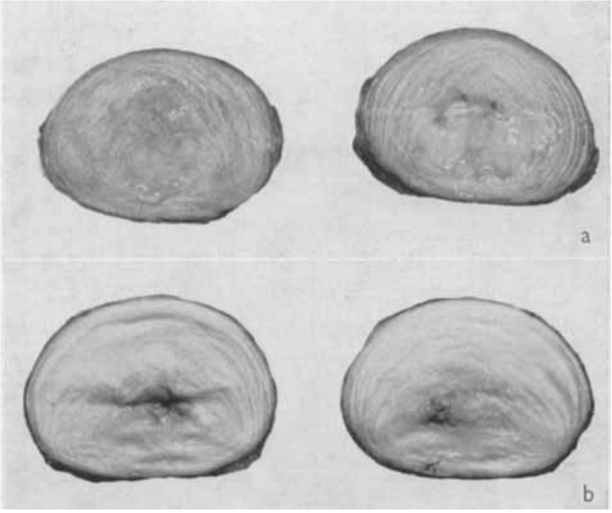


FIG. 14. Macroscopic view of two discs belonging to degeneration group 2. a. L 4, female, age 38 (310/59). b. L 3, male, age 25 (298/58). Scale 1:2.

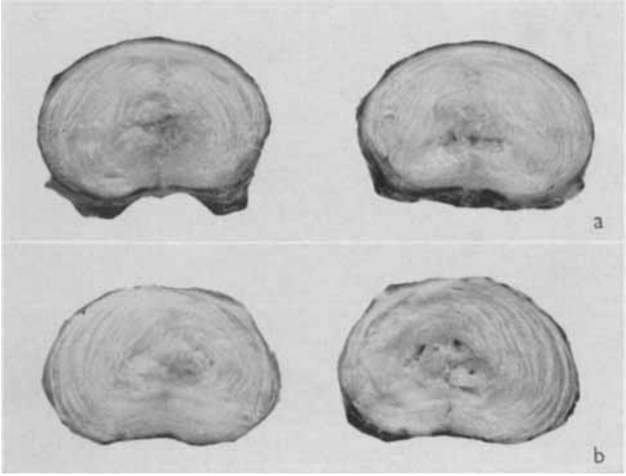


FIG. 15. Macroscopic view of two discs belonging to degeneration group 3. a. L 3, female, age 53 (602/59). b. L 3, male, age 65 (631/58). Scale 1:2.

of the vertebral bodies were made parallel to each other and, if possible, also parallel to the end-plates of the disc. The parallelism was checked with a water level. The specimens were prepared for intradiscal pressure measurement by removing attached muscles.

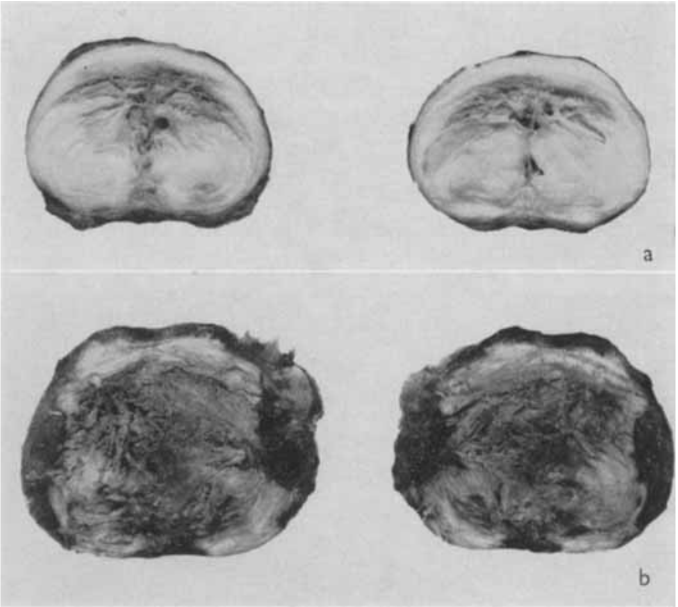


FIG. 16. Macroscopic view of two discs belonging to degeneration group 4. a. L 3, male, age 42 (292/58). b. L 3, male, age 77 (593/59). Scale 1:2.

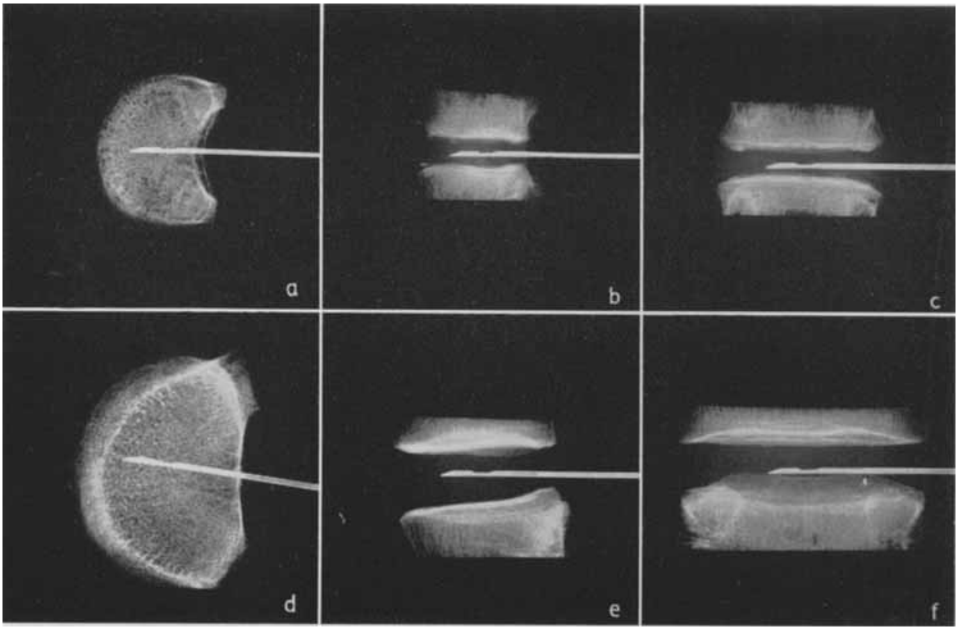


FIG. 17. Roentgenographic appearance of the discs 267/59 – L 1 (a, b and c) and 604/58 – L 4, (d, e and f.) shown in fig. 13. As seen, the position of the needle inside the disc is checked by roentgenograms in two planes. The above roentgenograms have been classified as normal (0). Scale 1:2.

In the majority of cases all the first four lumbar discs were used in the experiments. In those cases where this was not so, the rejected specimens had been damaged in some way. This occurred most often at post-mortem or when removing the lumbar vertebrae.

The total number of specimens included in this study is shown in Table 10 and Fig. 12, where the level and age distribution can be seen.

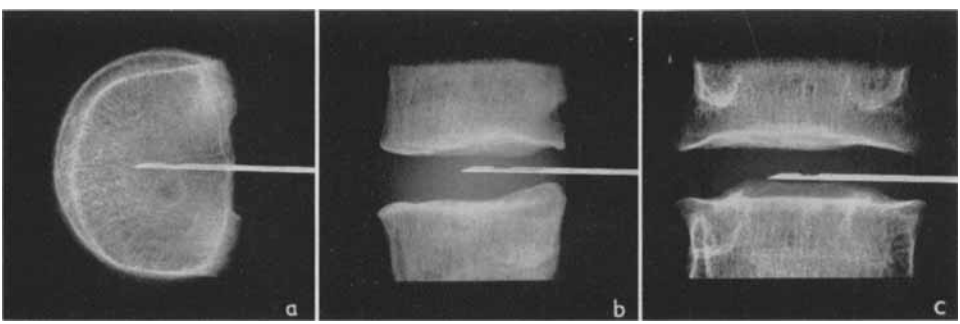


FIG. 18. Roentgenographic appearance of the disc 298/58 – L 3, shown in fig. 14. Classified as normal (0). Scale 1:2.

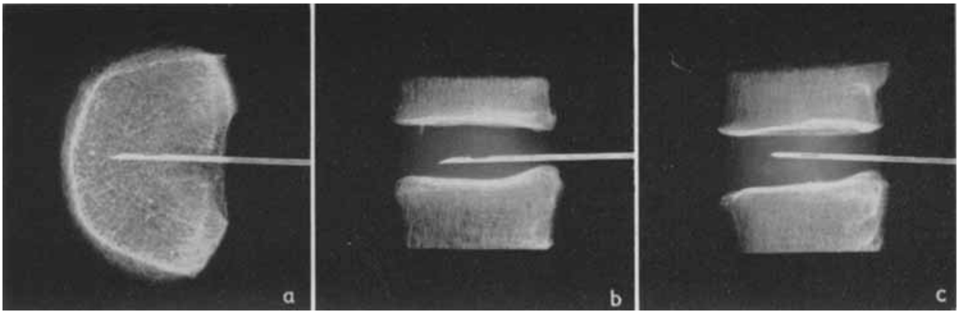


FIG. 19. Roentgenographic appearance of the discs 631/58 – L 3 (a and b) and 602/59 – L 3, (c) shown in fig. 15. Roentgenograms classified as normal (0). Scale 1:2.

Classification

Most writers have considered macroscopic inspection to be sufficient for the assessment of the degree of degeneration (Friberg and Hirsch 1949, Lindblom 1944 and 1951, Virgin 1951 and 1958, Naylor and Smare 1951, Hendry 1958, and others). The discs were assessed by macroscopic inspection and were divided into four groups according to the degree of degeneration.

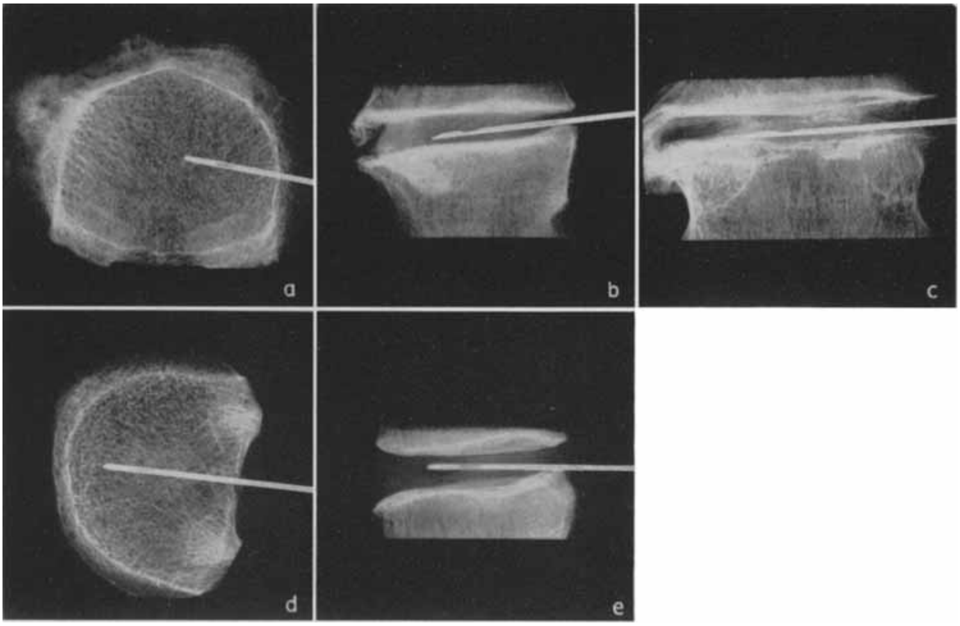


FIG. 20. Roentgenographic appearance of the discs 593/59 – L 3 (a, b and c) and 292/58 – L 3 (d and e), shown in fig. 16. These roentgenograms show clear signs of disc degeneration (+). Scale 1:2.

Table 11.

The degree of degeneration and the roentgenographic findings in all the discs studied.

The cross-sectional areas of the discs are also given.

No.	Age in years	Discs tested	Degree of degener.	Roentgen. findings	Area of cross-sectioned disc (cm²)	No.	Age in years	Discs tested	Degree of degener.	Roentgen. findings	Area of cross-sectioned disc (cm²)
614/59	6	L 1	1	0	5.8	310/59	38	L 3	2	0	16.8
		L 2	1	0	5.7			L 4	2	0	18.5
		L 3	1	0	6.3	288/58	41	L 1	2	0	19.2
		L 4	1	0	6.8			L 2	2	0	20.1
267/59	11	L 1	1	0	9.8			L 3	2	0	21.1
		L 2	1	0	11.1			L 4	2	0	18.6
		L 3	1	0	11.3	296/58	41	L 1	3	0	22.2
		L 4	1	0	10.8	292/58	42	L 1	2	0	16.2
606/59	12	L 1	2	0	16.1			L 2	2	0	17.5
		L 2	2	0	16.1			L 3	4	+	21.2
		L 3	2	0	18.0			L 4	4	+	21.6
		L 4	2	0	17.3	303/59	48	L 1	4	+	15.4
286/58	18	L 1	1	0	12.8			L 2	3	0	14.6
		L 2	1	0	13.2			L 3	4	0	15.4
		L 3	1	0	13.5			L 4	4	0	16.3
		L 4	1	0	13.9	577/58	51	L 1	2	0	13.6
552/59	20	L 1	2	0	16.3			L 2	3	0	16.0
		L 2	1	0	16.6	258/58	53	L 1	2	0	11.6
		L 3	2	0	17.4			L 2	2	0	14.8
		L 4	2	0	17.3			L 3	2	0	14.5
500/59	22	L 1	2	0	14.7			L 4	2	0	15.4
		L 2	2	0	17.3	602/59	53	L 1	2	0	14.4
		L 3	3	0	19.7			L 2	3	0	15.9
		L 4	3	0	18.4			L 3	3	0	16.7
298/58	25	L 1	1	0	17.4	262/58	54	L 1	2	0	15.6
		L 3	2	0	21.0			L 2	2	0	15.1
		L 4	3	0	20.2	470/58	55	L 1	2	0	14.2
617/58	27	L 1	1	0	17.5			L 2	2	0	14.2
		L 2	1	0	18.9			L 3	3	0	15.3
		L 3	1	0	19.6	309/59	55	L 1	3	0	17.4
		L 4	1	0	19.1			L 2	3	0	18.4
604/58	35	L 1	1	0	16.0			L 3	4	0	23.5
		L 2	1	0	16.0			L 4	4	0	19.8
		L 3	1	0	15.3	180/59	58	L 1	4	0	24.3
		L 4	1	0	16.3			L 2	4	+	29.8
607/59	36	L 1	2	0	17.6			L 3	4	+	30.9
		L 2	2	0	18.1	144/58	60	L 1	3	0	18.1
		L 3	2	0	19.5			L 2	3	0	20.7
		L 4	3	0	19.4			L 3	3	0	18.9
310/59	38	L 2	2	0	16.4			L 4	4	0	18.4

Table 11 (*cont.*)

No	Age in years	Discs tested	Degree of degener.	Roentgen. findings	Area of cross-sectioned disc (cm²)	No	Age in years	Discs tested	Degree of degener.	Roentgen. findings	Area of cross-sectioned disc (cm²)
573/58	60	L 2	4	+	19.2	270/58	71	L 1	3	0	11.8
		L 3	4	0	18.0			L 2	2	0	13.2
		L 4	4	+	22.8			L 3	3	0	13.4
580/58	65	L 2	3	0	17.0	311/58	74	L 1	3	0	15.0
		L 4	3	0	17.3			L 2	3	0	15.9
631/58	65	L 1	2	0	15.6	183/59	77	L 1	4	+	24.8
		L 2	2	0	16.5			L 2	4	+	25.9
		L 3	3	0	17.1			L 3	4	0	21.4
		L 4	4	0	19.3	593/59	77	L 1	4	+	25.2
310/58	67	L 2	2	0	21.5			L 2	4	+	30.0
		L 3	3	0	23.7			L 3	4	+	30.8
169/59	68	L 1	3	0	19.6	257/58	77	L 2	3	0	14.1
		L 2	4	0	22.5			L 3	3	0	15.0
		L 3	4	0	21.1			L 4	3	0	15.4
		L 4	4	+	23.6	259/58	81	L 2	2	0	13.2
572/58	68	L 1	4	+	18.9			L 3	2	0	15.3
		L 2	3	0	19.3	592/59	82	L 1	4	+	23.4
		L 3	3	0	19.4			L 2	4	+	27.2
		L 4	3	0	19.1			L 3	4	+	28.2
467/58	70	L 1	2	0	13.2			L 4	4	+	26.8
248/58	70	L 2	3	0	12.8						

Group 1. Discs without changes visible to the naked eye. In these cases a gelatinous shiny nucleus pulposus was seen; it was easily delimited from the annulus fibrosus, which was free from macroscopic ruptures (Fig. 13).

Group 2. Discs which showed macroscopic changes in the nucleus pulposus. The nucleus was somewhat more fibrous, but could be clearly distinguished from the annulus, which was intact (Fig. 14).

Group 3. Specimens which showed macroscopic changes in both the nucleus pulposus and the annulus fibrosus. The nucleus in these discs was more fibrotic but still soft. The boundary between nucleus and annulus was no longer so distinct, but could still be seen. Changes in the annulus fibrosus consisted of isolated fissures (Fig. 15).

Group 4. Specimens which showed more severe macroscopic changes. The discs in this group exhibited fissure formation and cavities in both the nucleus and the annulus. Marginal osteophytes were often found in adjoining vertebrae (Fig. 16).

From earlier studies (Friberg and Hirsch 1949, Lindblom 1950, 1951), it is known that the disc can show severe degenerative changes without visible abnormality on roentgenograms. For this reason, macroscopic assessment was considered sufficient for grouping the material. Knutsson (1940, 1942, 1944) described the roentgenographic signs of disc degeneration. If the specimens in this material were divided into two groups in relation to roentgenographic changes, as shown in Table 11, there was not one case with roentgenographic signs of degeneration, which was not also visible to the naked eye. On the other hand, a number of discs had undergone severe changes with nearly normal roentgen findings. Those discs, marked in Table 11 with 0, showed very mild or no changes on the roentgenograms while those with + had clear signs, such as decreased disc height, reactive changes of the edges of the vertebral bodies or vacuum phenomenon (Figs. 17–20). In a number of discs with mild macroscopic changes, it was possible to see occasional marginal osteophytes. This agrees well with the findings of Schmorl (1927) and Knutsson (1957) viz. that occasional osteophytes do not necessarily mean that the interior of the disc shows severe changes.

CHAPTER 7

The state of stress in the nucleus pulposus

The measurement of the compressive stress using the method described was presumed to apply to homogeneous substances, such as the nucleus pulposus in the healthy and in the moderately degenerated disc (groups 1, 2 and 3). If the nucleus behaves hydrostatically, it is implied that the compressive stresses are the same in all directions. However, it is sufficient to carry out measurements in three directions, provided that they are the so-called directions of principal stresses. Since the loaded disc has a horizontal and a vertical plane of symmetry, one knows that two of the directions of principal stresses are at right angles to these planes of symmetry. Furthermore, it is known that the directions of principal stresses are orthogonal (Fig. 21), so that the third direction of principal stress is also known.

Measurements in two or three of these directions of principal stresses were carried out on 64 discs (Fig. 22). The ages, degree of degeneration and levels of the specimens are shown in Table 12. For reasons previously stated, no specimen belonging to group 4 was included. The compressive stresses in the nucleus pulposus resulting from loads of 40, 85, 125, 175 and 220 kp were then measured.

It was previously pointed out that, in a number of discs, a load of 220 kp was

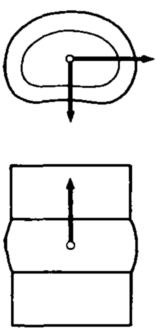


FIG. 21.

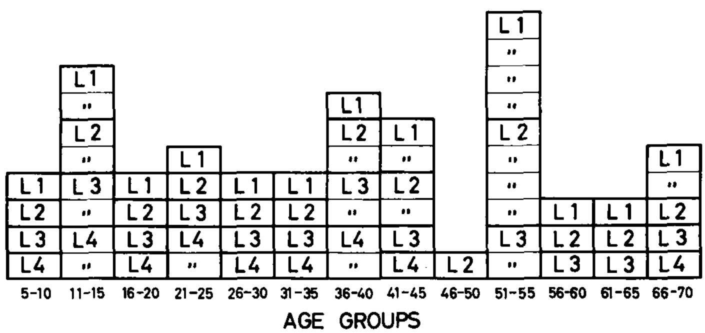


FIG. 22.

FIG. 21. Directions of principal stresses in the loaded disc.

FIG. 22. Discs subjected to measurements in more than one direction of principal stress. The disc level and age group can be seen.

TABLE 12.

Presentation of the discs where pressure measurement was carried out in more than one direction.

(64 discs from 22 individuals) (↑ = upwards; ↓ = downwards; ⇌ = sideways)

No.	Age in years	Discs tested	Degree of degener.	Roentgen. findings	Direction of needle opening: Dorsal insertion	— Lateral insertion	Storage temp. °C
614/59	6	L 1	1	0	⇅ ⇌	⇅ ⇌	0°
		L 2	1	0	⇅ ⇌	⇅ ⇌	
		L 3	1	0	⇅ ⇌	⇅ ⇌	
		L 4	1	0	⇅ ⇌	⇅ ⇌	
267/59	11	L 1	1	0	⇅ ⇌	⇅ ⇌	– 25°
		L 2	1	0	⇅ ⇌	⇅ ⇌	
		L 3	1	0	⇅ ⇌	⇅ ⇌	
		L 4	1	0	⇅ ⇌	⇅ ⇌	
606/59	12	L 1	2	0	↑ →	↑ →	0°
		L 2	2	0	↑ →	↑ →	
		L 3	2	0	↑ →	↑ →	
		L 4	2	0	↑ →	↑ →	
552/59	20	L 1	2	0	⇅ ⇌		– 25°
		L 2	1	0	↑ →	↑ →	
		L 3	2	0	⇅ ⇌		
		L 4	2	0	↑ →	↑ →	
500/59	22	L 1	2	0	↑ →	↑ →	– 25°
		L 2	2	0	↑ →	↑ →	
		L 3	3	0	↑ →	↑ →	
		L 4	3	0	↑ →	↑ →	
298/58	25	L 4	3	0	↑ →	↑ →	– 25°
617/58	27	L 1	1	0	↑ →		– 25°
		L 2	1	0	↑ →		
		L 3	1	0	↑ →		
		L 4	1	0	↑ →		
604/58	35	L 1	1	0	↑ →		0°
		L 2	1	0	↑ →	↑ →	
		L 3	1	0	↑ →	↑ →	
		L 4	1	0	↑ →	↑ →	
607/59	36	L 1	2	0	⇅ ⇌		0°
		L 2	2	0	⇅ ⇌		
		L 3	2	0	⇅ ⇌	⇅ ⇌	
		L 4	3	0	⇅ ⇌		
310/59	38	L 2	2	0	⇅ ⇌	⇅ ⇌	– 25°
		L 3	2	0	⇅ ⇌	⇅ ⇌	
		L 4	2	0	⇅ ⇌	⇅ ⇌	
288/58	41	L 1	2	0	↑ →		– 25°
		L 2	2	0	↑ →		
		L 3	2	0	↑ →		
		L 4	2	0	↑ →		

Table 12 (*cont.*)

No.	Age in years	Discs tested	Degree of degener.	Roentgen. findings	Direction of needle opening		Storage temp. °C
					Dorsal insertion	— Lateral insertion	
292/58	42	L1	2	0	↑ →	↑ →	0°
		L2	2	0	↑ →	↑ →	
303/59	48	L2	3	0	↑ →	↑ →	−25°
577/58	51	L1	2	0	↑ →		−25°
		L2	3	0	↑ →		
602/59	53	L1	2	0	↑ →	↑ →	0°
		L2	3	0	↑ →	↑ →	
		L3	3	0	↑ →	↑ →	
470/58	55	L1	2	0	⇅ ⇌		−25°
		L2	2	0	↑ →		
		L3	3	0	↑ →		
309/59	55	L1	3	0	↑ →		−25°
		L2	3	0	↑ →		
144/58	60	L1	3	0	↑ →		−25°
		L2	3	0	↑ →		
		L3	3	0	↑ →		
631/58	65	L1	2	0	↑ →		0°
		L2	2	0	↑ →		
		L3	3	0	↑ →		
572/58	68	L2	3	0	↑ →		0°
		L3	3	0	↑ →		
		L4	3	0	↑ →		
169/59	68	L1	3	0	⇅ ⇌		−25°
467/58	70	L1	2	0	↑ →		−25°

sufficient to fracture the end-plate and the remainder of the vertebral body. A number of specimens had a small area. For this reason, not all the discs were loaded up to 220 kp. In specimens from a six-year-old child, a sufficient number of values could be obtained with loads of 20, 40, 62 and 85 kp.

In 32 of the discs mentioned above, measurements were made of the compressive stresses in the three directions of principal stresses. In these cases, the opening of the needle covered by the membrane pointed upwards and sideways inside the disc. The needle was inserted from the dorsal and lateral border of the disc. In this way, the compressive stress in the vertical direction was measured twice. The mean of these two measurements was calculated. Tables 13, 14 and 15 show data for three of the discs in Figs. 13, 14 and 15 (pp. 38–39).

The mean pressure can here be defined by the following expression

$$p = \frac{|\sigma_l| + |\sigma_d| + |\sigma_v|}{3},$$

TABLE 13.

Results obtained from measuring in the three directions of principal stresses in the disc 267/59-L 1, (deg. group 1) female, age 11, shown in fig. 13 a page 38. The deviation of $|\sigma_v|$, $|\sigma_l|$ and $|\sigma_d|$ from the mean pressure is given in per cent.

Load kp	$\lvert\sigma_v\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_l\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_d\rvert$ kp/cm²	% dev. from mean	Mean (= p) kp/cm²
40	5.6	− 1.2	5.6	− 1.2	5.8	+ 2.3	5.67
85	11.85	+ 0.9	11.7	− 0.4	11.7	− 0.4	11.75
125	18.1	+ 1.3	17.3	− 3.2	18.2	+ 1.8	17.87

TABLE 14.

Results obtained from measuring in the three directions of principal stresses in the disc 310/59-L 4, (deg. group 2), female, age 38, shown in fig. 14 a page 38. The deviation of $|\sigma_v|$, $|\sigma_l|$ and $|\sigma_d|$ from the mean pressure is given in per cent.

Load kp	$\lvert\sigma_v\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_l\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_d\rvert$ kp/cm²	% dev. from mean	Mean (= p) kp/cm²
40	3.6	±0	3.7	+ 2.8	3.5	− 2.8	3.6
85	6.7	+ 3.1	6.4	− 1.5	6.4	− 1.5	6.5
125	10.05	+ 5.2	9.3	− 2.6	9.3	− 2.6	9.55
175	12.9	+ 4.9	12.0	− 2.4	12.0	− 2.4	12.3
220	15.4	±0	15.4	±0	15.4	±0	15.4

TABLE 15.

Results obtained from measuring in the three directions of principal stresses in the disc 602/59-L 3, (deg. group 3), female, age 53, shown in fig. 15 a page 39. The deviation of $|\sigma_v|$, $|\sigma_l|$ and $|\sigma_d|$ from the mean pressure is given in per cent.

Load kp	$\lvert\sigma_v\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_l\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_d\rvert$ kp/cm²	% dev. from mean	Mean (= p) kp/cm²
40	4.5	− 3.6	4.9	+ 4.9	4.6	− 1.5	4.67
85	8.85	− 1.9	9.2	+ 2.0	9.0	− 0.2	9.02
125	12.05	− 2.7	12.7	+ 2.6	12.4	+ 0.2	12.38
175	15.8	±0	16.0	+ 1.3	15.6	− 1.3	15.8
220	19.5	+ 0.9	19.5	+ 0.9	19.0	− 1.7	19.33

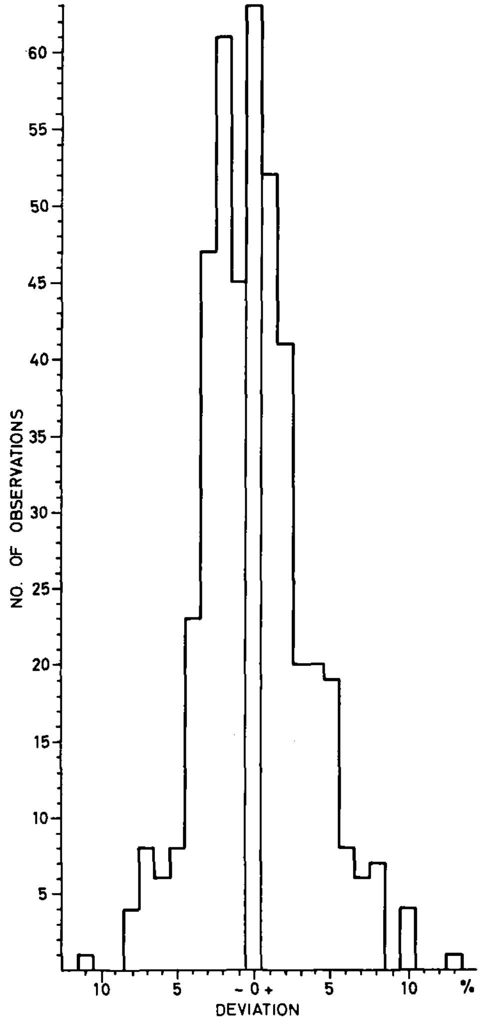


FIG. 23. The % deviation of $|\sigma_v|$, $|\sigma_l|$, and $|\sigma_d|$ from the mean pressure for every load on each of the 32 discs where the compressive stresses were measured in the three directions of principal stresses of the disc. The % values are approximated to the nearest whole number. The total no. of observations is 444. The mean of the absolute deviation from zero of the values in this diagram is 2.5%.

where $|\sigma_l|$ = compressive stress in the lateral direction, $|\sigma_d|$ = compressive stress in the dorsal direction, and $|\sigma_v|$ = the above-mentioned mean value of the two measurements of the compressive stress in the vertical direction. The percentage deviation of $|\sigma_l|$, $|\sigma_d|$ and $|\sigma_v|$ from the mean pressure for every load on each disc is represented in Fig. 23.

The diagram shows that most of the deviations are so small that they are less than the error of the method given in p. 35. (In this and the following diagrams, the percentage values are approximated to the nearest whole number.) The mean of the absolute deviation from zero of the values in this diagram is 2.5%. As previously shown the error from change in elasticity in the plastic tubing is about

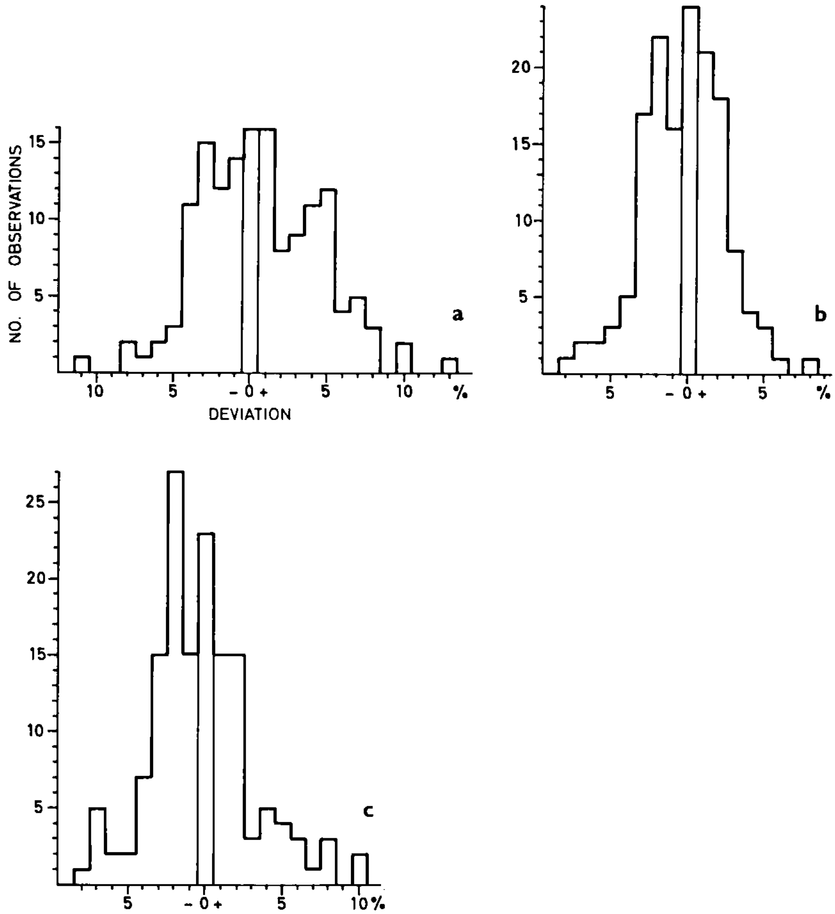


FIG. 24. The % deviation of $|\sigma_v|$ (a), $|\sigma_l|$ (b), and $|\sigma_d|$ (c) from the mean pressure for every load on each of the 32 discs.
a. $|\sigma_v|$. No. of observations: 148. Mean: +0.6%. The mean of the absolute deviation: 3.1%.
b. $|\sigma_l|$. No. of observations: 148. Mean: −0.3%. The mean of the absolute deviation: 2.0%.
c. $|\sigma_d|$. No. of observations: 148. Mean: −0.3%. The mean of the absolute deviation: 2.4%.

2%. Most of the variations are thus explained by this component of the error of the method.

Further investigations were made as to whether there was any suggestion of a systematic deviation, e.g. that the vertical compressive stress as a rule was greater than the mean stress. It is seen in Fig. 24, however, that no systematic deviation of any importance can be established. The percentage mean for the respective directions are: for $|\sigma_v|$: +0.6%, for $|\sigma_l|$: −0.3%, for $|\sigma_d|$: −0.3%.

When the 32 discs mentioned above are distributed according to degree of

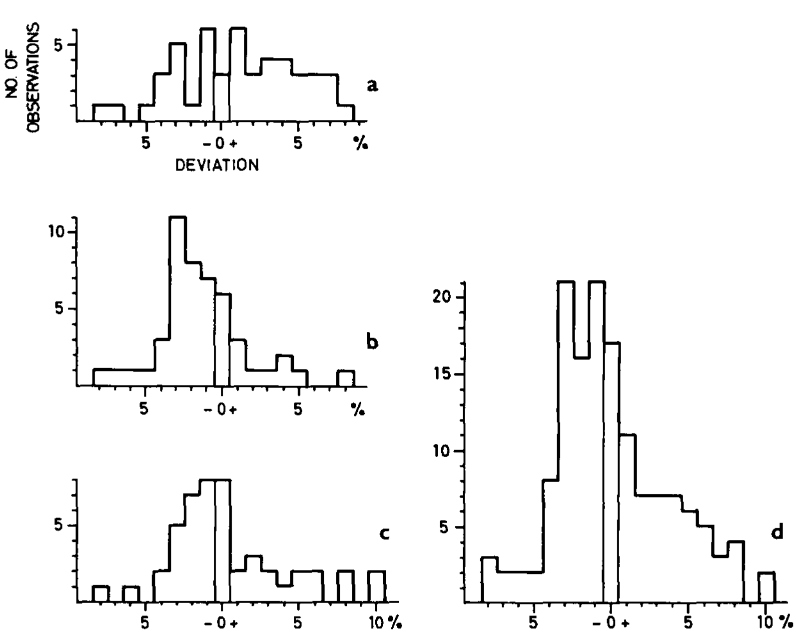


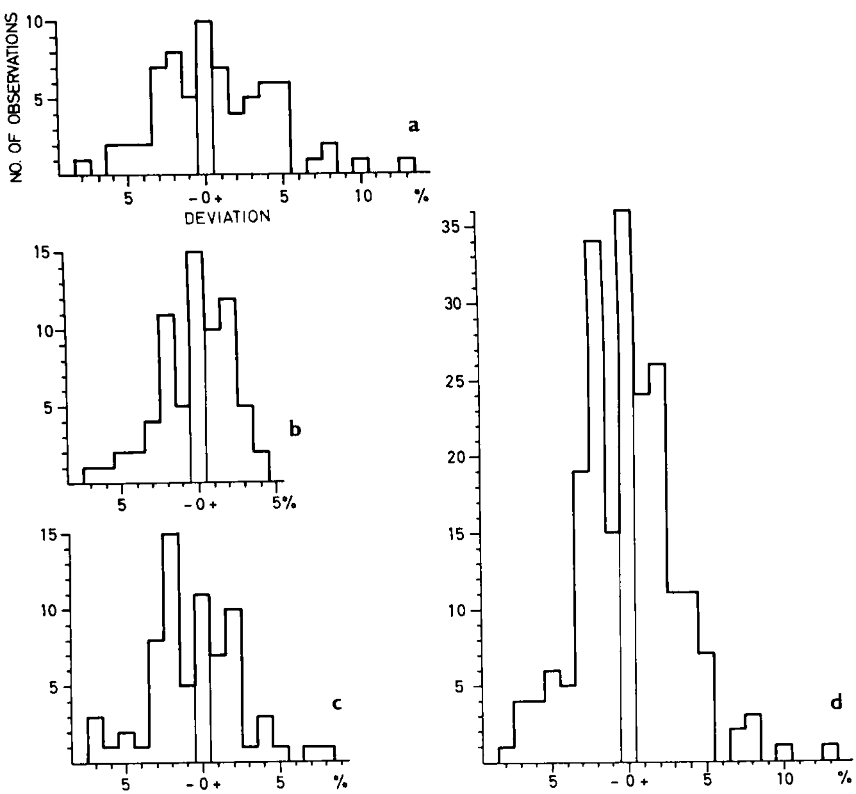
FIG. 25. The % deviation of $|\sigma_v|$ (a), $|\sigma_l|$ (b), and $|\sigma_d|$ (c) from the mean pressure in discs belonging to degeneration group 1.
a. $|\sigma_v|$. No. of observations: 48. Mean: +1.0%.
b. $|\sigma_l|$. No. of observations: 48. Mean: −1.3%.
c. $|\sigma_d|$. No. of observations: 48. Mean: +0.3%.
d. The composite diagram. No. of observations: 144.
The mean of the absolute deviation: 2.9%.

degeneration (1, 2 and 3), it can be seen from Figs. 25, 26 and 27 that there is no difference between these groups.

Thus, it can be said that the nucleus in discs of degeneration groups 1, 2 and 3 shows hydrostatic behaviour.

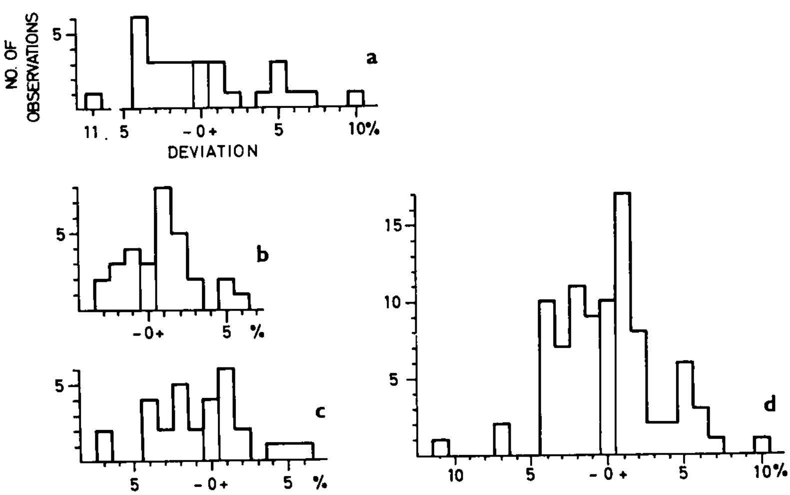
As a control, measurements were carried out on 12 discs with the needle inserted both dorsally and laterally. The compressive stresses were measured with the opening of the membrane pointing upwards, downwards and towards both sides. The percentage deviation of each of these values from the mean was calculated for every load on every one of these 12 discs. The total of these percentage deviations is shown in Fig. 28 a, and also in Fig. 28 b and c, distributed according to the loads 40+85 kp and 125–220 kp. The diagrams show that the percentage deviation is relatively small and the greatest deviations are found with the smallest loads. These diagrams also show that measurement in one direction in the disc gives the same result as measurement at an angle of 180° to this direction.

In all the 64 discs shown in Table 12 the needle was inserted dorsally. The vertical and lateral compressive stresses were measured. From these measurements



NO. OF OBSERVATIONS
DEVIATION
a
b
c
d

FIG. 26.



NO. OF OBSERVATIONS
DEVIATION
a
b
c
d

FIG. 27.

Table 16.

Results obtained from measuring in two directions of principal stresses (σ_v and σ_l) in the disc 604/58-L 4, (deg. group 1), male, age 35, shown in fig. 13 b page 38. The deviation of $|\sigma_v|$ and $|\sigma_l|$ from their mean is given in per cent.

Load kp	$\lvert\sigma_v\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_l\rvert$ kp/cm²	% dev. from mean	Mean kp/cm²
40	4.3	±0	4.3	±0	4.3
85	8.3	±0	8.3	±0	8.3
125	11.5	−2.1	12.0	+2.1	11.75
175	15.0	±0	15.0	±0	15.0
220	17.4	−1.7	18.0	+1.7	17.7

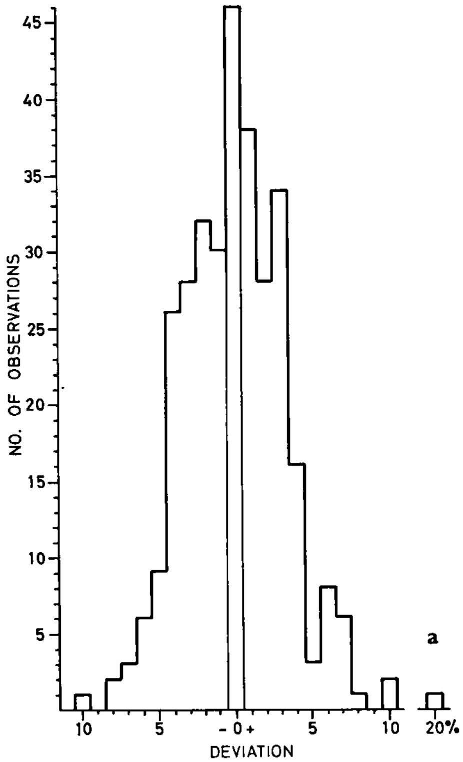
Table 17.

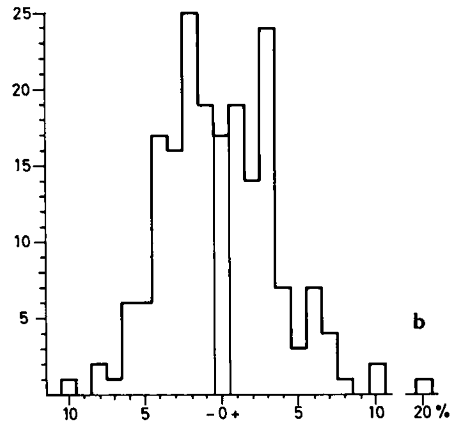
Results obtained from measuring in two directions of principal stresses (σ_v and σ_l) in the disc 631/58-L 3, male, age 65, (deg. group 3) shown in fig. 15 b page 39. The deviation of $|\sigma_v|$ and $|\sigma_l|$ from their mean is given in per cent.

Load kp	$\lvert\sigma_v\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_l\rvert$ kp/cm²	% dev. from mean	Mean kp/cm²
40	3.4	−1.4	3.5	+1.4	3.45
85	7.0	±0	7.0	±0	7.0
125	10.0	−1.0	10.2	+1.0	10.1
175	13.3	−1.1	13.6	+1.1	13.45
220	15.8	−0.6	16.0	+0.6	15.9

Fig. 26. The % deviation of $|\sigma_v|$ (a), $|\sigma_l|$ (b), and $|\sigma_d|$ (c) from the mean pressure in discs belonging to degeneration group 2.
a. $|\sigma_v|$. No. of observations: 70. Mean: +0.7 %.
b. $|\sigma_l|$. No. of observations: 70. Mean: −0.2 %.
c. $|\sigma_d|$. No. of observations: 70. Mean: −0.5 %.
d. The composite diagram. No. of observations: 210.
The mean of the absolute deviation: 2.3 %.

Fig. 27. The % deviation of $|\sigma_v|$ (a), $|\sigma_l|$ (b), and $|\sigma_d|$ (c) from the mean pressure in discs belonging to degeneration group 3.
a. $|\sigma_v|$. No. of observations: 30. Mean: −0.1 %.
b. $|\sigma_l|$. No. of observations: 30. Mean: +0.8 %.
c. $|\sigma_d|$. No. of observations: 30. Mean: −0.7 %.
d. The composite diagram. No. of observations: 90.
The mean of the absolute deviation: 2.5 %.





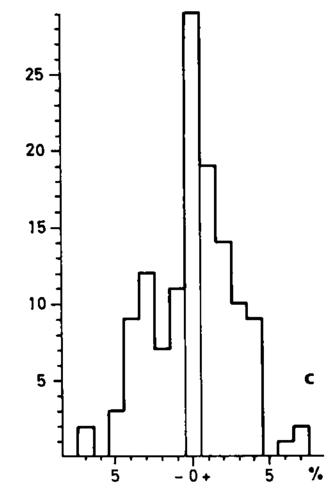
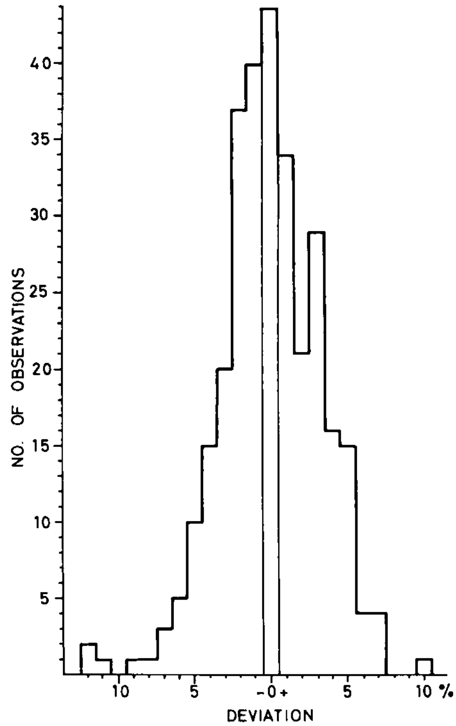
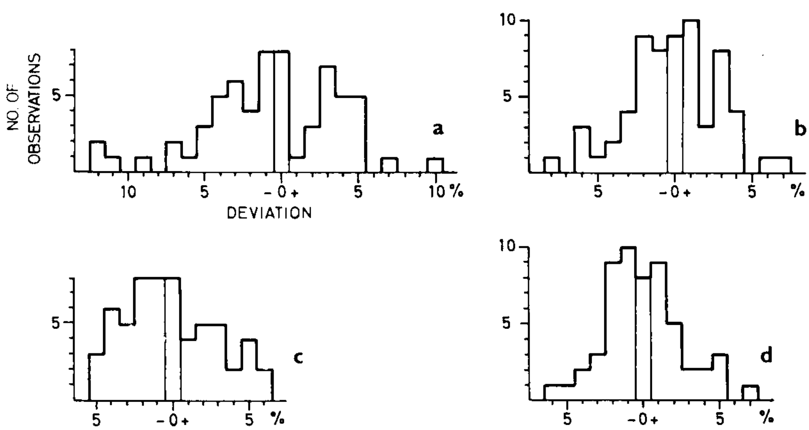


FIG. 28. The compressive stresses were measured both upwards and downwards and towards both sides in the nucleus pulposus of 12 discs, with the needle inserted both dorsally and laterally. The % deviation of the respective values from their mean for each load on every disc are represented.

a. The composite diagram. No. of observations: 320. The mean of the absolute deviation is 2.6%.
b. External loads 40 and 85 kp. No. of observations: 198
c. External loads 125, 175 and 220 kp. No. of observations: 122.

Fig. 29. The compressive stresses were measured in two directions of principal stresses in 64 discs, vertically (σ_v) and laterally (σ_l). The mean of these two values was calculated for each separate load on every disc. The % deviation of $|\sigma_v|$ from this mean value is represented in this diagram.
No. of observations: 303. Mean: −0.1 %. The mean of the absolute deviation is 2.5 %.





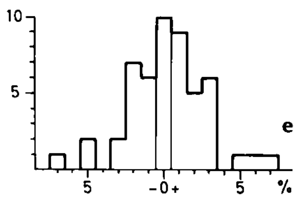


Fig. 30. The % deviation of $|\sigma_v|$ from the mean of $|\sigma_v|$ and $|\sigma_l|$ for various external loads.
a. 40 kp. No. of observations: 64. Mean: −0.7 %.
b. 85 kp. No. of observations: 64. Mean: −0.1 %.
c. 125 kp. No. of observations: 60. Mean: −0.2 %.
d. 175 kp. No. of observations: 56. Mean: −0.1 %.
e. 220 kp. No. of observations: 51. Mean: +0.2 %.

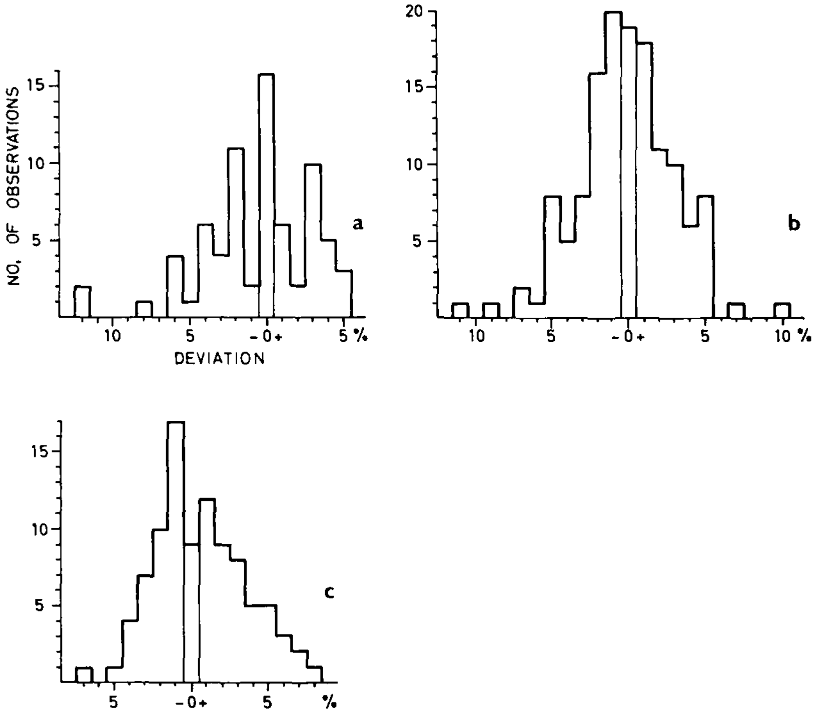


FIG. 31. The % deviation of $|\sigma_v|$ from the mean of $|\sigma_v|$ and $|\sigma_l|$ grouped according to the degree of degeneration.
a. Group 1. No. of observations: 73. Mean: −0.6%.
b. Group 2. No. of observations: 136. Mean: −0.2%.
c. Group 3. No. of observations: 94. Mean: +0.5%.

it is possible, to a certain extent, to check whether or not the nucleus functions hydrostatically, since it can be expected that a possible deviation from hydrostatic behaviour would express itself as a difference between the vertical compressive stress and both the dorsal and lateral compressive stresses. The latter should be equal.

The mean of the values for $|\sigma_v|$ and $|\sigma_l|$ was calculated for every individual load. The percentage deviation of the vertical compressive stress in comparison with this mean value was then calculated as in Tables 16 and 17. This percentage deviation of the vertical value in comparison with the mean, is reproduced diagrammatically for all the values in the 64 discs (Fig. 29). The percentage deviation is small. The mean for the whole series is – 0.1 %. In Figs. 30 a, b, c, d and e, the same percentage deviations are drawn for loads of 40, 85, 125, 175 and 220 kp. The numerical means are small and given in the diagrams. There is no practical difference between the different loads, but as shown earlier, the majority of the large deviations were found for a load of 40 kp. This depends on the fact

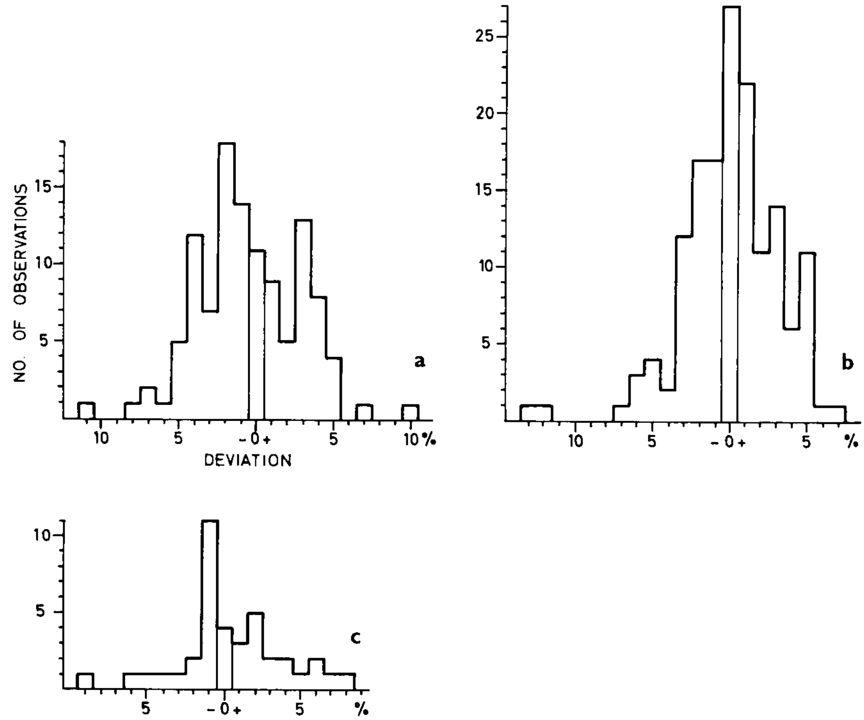


FIG. 32. The % deviation of $|\sigma_v|$ from the mean of $|\sigma_v|$ and $|\sigma_l|$ grouped according to age (30-year periods).
a. 0–30 years. No. of observations: 113. Mean: −0.5 %.
b. 31–60 years. No. of observations: 151. Mean: +0.1 %.
c. 61– years. No. of observations: 39. Mean: +0.4 %.

that, with this load, the values obtained are small and that a small difference in the reading gives a percentage deviation greater than with higher loads.

If this series, with measurements in two principal directions, is grouped according to the degree of degeneration, age, or the level of the disc in the lumbar spine, no differences of fundamental importance are found (Figs. 31, 32 and 33).

In 19 discs, the specimen was rotated 180° with the needle inserted dorsally and the opening pointing vertically or horizontally. Fig. 35 shows that, as previously mentioned, rotation through 180° does not produce any large deviations.

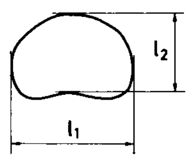
When measuring the compressive stresses in the nucleus, the aim has been to have the sensitive membrane lie as centrally as possible inside the disc. To achieve this in every case, a check was made partly by taking roentgen pictures in two planes, and partly by making use of the graduation marks on the needle. In addition, a check was made after the discs had been cut through for inspection and the needle laid on the surface of the cut disc (Fig. 34).

TABLE 18.

Position of needle opening in the discs.

(↑ = upwards, → = sideways)

No.	Discs tested	Direction of needle opening	Membrane from disc-border mm			Diameters of cross-sectioned disc	
						l_1 mm	l_2 mm
500/59	L 1	Dorsal ↑	21	16	11	49	34
		→	21	16	11		
		Lateral ↑	37	29	16		
		→	37	29	16		
	L 2	Dorsal ↑	16			53	38
		→	16				
		Lateral ↑	29	21			
		→	29	21			
602/59	L 1	Dorsal ↑	16	11	6	47	34
		→	16	11	6		
		Lateral ↑	31	21	11		
		→	31	21	11		
	L 2	Dorsal ↑	16	11	6	52	34
		→	16	11	6		
		Lateral ↑	31	21	11		
		→	31	21	11		
	L 3	Dorsal ↑	16			55	36
		→	16				
		Lateral ↑	31	21			
		→	31	21			
606/59	L 2	Dorsal ↑	21	16	11	51	37
		→		16			
		Lateral ↑	31	21			
		→		21			



In 6 discs, measurements were carried out at varying distances (Table 18) from the outer border of the disc in order to investigate whether or not a moderate change in the distance of the membrane from the outer surface of the disc had any effect on the results. These measurements were carried out with insertion both laterally and dorsally. In the majority of cases, three measurements were made at varying depths. Fig. 36 shows the percentage deviations of every pressure from

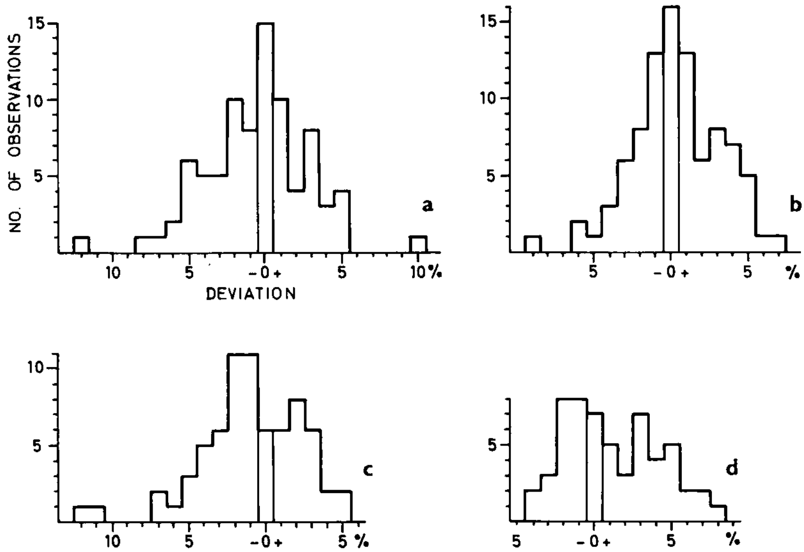


FIG. 33. The % deviation of $|\sigma_v|$ from the mean of $|\sigma_v|$ and $|\sigma_l|$ grouped according to level in the lumbar spine.
a. L 1. No. of observations: 84. Mean: −0.6%.
b. L 2. No. of observations: 91. Mean: +0.3%.
c. L 3. No. of observations: 71. Mean: −1.0%.
d. L 4. No. of observations: 57. Mean: +1.1%.

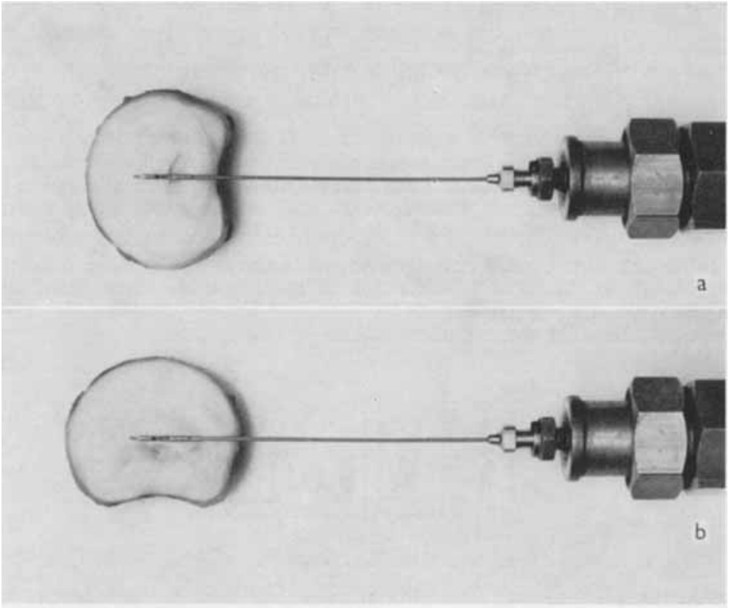


FIG. 34. Position of the needle in the disc. a. Dorsal insertion. b. Lateral insertion. Scale 1:2.

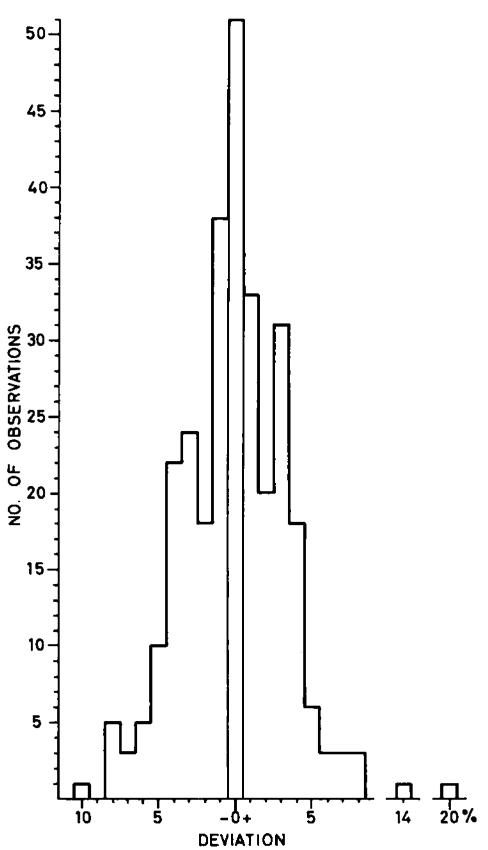


FIG. 35.

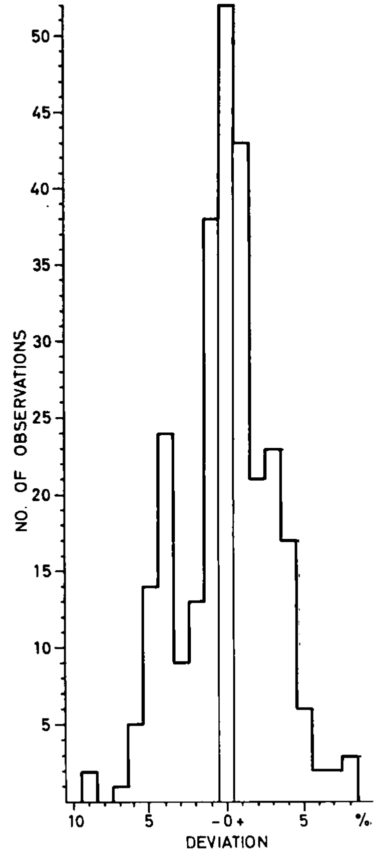


FIG. 36.

FIG. 35. The compressive stresses were measured both upwards and downwards and towards both sides in the nucleus pulposus of 19 discs, with the needle inserted dorsally. The % deviations of the respective values from their mean for each load on every disc are represented. No. of observations: 296. The mean of the absolute deviation: 2.5%.

FIG. 36. Measurements were carried out at varying distances from the outer border of six discs according to table 18, p. 58. The % deviations of the respective values from their mean for each load on every disc are represented.
No. of observations: 275. The mean of the absolute deviation: 2.2%.

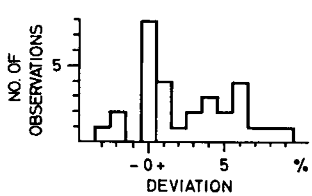


FIG. 37. The % deviation of $|\sigma_v|$ from the mean of $|\sigma_v|$ and $|\sigma_l|$ as measured with the "PE 200"-gauge.
No. of observations: 30. Mean: +2.5%.

the mean of all the measurements of pressure for every particular load. Thus, moderate variations in the depth to which the membrane was inserted into the disc, did not affect the results to any important extent.

Measurements of $| \sigma_v |$ and $| \sigma_l |$ with "PE 200" on 6 discs have not shown any great deviations (Fig. 37).

Discussion

From the results and the diagrams shown above, it can be concluded that it is justifiable to say that the nucleus pulposus in a lumbar intervertebral disc behaves hydrostatically when exposed to vertical loading. It was shown that, regarding the mean pressure and the hydrostatic behaviour, the nucleus pulposus, within the distances from the outer border of the disc given in Table 18 was similar to the central nucleus. Thus the pressure is distributed uniformly over the surrounding tissues.

In the present study, it can also be considered proved that no great difference exists in the hydrostatic behaviour of the nucleus for different loads within physiological limits. Neither is there any difference between healthy (group 1) and moderately degenerated discs (groups 2 and 3) or with varying age. The discs L 1–L 4 are, from the hydrostatic point of view, similar.

The mean of the absolute deviation from zero of the values in the diagrams is between two and three per cent, and is a deviation which can be explained by the previously mentioned errors of the method.

Thus, on comparison of the pressures in the different discs, with respect to the conditions found, it is justifiable to use the mean values obtained for the respective loads. For comparative purposes it is immaterial whether the pressure found for a particular load is calculated from one measurement or is a mean value of two or more measurements.

The above-mentioned conclusions hold for degeneration groups 1, 2 and 3.

(Regarding group 4, see chapter 11, p. 84.)

CHAPTER 8

Variations in the intradiscal pressure according to the degree of degeneration, level, and age

It was shown in Chapter 7, that an external force applied to the disc produced a pressure in the nucleus pulposus which was uniformly distributed in different directions in the nucleus, so that it was immaterial which of the pressures, measured in different directions, was used in comparing the different discs.

By using the planimeter the surface area of the disc was calculated. Thus the load per unit of area obtained with the various external loads could be estimated. In this connection, no attention was paid to the increase in area, which occurred with loading. This increase amounted to about 5 % of the area of the disc in the horizontally symmetrical plane in the unloaded state.

A graph was drawn for every disc, with the external load in kp/cm^2 on the abscissa, and the corresponding intradiscal pressure in kp/cm^2 on the ordinata as in Figs. 38, 39 and 40. The intradiscal pressures corresponding to external loads of 2, 4, 6, 8, 10 and in some cases 12 kp/cm^2 were read from these curves. It was seen that the intradiscal pressure was approximately proportional to and greater than the applied load per unit area.

Table 19 shows all the results. Those cases are also included which were previously measured with catheter "PE 60". These were included after it was observed that the nucleus behaves hydrostatically. (Those belonging to group 4, however, were excluded.)

Intradiscal pressure according to the degree of degeneration and level in the lumbar spine

The pressures obtained were grouped according to the macroscopic picture of the disc. It is seen in Table 20 that the mean values in groups 1, 2 and 3 remain the same with increasing outer loads. In this table no attention was paid to the disc level. The values on which these results are based were derived from a relatively large number of discs, although the number of individuals was rather small. Group 1 includes 7 individuals, group 2, 18, and group 3, 19.

Statistical examination of the agreement is set out in Table 21 where the

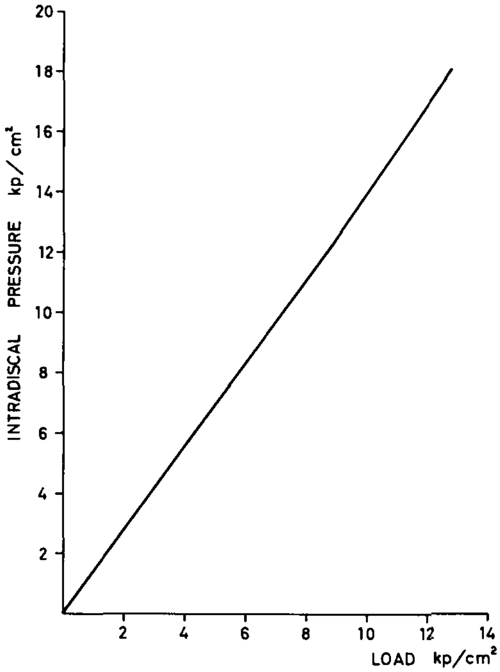


FIG 38.

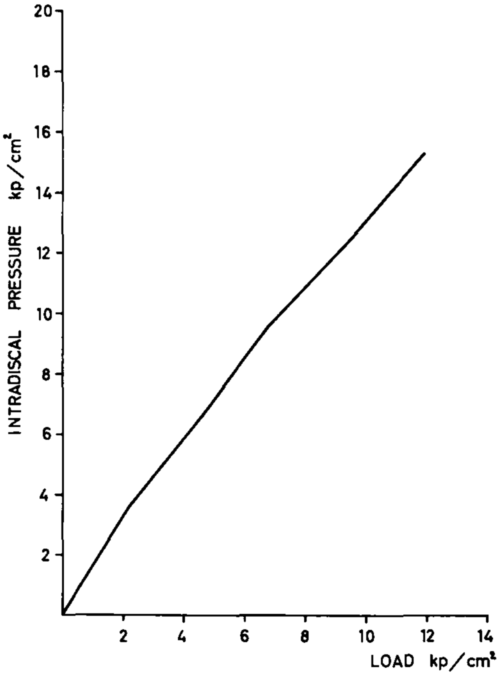


FIG. 39.

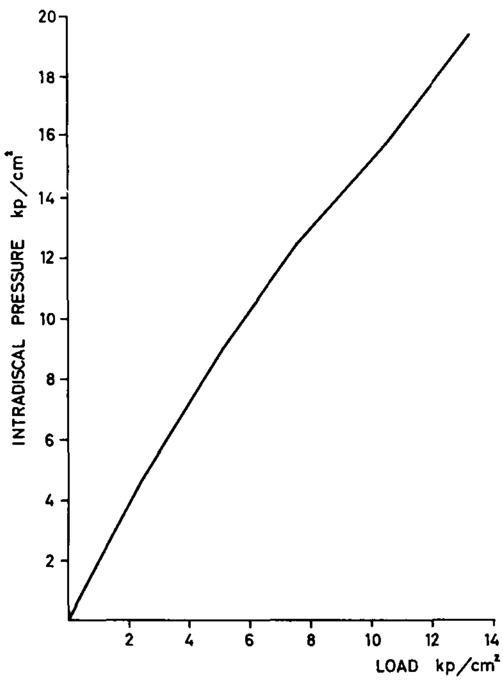


FIG. 40.

FIG. 38. Intradiscal pressure in kp/cm² resulting from increasing external load in the disc shown in Fig. 13 a (267/59 – L 1, age 11, deg. group 1). The surface area was 9.8 cm². Other basic data are given in Table 13, p. 48.

FIG. 39. Intradiscal pressure in kp/cm² resulting from increasing external load in the disc shown in Fig. 14 a (310/59 – L 4, age 38, deg. group 2). The surface area was 18.5 cm². Other basic data are given in Table 14, p. 48.

FIG. 40. Intradiscal pressure in kp/cm² resulting from increasing external load in the disc shown in Fig. 15 a (602/59 – L 3, age 53, deg. group 3). The surface area was 16.7 cm². Other basic data are given in Table 15, p. 48.

TABLE 19.

Intradiscal pressures obtained for different load in all discs tested. Also given are No., age, and storage temperature.

No.	614/59				267/59				606/59				286/58*			
Age in years	6				11				12				18			
Stor. temp. °C	±0°				−25°				±0°				−25°			
Discs tested	L 1	L 2	L 3	L 4	L 1	L 2	L 3	L 4	L 1	L 2	L 3	L 4	L 1	L 2	L 3	L 4
Degree of degeneration	1	1	1	1	1	1	1	1	2	2	2	2	1	1	1	1
Load kp/cm²	Intradiscal pressure kp/cm²															
2	2.7	2.6	2.7	2.7	2.8	2.9	3.2	2.9	2.1	2.1	2.6	2.4	3.5	3.8	3.6	3.5
4	5.3	5.2	5.4	5.3	5.6	5.8	6.4	5.8	4.5	4.5	5.3	5.0	6.7	7.3	6.9	6.6
6	7.9	7.8	8.1	7.8	8.3	8.7	9.1	8.4	7.2	7.0	8.0	7.6	9.3	10.6	9.8	9.6
8	10.6	10.4	10.5	10.4	11.0	11.5	11.8	10.9	9.7	9.3	10.2	9.9	12.6	14.1	13.2	13.0
10	13.3	12.9	12.9	13.0	13.9	14.4	14.7	13.6	11.6	11.0	12.2	11.5	16.1	17.5	16.2	15.8
12	15.8	15.2	15.2	15.4	16.9	—	—	—	13.8	13.0	14.3	13.5	18.9	20.5	18.4	18.3

No.	552/59				500/59				298/58			617/58			
Age in years	20				22				25			27			
Stor. temp. °C	−25°				−25°				−25°			−25°			
Discs tested	L 1	L 2	L 3	L 4	L 1	L 2	L 3	L 4	L 1	L 3	L 4	L 1	L 2	L 3	L 4
Degree of degeneration	2	1	2	2	2	2	3	3	1	2	3	1	1	1	1
Load kp/cm²	Intradiscal pressure kp/cm²														
2	3.2	3.5	3.2	4.0	3.5	3.5	3.7	3.0	3.6	3.5	3.5	2.4	2.7	2.8	2.7
4	6.2	7.0	6.3	7.5	6.6	6.3	6.6	5.9	6.6	6.1	6.2	4.7	4.9	5.3	5.2
6	9.3	10.5	9.4	11.0	9.6	8.9	9.8	9.0	9.5	8.5	9.0	7.0	7.4	7.7	7.7
8	12.5	13.8	12.3	14.3	12.8	11.4	12.3	11.7	12.0	11.0	11.1	9.2	9.3	9.9	9.9
10	14.9	16.5	14.9	17.0	15.4	13.9	14.6	14.2	14.1	13.4	13.5	11.2	11.2	12.0	12.0
12	17.2	19.0	17.0	19.6	17.9	16.8	—	16.9	16.7	—	—	13.3	—	—	—

No.	604/58				607/59				310/59			288/58			
Age in years	35				36				38			41			
Stor. temp. °C	±0°				±0°				−25°			−25°			
Discs tested	L 1	L 2	L 3	L 4	L 1	L 2	L 3	L 4	L 2	L 3	L 4	L 1	L 2	L 3	L 4
Degree of degeneration	1	1	1	1	2	2	2	3	2	2	2	2	2	2	2
Load kp/cm²	Intradiscal pressure kp/cm²														
2	4.0	4.1	3.8	3.7	2.9	3.6	3.1	3.2	3.4	3.3	3.3	3.0	3.3	3.1	3.0
4	7.3	7.3	6.7	6.8	5.9	6.6	5.9	6.2	6.1	6.1	5.8	5.8	6.0	5.9	5.7
6	10.4	10.2	9.4	9.7	8.9	9.6	8.9	9.3	8.8	8.8	8.5	8.4	8.6	8.7	8.3
8	13.5	13.0	12.2	12.4	11.5	12.1	11.3	11.8	11.6	11.5	10.9	10.6	10.5	10.4	10.3
10	15.8	15.3	14.3	14.4	13.9	14.4	13.6	14.2	13.7	13.6	13.1	12.9	12.7	13.0	12.2
12	18.4	17.8	16.5	16.4	16.3	16.8	—	—	16.2	15.8	—	—	—	—	—

Table 19 (*cont.*)

No.	296/58*	292/58				303/59				577/58		258/58*			
Age in years	41	42				48				51		53			
Stor. temp. °C	±0°	±0°				−25°				−25°		−25°			
Discs tested	L 1	L 1	L 2	L 3	L 4	L 1	L 2	L 3	L 4	L 1	L 2	L 1	L 2	L 3	L 4
Degree of degeneration	3	2	2	4	4	4	3	4	4	2	3	2	2	2	2
Load kp/cm²	Intradiscal pressure kp/cm²														
2	3.6	3.4	3.1	1.3	0.4	1.7	3.8	3.0	2.9	3.2	3.2	3.0	3.0	3.2	3.7
4	6.0	6.3	5.8	2.4	0.8	3.3	7.0	5.8	5.8	5.9	5.8	5.9	6.0	6.1	7.3
6	8.8	9.2	8.8	4.5	1.4	5.1	9.8	8.7	8.7	8.3	8.3	8.6	9.2	8.7	10.6
8	11.3	12.1	11.4	5.8	2.0	6.9	13.0	11.7	11.5	11.1	11.0	11.4	12.8	12.0	13.8
10	—	14.4	13.5	7.5	2.9	8.5	15.4	14.0	13.8	13.9	13.1	14.6	15.7	15.0	17.5
12	—	16.9	16.2	—	—	10.1	17.5	16.2	16.3	16.3	15.0	17.2	18.5	17.8	21.0

No.	602/59			262/58*		470/58			309/59				180/59		
Age in years	53			54		55			55				58		
Stor. temp. °C	±0°			−25°		−25°			−25°				−25°		
Discs tested	L 1	L 2	L 3	L 1	L 2	L 1	L 2	L 3	L 1	L 2	L 3	L 4	L 1	L 2	L 3
Degree of degeneration	2	3	3	2	2	2	2	3	3	3	4	4	4	4	4
Load kp/cm²	Intradiscal pressure kp/cm²														
2	3.1	4.0	3.8	3.2	3.4	3.7	3.5	3.0	3.5	3.1	2.3	0.6	2.6	2.7	1.1
4	6.1	7.4	7.2	6.3	6.5	6.9	6.4	5.7	6.3	5.9	4.7	2.3	5.0	5.6	2.3
6	9.1	10.5	10.3	9.4	9.5	9.7	9.0	8.5	8.8	8.3	6.9	4.9	7.6	8.1	3.3
8	11.9	13.4	13.0	12.7	12.8	12.8	11.5	11.8	11.0	10.4	9.1	7.3	9.7	—	—
10	14.4	16.0	15.2	15.5	15.6	16.0	13.8	14.2	13.0	12.4	—	9.6	—	—	—
12	16.8	18.5	17.8	18.5	18.4	19.2	16.0	—	15.5	14.5	—	—	—	—	—

No.	144/58				573/58			580/58		631/58				310/58*	
Age in years	60				60			65		65				67	
Stor. temp. °C	−25°				−25°			−25°		±0°				±0°	
Discs tested	L 1	L 2	L 3	L 4	L 2	L 3	L 4	L 2	L 4	L 1	L 2	L 3	L 4	L 2	L 3
Degree of degeneration	3	3	3	4	4	4	4	3	3	2	2	3	4	2	3
Load kp/cm²	Intradiscal pressure kp/cm²														
2	3.6	3.8	3.3	3.0	2.8	2.3	0.4	3.1	3.3	3.5	3.7	3.0	1.7	2.8	2.8
4	6.5	6.8	6.1	5.6	5.5	4.7	2.8	6.2	6.0	6.6	6.6	5.7	3.5	5.5	5.4
6	9.9	10.0	9.1	8.7	8.3	7.3	5.7	9.3	9.0	9.7	9.4	8.3	6.1	8.6	8.4
8	13.0	12.6	11.7	11.4	10.3	9.3	8.7	12.2	11.8	12.9	12.4	10.9	8.4	11.4	11.1
10	15.7	15.4	14.3	13.8	12.3	11.0	—	14.6	14.4	15.2	14.6	13.3	10.4	14.2	—
12	18.2	—	—	15.8	—	13.2	—	—	—	17.7	16.7	15.1	—	—	—

Table 19 (*cont.*)

No.	169/59				572/58				467/58	248/58*	270/58*			311/58*	
Age in years	68				68				70	70	71			74	
Stor. temp. °C	−25°				±0°				−25°	−25°	−25°			±0°	
Discs tested	L 1	L 2	L 3	L 4	L 1	L 2	L 3	L 4	L 1	L 2	L 1	L 2	L 3	L 1	L 2
Degree of degeneration	3	4	4	4	4	3	3	3	2	3	3	2	3	3	3
Load kp/cm²	Intradiscal pressure kp/cm²														
2	2.6	2.6	2.4	2.0	1.9	3.4	3.7	3.7	3.4	2.7	3.2	2.9	2.7	3.0	3.0
4	5.3	4.9	4.8	4.2	3.6	6.5	6.8	6.6	6.4	5.0	6.3	5.9	5.4	5.8	6.0
6	8.0	7.6	7.5	6.6	6.2	9.4	10.4	9.9	9.0	6.7	9.5	9.0	7.9	8.6	9.1
8	10.4	10.1	9.7	8.6	8.0	11.9	13.1	12.3	12.0	9.9	12.4	12.1	10.7	11.7	12.3
10	12.8	—	11.7	—	9.8	14.3	15.6	14.6	15.0	13.4	15.2	15.0	13.3	14.4	15.1
12	—	—	—	—	—	—	—	—	17.9	15.7	17.7	17.8	15.4	17.0	18.1

No.	183/59			593/59			257/58*			259/58*		592/59			
Age in years	77			77			77			81		82			
Stor. temp. °C	−25°			−25°			−25°			−25°		±0°			
Discs tested	L 1	L 2	L 3	L 1	L 2	L 3	L 2	L 3	L 4	L 2	L 3	L 1	L 2	L 3	L 4
Degree of degeneration	4	4	4	4	4	4	3	3	3	2	2	4	4	4	4
Load kp/cm²	Intradiscal pressure kp/cm²														
2	3.8	2.9	2.9	2.4	2.0	0.9	2.9	3.3	3.4	2.9	2.9	0.3	0.2	0.9	1.4
4	7.3	5.7	5.7	4.9	4.5	2.4	5.5	6.4	6.7	5.8	5.7	1.0	0.7	2.4	3.0
6	10.3	8.5	8.8	7.3	6.7	4.3	8.0	9.4	9.8	8.9	8.5	1.9	1.0	4.0	4.3
8	12.9	11.2	11.6	9.4	—	—	10.9	12.9	13.4	11.8	12.1	2.9	1.2	—	5.7
10	—	—	13.2	—	—	—	13.6	15.5	16.2	14.6	14.5	—	—	—	—
12	—	—	—	—	—	—	16.1	—	—	17.0	16.8	—	—	—	—

Those marked * are measured with the "PE 60"-gauge.

TABLE 20.

Mean values of intradiscal pressures according to load and degree of degeneration.

No. of specimens in each group is given in brackets [].

Degree of degeneration		1		2		3	
		kp/cm²		kp/cm²		kp/cm²	
Load kp/cm²	2	3.2	[22]	3.2	[39]	3.3	[31]
	4	6.1	[22]	6.1	[39]	6.2	[31]
	6	8.9	[22]	8.9	[39]	9.1	[31]
	8	11.6	[22]	11.7	[39]	11.8	[31]
	10	14.1	[22]	14.2	[39]	14.4	[29]
	12	17.0	[16]	16.9	[31]	16.6	[15]

TABLE 21.

Mean values of pressure in nucleus pulposus in kp/cm² ± error of the mean.

Level	L 1	L 2	L 3	L 4
Degree of degeneration	1	1	1	1
Load kp/cm² 2	3.17±0.25	3.27±0.25	3.22±0.22	3.10±0.21
4	6.03±0.40	6.25±0.44	6.14±0.33	5.94±0.33
6	8.73±0.50	9.20±0.58	8.82±0.40	8.64±0.43
8	11.48±0.63	12.02±0.79	11.52±0.59	11.32±0.59
10	14.07±0.73	14.63±0.95	14.02±0.73	13.76±0.64
12	16.67±0.82	18.13±1.12	16.70±0.66	16.70±0.60

Level	L 1	L 2	L 3	L 4
Degree of degeneration	2	2	2	2
Load kp/cm² 2	3.17±0.11	3.17±0.12	3.11±0.10	3.28±0.28
4	6.11±0.16	6.00±0.16	5.93±0.11	6.26±0.49
6	8.95±0.19	8.87±0.18	8.69±0.14	9.20±0.67
8	11.85±0.27	11.62±0.26	11.35±0.28	11.84±0.92
10	14.44±0.33	14.05±0.34	13.78±0.34	14.26±1.25
12	17.14±0.39	16.67±0.45	16.34±0.36	18.03±2.30

Level	L 1	L 2	L 3	L 4
Degree of degeneration	3	3	3	3
Load kp/cm² 2	3.25±0.16	3.30±0.14	3.26±0.14	3.35±0.10
4	6.03±0.18	6.21±0.23	6.14±0.21	6.27±0.13
6	8.93±0.28	8.94±0.36	9.12±0.30	9.33±0.17
8	11.63±0.39	11.76±0.37	11.94±0.31	12.02±0.10
10	14.22±0.58	14.33±0.34	14.50±0.32	14.52±0.37
12	17.10±0.59	16.49±0.59	16.10±0.85	16.90±

means and the errors of the means for groups 1, 2 and 3 are given. For each level (L 1–L 4) values have been given for loads from 2–12 kp/cm². Table 22 shows the differences between groups 1 and 3 with regard to the mean pressures for every disc and for every outer load, together with ± the error of the mean for these differences. It should be noticed, that in this comparison, each individual contributes only one pressure value for each difference.

The similarity between degeneration groups 1 and 3 is evident in Table 20, but is not so striking on closer statistical analysis (Tables 21 and 22). There

TABLE 22.

Difference (± mean error) between the degenerative groups 3 and 1, with respect to mean of intradiscal pressures.

Load		L 1	L 2	L 3	L 4
kp/cm^2	**2**	0.1 ± 0.3	0.0 ± 0.3	0.0 ± 0.3	0.2 ± 0.2
	4	0.0 ± 0.4	0.0 ± 0.5	0.0 ± 0.4	0.3 ± 0.4
	6	0.2 ± 0.6	-0.3 ± 0.7	0.3 ± 0.5	0.7 ± 0.5
	8	0.2 ± 0.7	-0.3 ± 0.9	0.4 ± 0.7	0.7 ± 0.6
	10	0.1 ± 0.9	-0.3 ± 1.0	0.5 ± 0.8	0.8 ± 0.7
	12	0.4 ± 1.0	-1.6 ± 1.3	-0.6 ± 1.1	$0.2 \pm$

are, however, no significant differences between the two groups. Thus, it can be seen that the recorded differences are substantially less than the errors of the means, which are, however, of such a size that it is uncertain whether an investigation based on a larger material would give the same good agreement as that shown in the table of mean values (Table 20). It can be established that pressures in groups 1 and 3 are of the same order of magnitude within a range of 15%, i.e. that the difference plus the error does not exceed 15% of the average pressure for the respective load and disc. The same can be said of the difference minus the error of the mean. These statistical calculations also show that the level of the disc in the lumbar region does not affect the pressures obtained to any great extent.

Intradiscal pressure according to age

In comparing different age groups, notice must be taken of a number of different factors. Certain of these factors, such as the level of the disc in the lumbar spine and the degree of degeneration, have been described in this material. Other factors, such as the water content of the nucleus pulposus and its chemical composition, were not recorded.

In this analysis, the material was divided into different degrees of degeneration. Because of this, notice had to be taken of these factors when comparisons were made of the different age groups. However, Tables 20 and 21 show that groups 1, 2 and 3 do not react in different ways to pressure, so that a possible difference between age groups concerning pressure values could not be traced to differences in the types of macroscopic changes in the discs collected here. Table 23 shows the mean values of the increase in pressures in the nucleus pulposus with external loading of 2–12 kp/cm^2 for the different age groups 0–15 years, 16–30, 31–45, 46–60, 61 and older.

TABLE 23.

Mean values of intradiscal pressures according to load and age group.

Number of specimens in each group is given in brackets [ ].

Age group	0–15		16–30		31–45		46–60		>60	
	Intradiscal pressure kp/cm²									
Load kp/cm² 2	2.6	[12]	3.3	[19]	3.4	[18]	3.4	[20]	3.1	[23]
4	5.3	[12]	6.3	[19]	6.2	[18]	6.4	[20]	6.0	[23]
6	8.0	[12]	9.1	[19]	9.1	[18]	9.3	[20]	8.9	[23]
8	10.5	[12]	11.9	[19]	11.6	[18]	12.2	[20]	11.9	[23]
10	12.9	[12]	14.4	[19]	13.8	[17]	14.8	[20]	14.5	[22]
12	14.8	[9]	17.7	[13]	16.7	[10]	17.5	[17]	16.8	[13]

In Fig. 41, the material is grouped so that the mean value of the nucleus pressures in the respective age groups for every individual load is graphically reproduced. The difference between the younger and older age groups can be seen in these graphs. It is clear that the values for the youngest age group diverge from the others. It is also seen that the pressures in the oldest age group show a tendency to fall for each external load; this is, however, not statistically significant.

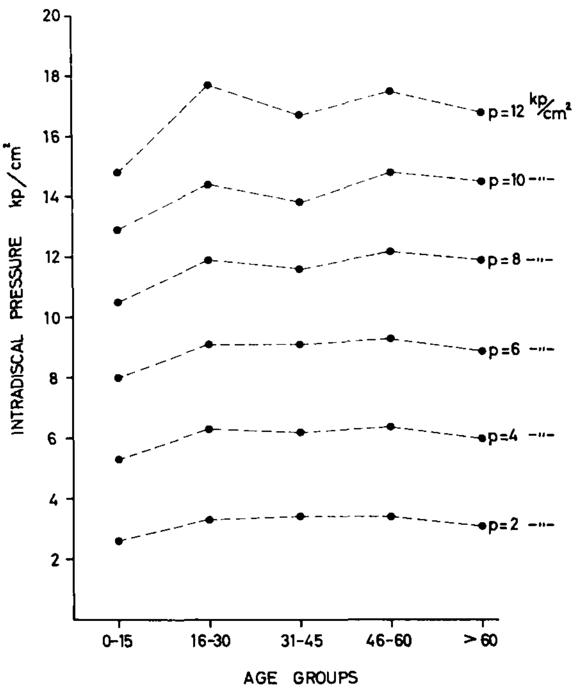


FIG. 41. Intradiscal pressures according to age group and different external loads (p).

If the pressures from individuals under 16 years of age are compared with those from individuals between 16 and 45 years of age, it is seen that pressures in the youngest group are lower than in the elder. A closer analysis shows furthermore that this difference is statistically significant. For this purpose, use was made of a rank-test.

The material comprises 14 individuals, 3 in the younger and 11 in the elder group. These 14 individuals were ranked in relation to the pressures corresponding to loads of 2, 4, 6, 8 and 10 kp/cm². The ranking was based on the individual mean pressure from discs L 1, L 2, L 3 and L 4. The individual with the lowest mean pressure was ranked as no. 1, the next was ranked as no. 2, etc. The individuals in the younger group, were given the following order of rank. With a load of:

2 kp/cm²	1, 3 and 4
4 kp/cm²	1, 3 and 5
6 kp/cm²	1½, 3 and 6
8 kp/cm²	2, 4 and 6
10 kp/cm²	1, 4 and 7
all the above loads	1, 3 and 5

The probability of finding three younger persons out of 14 occupying three of the four lowest rank numbers by chance, is

$$\frac{4 \cdot 3 \cdot 2}{14 \cdot 13 \cdot 12} = \frac{1}{91} \approx 1\,\%$$

With a load of 2 kp/cm² it is found that the three youngest individuals occupy three of the four lowest rank numbers. There is thus a significant difference at the 1 % level between the intradiscal pressures of younger and elder persons for this load.

With a load of 4 kp/cm² and ranking based on all the loads from 2–10 kp/cm² it is found that the younger individuals occupy three of the five lowest rank numbers. The corresponding probability is

$$\frac{5 \cdot 4 \cdot 3}{14 \cdot 13 \cdot 12} = \frac{5}{182} \approx 3\,\% < 5\,\%$$

There is thus a significant difference at the 5 % level between the disc pressures of younger and elder individuals. The tendency to lower pressures in the youngest age group seen in Fig. 41 is thus statistically significant.

Technical considerations

The values of intradiscal pressures presented, show that they exceeded the external load per unit of area which was applied in a vertical direction to a preparation consisting of a lumbar intervertebral disc with adjacent slices of bone. The pressures in the nucleus pulposus were found to be about 50 % greater than the applied load per unit of area. From this fact it follows that the vertical pressure in the annulus fibrosus is less than the applied load per unit of area.

In fact, one obtains the following equation:

$$p_a \cdot A_a + p_n \cdot A_n = p\ (A_a + A_n), \tag{1}$$

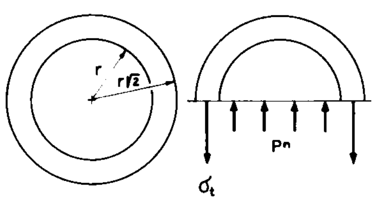
where p_a = vertical load on annulus per unit of area, p_n = pressure in nucleus pulposus, p = total vertical load per unit of area, A_a = area of annulus, and A_n = area of nucleus. Thus one obtains

$$p_a = p\left(1 + \frac{A_n}{A_a}\right) - p_n \cdot \frac{A_n}{A_a} \tag{2}$$

Thus because $p_n \approx 1.5\ p$ and $A_n \approx A_a$ in the groups 1, 2, 3, one obtains $p_a \approx 0.5\ p$, i.e. the vertical load on annulus per unit of area was about 50% of the mean load per unit of area.

Because of the relatively high pressure in the nucleus, however, the annulus fibrosus was exposed to considerable tensile stresses in a tangential direction. Assume for simplicity that the nucleus and annulus formed two concentric circular cylinders (Fig. 42) with outer radii r and $r\sqrt{2}$, respectively. One then obtains approximately (symbols are given in Fig. 42)

FIG. 42.



$$\sigma_t \cdot 2(r\sqrt{2} - r) = p_n \cdot 2r$$

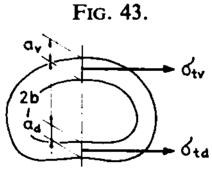
$$\sigma_t = \frac{1}{\sqrt{2} - 1} p_n \approx 2.5\, p_n$$

$$\text{with } p_n \approx 1.5\, p$$

$$\sigma_t \approx 3.75\, p \tag{3}$$

The radial thickness of annulus is far from constant. Fig. 43 shows a cross-section of a typical disc. One obtains approximately:

FIG. 43.



$$\begin{cases} \sigma_{tv} \cdot a_v + \sigma_{td} \cdot a_d = p_n \cdot 2b \\ \sigma_{tv} \cdot a_v \left(b + \frac{a_v}{2}\right) = \sigma_{td} \cdot a_d \left(b + \frac{a_d}{2}\right), \end{cases}$$

where the symbols are explained by Fig. 43.

Thus

$$\sigma_{td} = \frac{2b\,(2b + a_v)}{a_d(4b + a_d + a_v)} p_n \tag{4}$$

For instance, for a disc (604/58 – L 4, Fig. 13 b, p. 38) $b = 14$ mm, $a_v = 7$ mm, $a_d = 4$ mm, and thus $\sigma_{td} = 3.7\ p_n$.

Further for a load per unit of area $p=10$ kp/cm^2 on the disc under consideration, the measurements have shown $p_n=14.4$ kp/cm^2 and thus

$$\sigma_{td}=3.7\times 1.44\ p=5.3\ p. \tag{5}$$

Now the value of σ_{td} applied to a healthy disc, i.e. one where no changes are seen in the nucleus pulposus or the annulus fibrosus. Only in such discs is it possible to give a more exact measurement of the breadth of the annulus. In discs with degenerative changes, it was found more difficult to define a_v and a_d respectively.

If the same calculation was carried out on the disc in Fig. 15 a, p. 39 (602/59 – L 3), the result obtained is $a_v=12$ mm, $a_d=6$ mm, $b=10$ mm, and thus, according to the formula (4), $\sigma_{td}=1.84\ p_n$.

For a load per unit of area $p=10$ kp/cm^2 on the disc under consideration, the intradiscal pressure $p_n=15.2$. Thus

$$\sigma_{td}=1.84\cdot 1.52\ p=2.8\ p. \tag{6}$$

The selected discs can be said to provide rather extreme examples of the distribution between a_v+a_d and b in a cross-section according to Fig. 43.

The values obtained for σ_{td} thus agree rather well with the approximate relation (3).

Thus it has been shown that, due to the comparatively high pressure in the nucleus, the vertical stress in the annulus was comparatively small, while the tangential stress was rather high, between 3 and 5 times the total load per unit of area.

The radial stiffness of the end-plate of the discs, however, will tend to lower the tangential strain on the annulus and thus the tangential stress will be somewhat lower too. Thus radial stresses are set up in the end-plates in such a way, that a high radial stress in the end-plate implies a lower tangential stress in the annulus and vice versa. It has not been possible to ascertain whether the radial stresses in the end-plate or the tangential stresses in the annulus play the most important part in the production of damage to the disc. On the other hand it is known that the tangential stress is distributed somewhat differently over the breadth of the annulus, so that the innermost parts must withstand a somewhat higher strain than the outer. For this reason, the above estimation of the tangential stress is not considered unrealistic, at least concerning the inner sheets of the annulus.

Discussion

Many authors have come to the conclusion that there is much to support the theory of a strong mechanical component when the annulus ruptures (Keyes and

Compere 1932, Williams 1937, Junghanns 1954, Hirsch and Nachemson 1954, and others). In animal experiments, Hansen (1950, 1956), Lindblom (1951, 1957) and others found that radial fissures are generally encountered in those places, where the mechanical strains are greatest.

The annulus fibrosus is laid down mainly in cylindrical sheets around the disc, arranged biaxially to procure elasticity. In these cylinders the collagen fibrils are oriented almost perpendicular to the vertebral column (Happey, Mac Rae and Naylor 1953). The collagen fibrils in the different sheets go in an oblique spiral from one vertebral body to another (Armstrong 1952), and Horton (1958) showed the increase in the angle between the different sheets of these collagen fibrils were probably associated with the elasticity of the disc.

Thus the structure of the annulus would seem to be designed to take up tensile stresses.

The results of this study demonstrate that the pressures in the nucleus pulposus are higher than the applied load per unit of area. This is accompanied by an increased tangential stress in the annulus fibrosus, while the vertical pressure in the annulus fibrosus is lower in comparison with the applied load per unit of area. If the nucleus has a larger surface than the annulus, the vertical pressure in the annulus fibrosus is given by eq. (2).

It can also be established from eq. (4) that the tensile stresses in the annulus fibrosus are rather high, between three and five times the applied load per unit of area.

The tensile strength of isolated parts of the annulus fibrosus, which had been cut out, was investigated by Brown, Hansen and Yorra (1957), who found it to be 30–50 kp/cm^2. According to eqs. (5) and (6) these values approximate $p = 8$–13 kp/cm^2 and 10–17 kp/cm^2 respectively. These values for p, however, are rather small. The mean area of the 80 cross-sectioned discs from individuals > 15 years of age in the groups 1–3 in this material is 16.7 cm^2 (11.6–23.7 cm^2). For instance, for a value of $p = 10$ kp/cm^2 the total load (P) sufficient to tear the annulus, would then be $P = p \cdot A \approx 170$ kp.

It is clearly seen that this value is too small, because no tensile fractures in the sheets of the annulus fibrosus have been observed as a result of static compression to this load. The value for the tensile strength given by the above-mentioned authors might be too low (their conclusions are based on 2 experiments on isolated parts of the annulus fibrosus). On the other hand the explanation might lie in the fact that the radially acting pressure from the nucleus pulposus is taken up by radial stresses in the end-plate, which, as mentioned above, implies a decrease of the tangential stress in the annulus fibrosus.

The pattern of the ruptures in the annulus fibrosus, which are sometimes seen in cross-sectioned discs, agrees well with that of so-called tensile fractures (Fig. 15, p. 39).

On comparing the different age groups, it was found that the pressures in the nucleus pulposus obtained from vertical loading of the discs were lower in individuals under 16 years than in those who were older. The pressures remain rather similar, independent of whether the discs are intact (group 1) or whether they show a mild degree of degeneration (groups 2 and 3). The level of the disc in the lumbar spine does not influence the amount of the pressures, assuming that it is not affected by any severe structural changes.

CHAPTER 9

The influence of removal of the pedicles and facets on the intradiscal pressure

The pedicles arise from the upper two-thirds of the vertebral bodies and join the laminae. The articular processes which arise from the junction of pedicles and laminae behind the transverse processes are almost vertical. The articular facets on the superior processes are concave, while those on the inferior process are convex. The position of the facets can vary considerably (Güntz 1934, Hagelstam 1949). In general, it is considered that a vertical load placed on the back is transmitted from one vertebral body to another through the intervertebral disc. The facets have usually been considered as important only in preventing forward and backward gliding and rotation (Fick 1904, Keyes and Compere 1932, Armstrong 1952, Spurling 1953, and others).

Kelly (1958) was of the opinion that the most important force-bearing structures in the back were the pedicles and the joint processes.

During experiments on post-mortem specimens, Hirsch and Nachemson (1954)

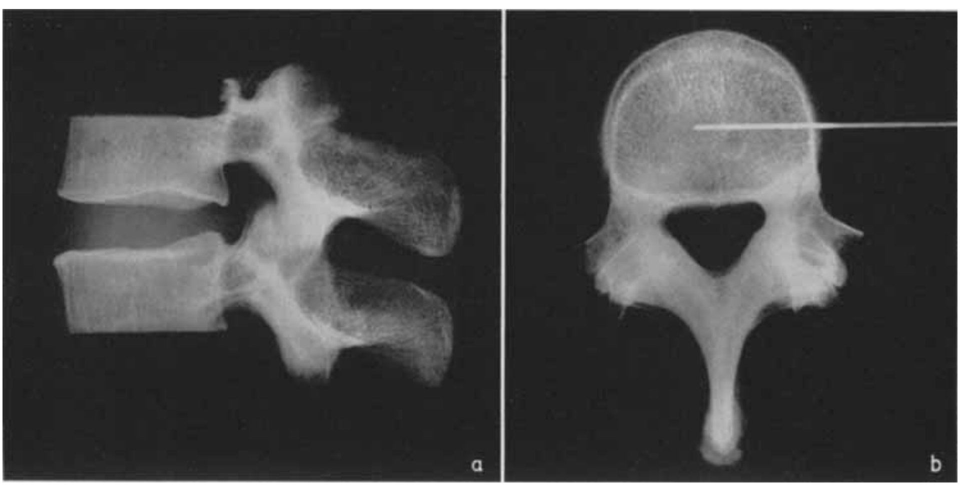


FIG. 44. Roentgenographic appearance of a specimen (298/58 – L 3, age 25, deg. group 2, fig. 14 b) where the pedicles and facets have been preserved. Scale 1:2.

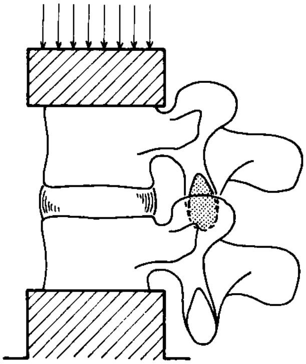


FIG. 45. Method of loading the specimens with preserved pedicles and facets.

were unable to find that removal of the pedicles and facets on one or both sides had any appreciable influence on the amount of compression of the different discs.

It was therefore thought to be of interest to study in addition what effect the removal of the arches and articular facets would have on the pressure of the nucleus pulposus.

The discs were prepared so that the greater part of the arches and the joint processes was saved, and thus a posterior connection was formed from the upper to the lower of the vertebral bodies adjoining the disc (Fig. 44). The way in which the specimen was then put into the compression apparatus is shown schematically in Fig. 45. A certain amount of the load might then be taken up by the intervertebral joints via the pedicles. In these cases the measurements of pressure in the nucleus pulposus were made with the needle inserted from the lateral border of the disc. Of the fourteen discs, prepared in this way, four were transferred to degeneration group 4 after the experiments and not included in Table 24

TABLE 24.

Specimens subjected to experiments with and without posterior bony elements.

No.	Age in years	Discs tested	Degree of degeneration	Compressive stress measured
267/59	11	L 3	1	$\lvert\sigma_v\rvert$
552/59	20	L 2	1	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
		L 4	2	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
500/59	22	L 2	2	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
298/58	25	L 1	1	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
		L 3	2	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
607/59	36	L 3	2	$\lvert\sigma_d\rvert$
292/58	42	L 1	2	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
303/59	48	L 2	3	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
602/59	53	L 3	3	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$

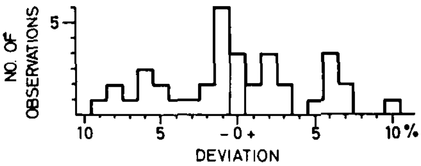


FIG. 46. The % deviation of $|\sigma_v|$ from the mean of $|\sigma_v|$ and $|\sigma_d|$ in specimens with preserved pedicles and facets.
No. of observations: 40. Mean: −0.3 %.

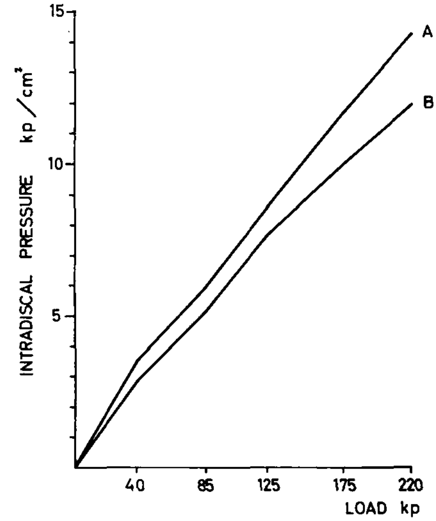


FIG. 47. Intradiscal pressure in a disc (298/58 – L 3, figs. 14 b and 44) after (a) and before (b) removal of the posterior bony elements.

which shows number, level, degree of degeneration and directions of compressive stresses studied. In eight of these discs the compressive stresses were measured in two different directions.

In Fig. 46 is shown the deviation of the vertically measured values in % from the mean of the vertical and horizontal measurements. As seen from this diagram, the compressive stresses in these directions were almost the same. This agrees completely with the results on the discs in groups 1, 2 and 3 previously described.

After this, the arches and joint processes were removed and new measurements of pressure carried out (Fig. 47). In Table 25 the % difference is shown for the pressures of each disc at each different load, between values obtained before and after removal of the pedicles and facets. This shows that under these conditions, the removal of the arches and joint processes increases the intradiscal pressure on the average by 18%. The individual variations are rather large and could be thought to depend on the variations in position and form of the facets.

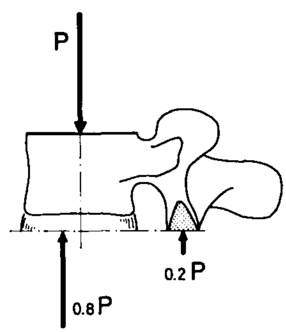


FIG. 48. The force-bearing capacity of the pedicles and facets, when the disc is loaded as shown in fig. 45, p. 76.

TABLE 25.

Changes in intradiscal pressure with varying loads following removal of posterior bony elements.

The increase in pressure is given as % of the value obtained before the removal of the posterior bony elements.

No.	267/59	552/59		500/59	298/58		607/59	292/58	303/59	602/59
Age in years	11	20		22	25		36	42	48	53
Discs tested	L 3	L 2	L 4	L 2	L 1	L 3	L 3	L 1	L 2	L 3
Degree of degeneration	1	1	2	2	1	2	2	2	3	3
Load kp **40**	+38	+22	+16	+21	+14	+22	+12	+17	+24	+11
85	+27	+26	+19	+ 7	+16	+19	+ 3	+23	+28	+14
125	+31	+23	+17	+ 8	+11	+12	+ 3	+21	+36	+13
175		+21	+18	+12	+12	+12	+ 6	+26	+25	+12
220		+22	+15	+14	+11	+18	+ 5	+26	+29	+12

Mean + 18 %.

40 kp: + 20 %, **85** kp: + 18 %, **125** kp: + 18 %, **175** kp: + 16 %, **220** kp: + 17 %.

Discussion

The results show that, when the disc was loaded as shown in Fig. 45, removal of the arches and joint processes caused the intradiscal pressure to rise. The implication was that the facets took up a certain share of the vertical load applied to the spine. This is made clear schematically in Fig. 48. If this load was similar to that used during the experiments, this part amounted to about 20%.

CHAPTER 10

The influence of storage in the refrigerator and deep-freezer on the pressure in the nucleus pulposus

Spurling (1953) claimed that since the disc serves a purely mechanical purpose, it is probably capable of maintaining its structure at a very low metabolic rate. The investigations of disc elasticity previously performed (Göcke 1932, Virgin 1951 and 1958, Ingelmark and Ekholm 1952, Hirsch and Nachemson 1954, Perey 1957, Evans 1957, Brown, Hansen and Yorra 1957, Evans and Lissner 1959, and others) were made on post-mortem material. After removal at post-mortem, the lumbar spine was kept in the refrigerator or deep-freezer. Bartelink (1957), Decoulx and Rieunau (1958), Evans and Lissner (1959) have pointed out that it is unlikely that the discs undergo a sudden physical change. A few days' storage in the deep-freezer before the specimen was tested was not considred to influence the physical properties of the disc (Bartelink 1957, Hardy, Lissner, Webster and Gurdjian 1958).

Rauber (1876) showed that the modulus of elasticity for bone varied with temperature and degree of moisture in the bone.

Since it must be assumed that discs undergo post-mortem changes, it would naturally have been of interest to study the properties of the disc immediately after death. This was not possible for practical reasons.

Since the specimens included in this material were stored in two different ways, an investigation was made whether the hydrostatic properties of the disc and the size of the pressures were appreciably changed following storage in a deep-freezer or refrigerator. All the bodies during the 1–6 days between death and removal of the lumbar spines, were kept in cold storage.

As previously shown in Table 10, p. 37, the experiments were carried out either after storage for one more day in the refrigerator, or after a number of days in the deep-freezer. Thus the material, consisting of 64 discs, shown in the Fig. 22, was stored either in the refrigerator or in the deep-freezer before the experiments were carried out. If this material is divided in relation to the different methods of storage, no difference is found whether one chooses to study:

1. The percentage deviations of $|\sigma_v|$, $|\sigma_d|$ and $|\sigma_l|$ from the mean pressure (Fig. 49).
2. The percentage deviation of $|\sigma_v|$ in comparison with $|\sigma_l|$ (Fig. 50).

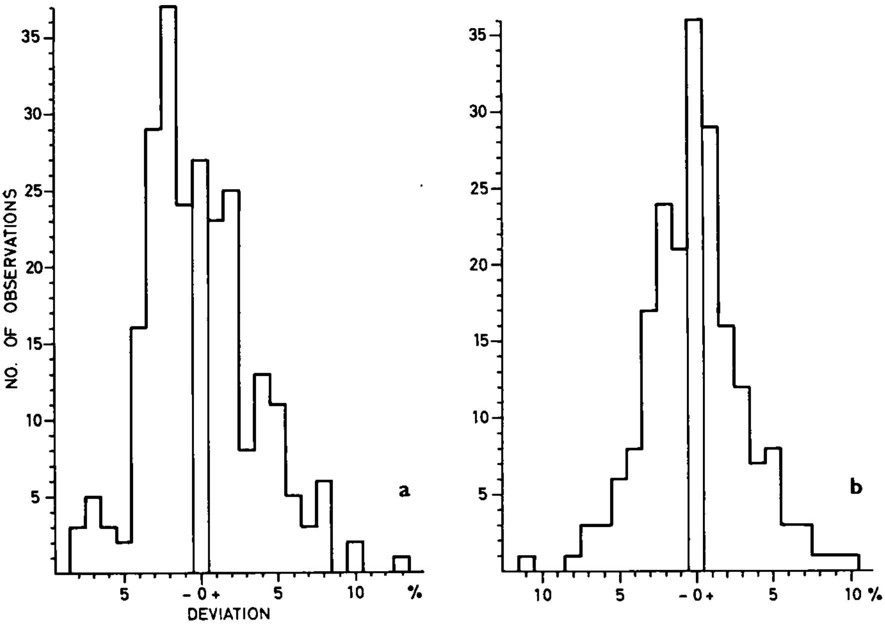


FIG. 49. The % deviation of $|\sigma_v|$, $|\sigma_l|$ and $|\sigma_d|$ from the mean pressure when the material is divided in relation to the different methods of storage.
a. Refrigerator. No. of observations: 243. The mean of absolute deviation: 2.7%.
b. Deep-freezer. No. of observations: 201. The mean of absolute deviation: 2.3%.

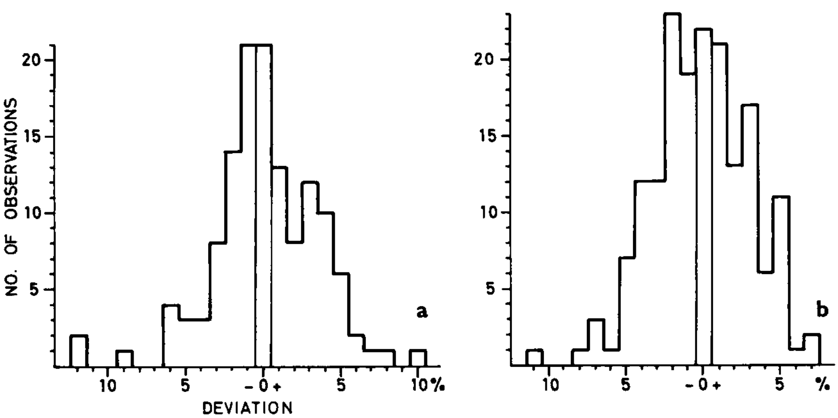


FIG. 50. The % deviation of $|\sigma_v|$ from the mean of $|\sigma_v|$ and $|\sigma_l|$ grouped according to different methods of storage.
a. Refrigerator. No. of observations: 131. Mean: +0.1%. The mean of absolute deviation: 2.5%.
b. Deep-freezer. No. of observations: 172. Mean: −0.2%. The mean of absolute deviation: 2.4%.

TABLE 26.

Mean values of intradiscal pressures for various external loads, with respect to level and storage temperature.

The number of specimens in each group is given in brackets [ ].

Level	L 1		L 2		L 3		L 4	
Storage temp. °C	±0°	−25°	±0°	−25°	±0°	−25°	±0°	−25°
	kp/cm²	kp/cm²	kp/cm²	kp/cm²	kp/cm²	kp/cm²	kp/cm²	kp/cm²
Load kp/cm²								
2	3.1 [9]	3.2 [16]	3.2 [10]	3.2 [19]	3.2 [8]	3.2 [14]	3.1 [5]	3.3 [11]
4	6.0 [9]	6.1 [16]	6.1 [10]	6.1 [19]	6.1 [8]	6.1 [14]	6.0 [5]	6.2 [11]
6	8.9 [9]	8.9 [16]	9.0 [10]	8.9 [19]	9.0 [8]	8.9 [14]	8.9 [5]	9.2 [11]
8	11.7 [9]	11.7 [16]	11.8 [10]	11.9 [19]	11.5 [8]	11.7 [14]	11.4 [5]	11.9 [11]
10	14.1 [8]	14.4 [16]	14.1 [10]	14.3 [19]	13.9 [7]	14.2 [14]	13.5 [5]	14.5 [11]
12	16.6 [8]	17.2 [14]	16.5 [8]	17.1 [14]	15.8 [5]	16.9 [6]	15.1 [3]	19.0 [4]

3. The size of the pressures by comparing the mean values for the varying loads on the discs in the different groups (Tab. 26).

In addition, the measurements were repeated on seven specimens after one day's storage in the refrigerator and a slow warming up to room temperature. The percentage deviation of $|\sigma_v|$ in comparison with the mean value of $|\sigma_v|$ and $|\sigma_l|$ has been calculated for the repeated measurements (Fig. 51 a). The percentage

TABLE 27.

Repeated experiments on specimens after 1 day of storage at ±0°C.

In the table are shown the differences in % between the second and the first measurements of intradiscal pressure (i.e. $\frac{\text{second value} - \text{first value}}{\text{first value}} \cdot 100$).

No.	298/58			606/59			
Discs tested	L 1	L 3	L 4	L 1	L 2	L 3	L 4
Degree of degeneration	1	2	3	2	2	2	2
Load kp **40**	−3.6	−6.0	±0	+9.8	+2.0	−1.8	+0.9
85	−4.8	−3.7	+8.1	−1.2	−3.9	+2.5	−3.7
125	−2.0	+0.6	+3.2	−3.4	−2.2	−3.3	−4.9
175	+3.7	+0.4	+4.4	+1.2	+3.6	+1.5	+0.9
220	+2.2	−2.9	+2.9	−0.2	+3.1	−0.9	±0

Mean +0.1 %.
The mean of the absolute deviation: 2.8 %.

Table 28.

Repeated experiments on specimens after storage at $-25°C$.

In the table are shown the number of days stored and the differences in % between the second and the first measurements of intradiscal pressure (i.e. $\frac{\text{second value} - \text{first value}}{\text{first value}} \cdot 100$).

No.	602/59	577/58		631/58			607/59			
Discs tested	L 3	L 1	L 2	L 1	L 2	L 3	L 1	L 2	L 3	L 4
Degree of degeneration	3	2	3	2	2	3	2	2	2	3
Days stored	3	12	12	14	14	14	16	16	16	16
Load kp 40	− 5.4	−5.5	−6.3	− 2.2	−2.2	+13.0	−2.9	− 2.5	−4.6	−8.8
85	−10.4	−6.9	−1.4	− 4.5	−3.1	+ 2.1	−7.8	− 8.5	±0	−3.7
125	− 5.4	−7.4	−4.2	−10.9	−3.8	+ 4.0	−6.7	−10.3	−6.2	−9.1
175	− 4.9	−6.6	+2.8	− 6.0	−1.7	− 0.7	−2.2	−10.7	−6.3	−9.7
220	− 7.3		+0.3	− 4.7	±0	+ 5.0	−2.4	− 5.9	−4.2	−7.9

No.	604/58		500/59		288/58		267/59			
Discs tested	L 3	L 4	L 1	L 2	L 2	L 3	L 1	L 2	L 3	L 4
Degree of degeneration	1	1	2	2	2	2	1	1	1	1
Days stored	16	16	22	22	22	22	24	24	24	24
Load kp 40	−10.0	−5.4	+5.8	+ 5.0	+10.6	+10.2	+7.4	+ 7.8	+5.3	+4.2
85	− 6.2	−6.4	+1.6	+ 9.8	+ 2.4	+ 6.8	+5.1	+ 7.1	+8.6	+5.6
125	− 3.2	−6.0	−0.6	+14.5	+ 0.6	− 1.2	+8.3	+11.4	+7.0	+7.0
175	− 2.2	−1.2	+1.1	+14.3	+ 1.4	+ 5.1				
220	− 1.9	+0.6	−3.0	+12.0	+ 1.8	+ 5.2				

Mean −0.6 %. The mean of the absolute deviation: 5.5 %.

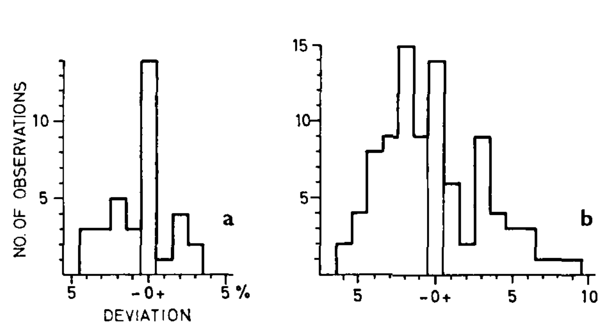


FIG. 51.

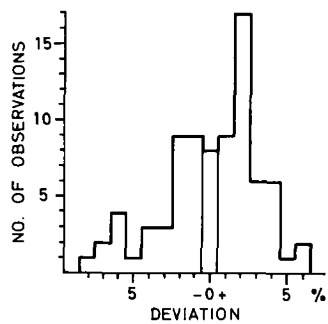
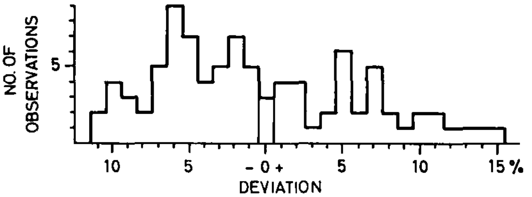


FIG. 52.

FIG. 53. The % deviations of pressure values obtained after 3–24 days deep-freeze storage from the pressure values obtained in the first measurements of intradiscal pressure. (Table 28.)
No. of observations: 91. Mean: −0.6%.
The mean of the absolute deviation: 5.5%.



deviation of the pressures thus obtained in comparison with those from the previous day, can be seen in Table 27. It is shown that neither the pressures nor the hydrostatic conditions are appreciably changed.

The effect of prolonged storage in the deep-freezer has been studied on 28 specimens. Of these, 8 discs showed severe macroscopic changes and were excluded. After the first series of experiments, the specimens were stored in the deep-freezer for varying times between 3 and 24 days, and were then subjected to repeated experiments after thawing and warming up to room temperature. Fig. 51 b shows the percentage deviation of $|\sigma_v|$ in comparison with the mean value of $|\sigma_v|$ and $|\sigma_l|$, and Fig. 52 the percentage deviation of $|\sigma_v|$, $|\sigma_l|$ and $|\sigma_d|$ from the mean pressure. It is seen that there was no hydrostatic change in the nucleus. In Table 28 and Fig. 53, the deviation for every pressure with a particular load has been calculated as a percentage of the values obtained in the first experiment. The deviation is $\pm 10\%$, but the mean is $-0{,}6\%$ for the 20 discs. Thus, the possibility cannot be completely excluded that deep-freeze storage has some effect on the results, but this influence is clearly not uniform. In this connection it should be pointed out that a number of these specimens were thawed on two occasions from a temperature of $-25°C$. No certain variation could be elicited with respect to the length of storage time in the deep-freezer, or with respect to the degeneration (groups 1–3).

Discussion

Even if the occurrence of physical changes during storage of the specimens in the refrigerator or deep-freezer cannot be excluded from the above investigation, it has not provided any certain basis for supposing that the difference is large enough to prevent a comparison between the results from the different discs. It was not possible to decide whether any post-mortem changes occurred.

FIG. 51. The % deviation of $|\sigma_v|$ from the mean of $|\sigma_v|$ and $|\sigma_l|$ in the repeated experiments after storage in
a. Refrigerator. No. of observations: 35. Mean: −0.5%.
b. Deep-freezer. No. of observations: 91. Mean: −0.2%.

FIG. 52. The % deviation of $|\sigma_v|$, $|\sigma_l|$, and $|\sigma_d|$ from the mean pressure in seven discs where measurements were repeated after 3–24 days deep-freeze storage. No. of observations: 81.

CHAPTER 11

Results from discs with severe degenerative changes

Many authors have previously stated that a degenerative change in the nucleus pulposus alters the mechanics of the disc, the annulus fibrosus taking up a larger load than in the healthy disc (Schmorl 1927, Keyes and Compere 1932, Junghanns 1951, Perey 1957, and others). On the other hand, Coventry, Ghormley and Kernohan 1945, considered that "in the elder ages stress upon the annulus is not so great as among young persons". They thought that the increased load would affect the ligaments around the disc. As previously stated, a severely degenerated disc (group 4) cannot be considered to fulfil those conditions which have been given for measuring pressure with the method used. Measurements were performed, however, on a number of such discs, since it was not possible to confirm whether or not the disc was severely degenerated until after the experiment. Table 11, p. 42 and Fig. 12, p. 36 shows how these are distributed according to age and level. Table 29 shows the experiments performed on these discs (different directions measured).

If a diagram is made, corresponding to that which was made for discs in groups 1, 2 and 3, where the compressive stresses in the three directions of principal stresses were studied (Table 30), it is found that the values obtained in group 4 are considerably scattered (Fig. 54 a, b, c and d). If only the values $|\sigma_v|$ and $|\sigma_l|$ are compared (Table 31), scattered values are obtained too (Fig. 54 e).

In some discs, zero pressure was recorded at lower loads. The interpretation of this is that the needle lay in a cavity or that the tissue round the membrane was too rigid to be able to act upon it. In some discs, the needle had probably come to rest in positions where the measured values in different directions were

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FIG. 54. Values obtained from severely degenerated discs. Diagrams a, b, c and d show the % deviation of the obtained values in the three directions of principal stresses from their mean.

a. The composite diagram. No. of observations: 180. The mean of the absolute deviation 16.3%.
b. The values obtained in vertical direction. No. of observations: 60. Mean: − 7.3%.
c. The values obtained in lateral direction. No. of observations: 60. Mean: − 5.4%.
d. The values obtained in dorsal direction. No. of observations: 60. Mean: +12.3%.
e. The values obtained from comparing the vertical value with the mean of the vertical and lateral values. No. of observations: 135. Mean: −3.0%. The mean of the absolute deviation: 13.3%.

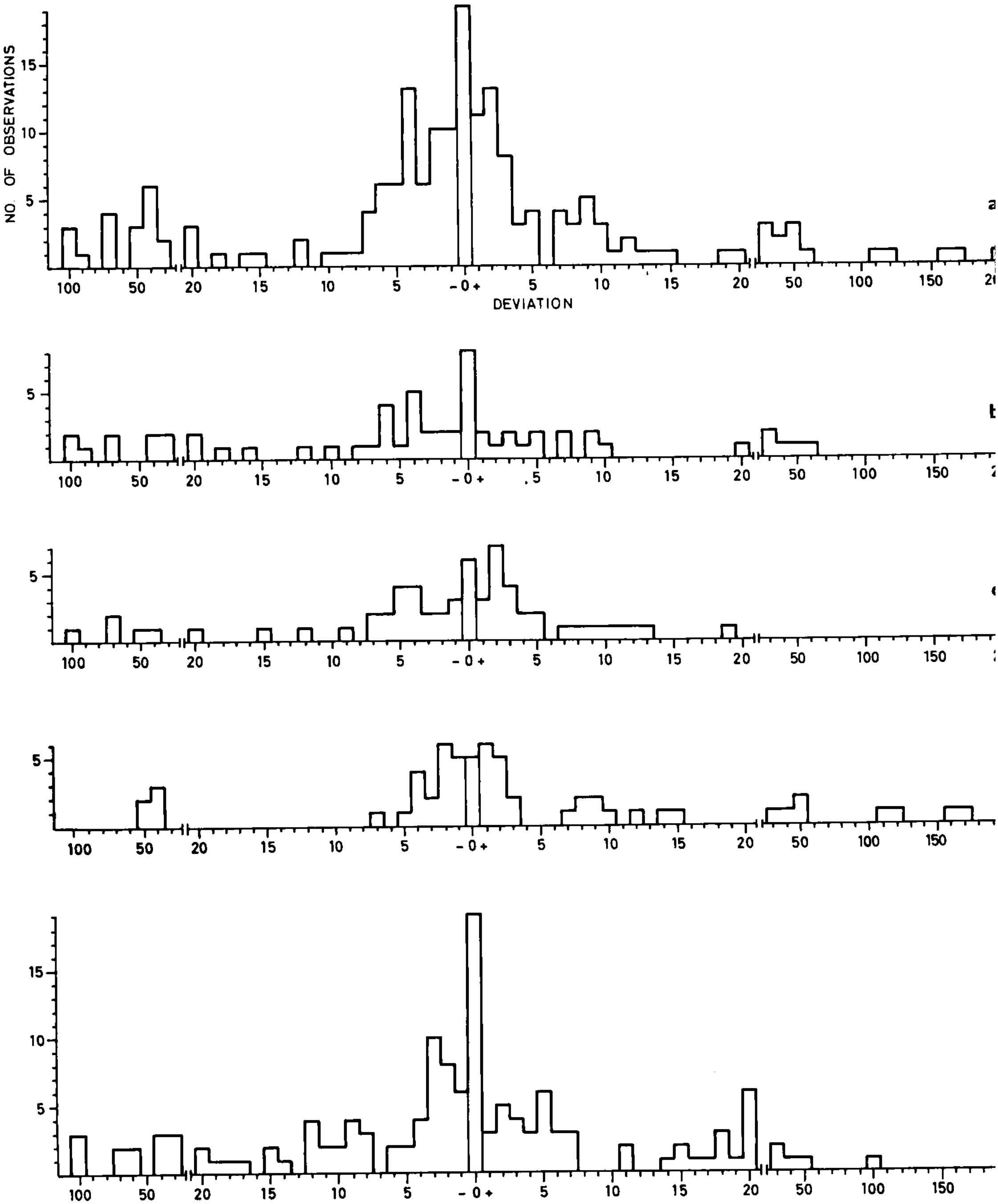
NO. OF OBSERVATIONS
DEVIATION
5
10
15
100 50 20 15 10 5 - 0 + 5 10 15 20 50 100 150
a

FIG. 54.

TABLE 29.

Discs with degenerative changes (grp 4) where the compressive stress has been measured in more than one direction.

The arrows show the direction of the needle opening in the disc.
(↑ = upwards, ↓ = downwards, → resp. ← = sideways.)

No.	Age in years	Discs tested	Degree of degener.	Roentgen. findings	Direction of needle opening: Dorsal insertion	Direction of needle opening: Lateral insertion
292/58	42	L 3	4	+	↑ →	
		L 4	4	+	↑ →	↑ →
303/59	48	L 1	4	+	⇅ ⇄	⇅ ⇄
		L 3	4	0	⇅ ⇄	⇅ ⇄
		L 4	4	0	⇅ ⇄	⇅ ⇄
309/59	55	L 3	4	0	↑ →	
		L 4	4	0	↑ →	
180/59	58	L 1	4	0	⇅ ⇄	
		L 2	4	+	⇅ ⇄	
		L 3	4	+	⇅ ⇄	
144/58	60	L 4	4	0	↑ →	
573/58	60	L 2	4	+	↑ →	
		L 3	4	0	↑ →	
		L 4	4	+	↑ →	
631/58	65	L 4	4	0	↑ →	
169/59	68	L 2	4	0	⇅ ⇄	
		L 3	4	0	↑ →	↑ →
		L 4	4	+	↑ →	↑ →
183/59	77	L 1	4	+	⇅ ⇄	⇅ ⇄
		L 2	4	+	⇅ ⇄	⇅ ⇄
		L 3	4	0	⇅ ⇄	⇅ ⇄
593/59	77	L 1	4	+	↑ →	↑ →
		L 2	4	+	↑ →	↑ →
		L 3	4	+	↑ →	↑ →
592/59	82	L 1	4	+	↑ →	
		L 2	4	+	↑ →	
		L 3	4	+	↑ →	
		L 4	4	+		↑ →

approximately equal. If these discs are grouped together, it is seen that the values measured are less than the corresponding values for groups 1, 2 and 3 (Table 32). The discs which were included in this comparison are those where the $|\sigma_v|$ value for all loads deviated less than 15 % in comparison with the mean of the $|\sigma_v|$ and $|\sigma_l|$ values.

TABLE 30.

Results obtained from measuring in the three directions of principal stresses in the disc 593/59-L 3 (deg. group 4), male, age 77, shown in fig. 16 b page 39. The deviation of $|\sigma_v|$, $|\sigma_l|$ and $|\sigma_d|$ from their mean value is given in per cent.

Load kp	$\lvert\sigma_v\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_l\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_d\rvert$ kp/cm²	% dev. from mean	Mean kp/cm²
40	0.75	+45	0.5	− 3.2	0.3	−42	0.52
85	2.35	+58	1.4	− 5.6	0.7	−53	1.48
125	4.0	+46	2.8	+ 2.4	1.4	−49	2.73
175	5.85	+33	4.8	+ 9.5	2.5	−43	4.38
220	7.55	+25	6.7	+11.0	3.8	−37	6.02

TABLE 31.

Results obtained from measuring in two directions of principal stresses (σ_v, and σ_l) in the disc 292/58-L 3, male, age 42 (deg. group 4), shown in fig. 16 a page 39. The deviation of $|\sigma_v|$ and $|\sigma_l|$ from their mean value is given in per cent.

Load kp	$\lvert\sigma_v\rvert$ kp/cm²	% dev. from mean	$\lvert\sigma_l\rvert$ kp/cm²	% dev. from mean	Mean kp/cm²
40	0.8	−36.0	1.7	+36.0	1.25
85	2.0	−17.0	2.8	+17.0	2.4
125	4.0	− 8.0	4.7	+ 8.0	4.35
175	5.5	− 8.3	6.5	+ 8.3	6.0
220	7.6	− 3.8	8.2	+ 3.8	7.9

TABLE 32.

Values for intradiscal compressive stress obtained for different loads in discs belonging to deg. group 4.

In these discs the values of compressive stress in the different directions do not deviate from their mean more than 15 %.

No.	303/59	309/59	180/59		144/58	573/58		631/58	169/59		183/59			593/59
Age in years	48	55	58		60	60		65	68		77			77
Discs tested	L 4	L 3	L 1	L 2	L 4	L 2	L 3	L 4	L 2	L 3	L 1	L 2	L 3	L 1
Load kp/cm²	Mean intradiscal compressive stress in kp/cm²													
2	2.9	2.3	2.6	2.7	3.0	2.8	2.3	1.7	2.6	2.4	3.8	2.9	2.9	2.4
4	5.8	4.7	5.0	5.6	5.6	5.5	4.7	3.5	4.9	4.8	7.3	5.7	5.7	4.9
6	8.7	6.9	7.6	8.1	8.7	8.3	7.3	6.1	7.6	7.5	10.3	8.5	8.8	7.3
8	11.5	9.1	9.7	—	11.4	10.3	9.3	8.4	10.1	9.7	12.9	11.2	11.6	9.4
10	13.8	—	—	—	13.8	12.3	11.0	10.4	—	11.7	—	—	13.2	—

Mean values: **2** kp/cm²: 2.7. **4** kp/cm²: 5.3. **6** kp/cm²: 8.0. **8** kp/cm²: 10.4. **10** kp/cm²: 12.3.

Discussion

The conclusions which can be drawn from the results must be limited to the statement that the severely degenerated discs can be looked upon as mechanically deranged.

Because of cavities and other tissue irregularities in these severely degenerated discs, it can be expected that the nucleus cannot bear and distribute as high a force as can the nucleus in degeneration groups 1, 2 and 3. The occurrence of more compact areas in the nucleus in the severely degenerated disc also indicates that the pressure of the nucleus against the annulus is lower than if hydrostatic behaviour prevails. Because of the properties of the nucleus in the severely degenerated disc, the vertical stress on the annulus increases at the same time as the tension in the tangential direction diminishes, when the disc is vertically loaded.

CHAPTER 12

The effect of experimental fractures on the intradiscal pressure

Keyes and Compere, in 1932, and Key and Ford, in 1948, showed by experiments in dogs that through damage to the cartilaginous end-plate an intraspongious prolapse is sustained. After a rather short time, roentgenographic changes of disc degeneration were seen.

In 600 specimens post-mortem, Donohue (1939) was able to establish that injury can cause rupture of the cartilaginous plate and that these can gradually produce degeneration of the disc in young people.

Ohlin (1937) made a follow-up investigation of a series of spinal fractures and concluded that 84% had involvement of the disc with extrusion of the nucleus pulposus into the vertebral body, producing a diminution of the disc height. In 1939 he wrote "... the elastic tension of the annulus fibrosus, the pressure of which extrudes the nucleus pulposus material is also aided by the muscle tone and static stresses from one vertebral body to the next". This author considered that the intraspongious hernias, which he claimed occurred following trauma, produce symptoms. The more the nucleus pulposus intruded into the vertebra, the more the function of the disc was disturbed.

Coventry, Ghormley and Kernohan (1945) considered that a "Knorpel-knötchen" could be the cause of the disc degenerating earlier than would otherwise be the case.

Brown, Hansen and Yorra (1957) pointed out that an end-plate fracture can cause lumbago and Perey (1957) showed experimentally that end-plate fractures can arise following fast-acting trauma. Isolated damage to the disc was never found in his loading experiments. He considered those intraspongious hernias resulting from end-plate fractures to be of clinical importance. Repeated compression with high loads (2–300 kp) can result in rupture of the nucleus pulposus into the adjacent vertebral body (Hardy, Lissner, Webster and Gurdjian 1958).

To find out to what extent differences could be measured after fracturing the specimen, spinal fractures were experimentally performed on 11 of the specimens. This was performed by loading the discs in an Amsler Universal Testing Machine up to their breaking point. Some specimens, however, were fractured by a load as small as 220 kp in the compression apparatus (Table 33). Before these ex-

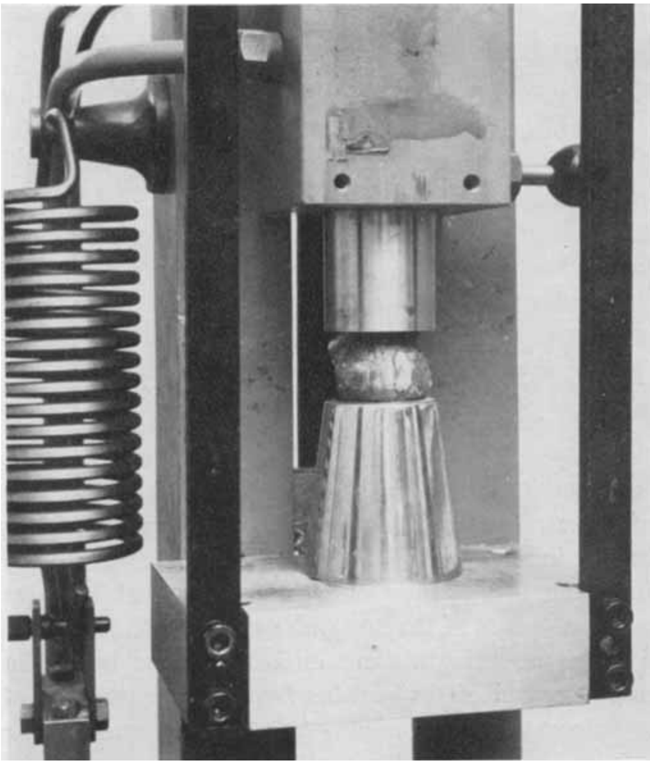

FIG. 55. A fractured specimen in the Amsler universal testing machine. The disc shows a ventral herniation of nucleus pulposus which occurred at a load of 1200 kp.

TABLE 33.

Specimens subjected to experimental fractures.

No.	Age in years	Discs tested	Degree of degener.	Load at which fracture occurred, kp	Compressive stress measured
552/59	20	L 3	2	1000	$\lvert\sigma_l\rvert$
500/59	22	L 3	3	1400	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
		L 4	3	1100	$\lvert\sigma_v\rvert + \lvert\sigma_d\rvert$
303/59	48	L 3	4	460	$\lvert\sigma_d\rvert + \lvert\sigma_v\rvert + \lvert\sigma_l\rvert$
602/59	53	L 1	2	250	$\lvert\sigma_d\rvert + \lvert\sigma_l\rvert$
		L 2	3	200	$\lvert\sigma_d\rvert + \lvert\sigma_l\rvert$
580/58	65	L 2	3	220	$\lvert\sigma_v\rvert$
		L 4	3	220	$\lvert\sigma_v\rvert$
169/59	68	L 1	3	320	$\lvert\sigma_v\rvert + \lvert\sigma_l\rvert$
		L 2	4	470	$\lvert\sigma_v\rvert + \lvert\sigma_l\rvert$
		L 3	4	450	$\lvert\sigma_v\rvert + \lvert\sigma_l\rvert$

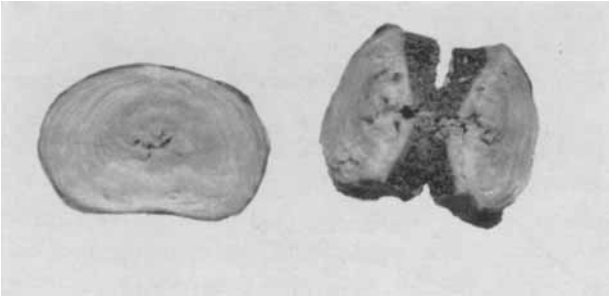

FIG. 56. Macroscopic appearance of a fractured specimen (580/58 – L 4, female age 65). Fracture occurred at a load of 220 kp. Scale 1:2.

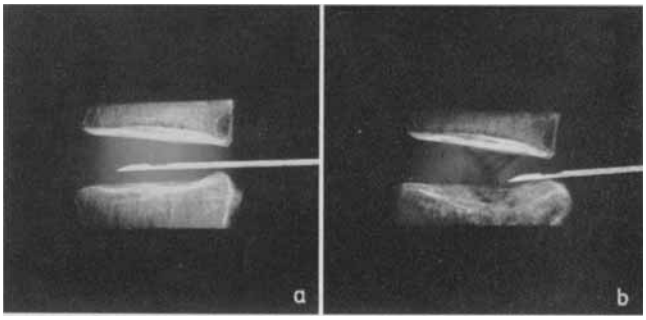

FIG. 57. Roentgenographic appearance of the specimen shown in fig. 56. a. Before fracture. b. After fracture at a load of 220 kp. The needle is withdrawn from the nucleus pulposus to show the changes more clearly. Scale 1:2.

TABLE 34.

Table showing the % deviation of the two directions of principal stresses in fractured specimens from their mean value.

The discs in group 4 have been excluded.

No.	500/59		602/59		169/59
Discs tested	L 3	L 4	L 1	L 2	L 1
Compressive stress measured	$\|\sigma_v\| + \|\sigma_d\|$	$\|\sigma_v\| + \|\sigma_d\|$	$\|\sigma_d\| + \|\sigma_l\|$	$\|\sigma_d\| + \|\sigma_l\|$	$\|\sigma_v\| + \|\sigma_l\|$
Load kp **40**	±11	±18	±4	±20	±11
85	± 7	±16	±0	±29	±19
125	± 4	±20	±0	±23	±10
175	±11	±21	±1	±19	± 9
220	±25	±18	±1	±20	±11

The mean of the absolute deviation: 13.1 %.

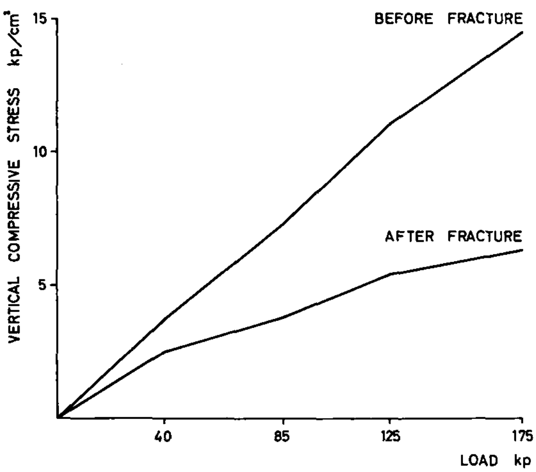

FIG. 58. Vertical compressive stress in the disc 580/58 - L 4 measured before and after fracture.

TABLE 35.

Mean values of measurements made before and after fracture.

As seen in the table all values obtained after fracture are lower than those obtained before fracture, but the differences vary rather much between the different discs.
The measured values are given in kp/cm².

No.	500/59				602/59			
Discs tested	L 3		L 4		L 1		L 2	
	before	after	before	after	before	after	before	after
Load kp **40**	3.7	1.8	3.3	2.0	4.4	3.9	5.0	1.9
85	7.0	3.8	6.8	3.7	9.0	7.4	9.5	3.8
125	10.3	4.8	10.3	5.3	12.9	10.5	13.3	6.2
175	13.3	5.7	13.5	6.4	17.0	13.8	17.3	8.6
220	16.0	7.2	16.9	7.1	20.8	16.9	20.8	10.5

No.	580/58				552/59		169/59	
Discs tested	L 2		L 4		L 3		L 1	
	before	after	before	after	before	after	before	after
Load kp **40**	3.7	3.2	3.7	2.5	3.7	3.2	2.6	2.4
85	7.8	5.0	7.3	3.8	7.8	6.6	5.8	4.9
125	11.5	6.5	11.0	5.4	11.3	10.2	8.6	6.7
175	15.0	7.3	14.5	6.3	15.1	13.2	11.4	8.1
220					17.6	16.3	14.2	9.3

periments were performed, the relation between the nucleus pressure and the outer load was measured in the ordinary way. Those specimens included in the table, which after the experiments were found to belong to degeneration group 4, were not considered further.

As Perey (1957) showed, it is sometimes very difficult to detect an end-plate fracture on the roentgenograms. This was also the case in these experiments. Despite clear indications of damage to the specimen, e.g. fracture sounds were heard and the stress-strain diagram exhibited an abrupt change of slope, it was difficult in a few cases to detect fractures on the roentgenograms. It could be felt, however, that the specimen had been fractured.

In two specimens, anterior herniation of disc substance occurred together with the fractures (Fig. 55). In Fig. 56 and Fig. 57 it is clearly seen how the nucleus pulposus herniated through the fractured end-plate into the vertebral body.

The compressive stresses in five of these fractured specimens were measured in two directions as shown in Table 34 in which only discs belonging to groups 1–3 were considered; a clearly disturbed distribution of stresses was found in these cases, which must have depended on a loss of part of the substance of the nucleus pulposus.

It can be seen from Table 35 that after a fracture, the increased loading of the discs in certain cases does not produce a corresponding increase in the compressive stresses of the nucleus pulposus. This could probably be explained by the fact that more and more of the substance of the nucleus pulposus intrudes into the vertebral body. The values are also less than those obtained before the specimens were fractured (Fig. 58).

Discussion

It can naturally be discussed whether the conditions for measuring pressure given previously (p. 22) were fulfilled. It may be said, however, that the conclusion can be drawn from these experiments that the mechanics of the disc are clearly disturbed when vertebral fractures are produced as described and that the compressive stresses in a nucleus pulposus diminish considerably. As previously shown this leads to a diminution in the tangential tension in the annulus, while the vertical stress on the annulus increases. Thus in this respect there seems to be a certain similarity between the behaviour of discs with end-plate fractures and those with severe degeneration.

CHAPTER 13

Summary and conclusions

There is at present strong support for the belief that mechanical disturbances in the lumbar intervertebral discs under certain conditions may produce low-back pain. Attempts have therefore been made to correlate the deformations produced in the outer circumference of the discs by various loads with different degrees of degeneration. The information obtained so far, however, does not constitute sufficient explanation of the mechanism of production of low-back pain.

Attempts have also been made to measure the pressure generated by the nucleus pulposus when immersed in water or physiological saline solution. It has been found, however, that due to the specific properties of the nucleus pulposus pressure measurements inside the disc with an open system do not give reproduceable values.

In order to elucidate the mechanical reaction of the nucleus pulposus when the intervertebral disc is loaded, the author has developed a method for pressure measurement inside the disc. A soldered Luer–Lok needle with a hole in the side near the tip was used. An elastic tubing was threaded over this hole, thus forming a membrane, sensitive to outer pressure. Polyethylene tubing "no. 90" was selected because it possessed the suitable elastic properties. The method is based on the principle that the compressive stresses in the nucleus pulposus act on the elastic polyethylene tubing, which in its turn through water in the manometer system acts upon a copper membrane. The movements of the membrane are transduced to electrical equivalents through strain-gauges.

The gauge was calibrated in a specially constructed pressure chamber before and after each experiment. The needle was inserted in specimens consisting of a disc with adjacent slices of bone. The position of the membrane opening in the nucleus pulposus was checked by roentgenograms in two planes. The disc was loaded in a vertical direction and the compressive stresses recorded.

This method was found suitable for pressure measurement in homogeneous substances. Thus it could be used for all but the most severely degenerated discs.

The error of the method was calculated as approximately 3%, a figure which to some extent has been corroborated by the results.

The state of stress in the nucleus pulposus of the first four lumbar interspaces from individuals of different ages, and showing varying degrees of degeneration, were studied. Results are reported for a total of 121 lumbar intervertebral discs from 38 individuals.

By measuring the compressive stresses in the three directions of principal stresses in the disc, the author succeeded in showing that the state of stress in the nucleus pulposus in all but the most severely degenerated discs is hydrostatic and that the pressure is uniformly distributed in the nucleus pulposus. This implies that the mechanical behaviour of the nucleus is similar to that of a liquid.

According to their macroscopic appearance, the discs were classified into 4 different groups. Group 1 consisted of discs without any gross changes, group 2 of those with slight changes in the nucleus pulposus, group 3 comprised discs with isolated fissures in the annulus, and group 4 discs with severe structural changes.

Clear roentgenologic evidence of disc degeneration was only seen in specimens with severe macroscopic changes.

The hydrostatic behaviour of the nucleus pulposus is not influenced by moderate degeneration (groups 2–3), nor by variation of the external loads (40–220 kp), the level of the disc in the lumbar spine (L 1–L 4), or age (6–82 years).

The investigation has furthermore shown that the nucleus pulposus, when the disc is not loaded, is under very low pressure; so low, in fact, that no exact recording was possible with the method used (0–0.3 kp/cm^2).

The pressures in the nucleus pulposus produced by increasing external loads were recorded for each disc. The discs were subsequently cross-sectioned and the cross-sectional area measured with a planimeter. Thus the external load per unit of area could be determined. This permitted comparison of the results from the different specimens.

The pressure in the loaded nucleus pulposus on the whole shows a linear increase with increasing external loads. The intradiscal pressures are on an average 30–50% higher than the applied load per unit of area. This means that the intradiscal pressure in a disc loaded by 10 kp/cm^2 is 13–15 kp/cm^2.

On comparing different adult individuals, it was found that the intradiscal pressure produced by the same external load per unit of area was constant (about 50% higher than the applied load per unit of area). A statistical analysis of the material proved that the pressures in the nucleus pulposus within a range of $\pm$15% are the same regardless of whether the disc is intact or shows moderate degenerative changes (groups 1–3). Neither does the level of the disc in the lumbar spine (L 1–L 4) influence the results.

On comparing the youngest age group with the elder groups, it was found that the pressures in the nucleus pulposus in individuals under 16 years of age were lower than in older people for the same external load. Even in the youngest age group, however, the intradiscal pressure was approximately 30% higher than the applied load per unit of area.

From the investigation a conclusion may be drawn, therefore, that the mechanical behaviour of a lumbar intervertebral disc in adults does not undergo any appreciable changes, provided that the disc is not the site of severe degeneration.

It was possible to present a relationship between the forces acting in the nucleus pulposus and the annulus fibrosus in a lumbar intervertebral disc when subjected to static vertical loads.

Approximate formulas are given for calculation of the stresses on the annulus arising from the pressure in the nucleus. According to these formulas the vertical stress on the annulus fibrosus is approximately 50% of the applied external load per unit of area, provided that in a cross-section of the disc the nucleus and annulus occupy equally large areas. If the relative area of the nucleus pulposus increases, the vertical stress on the annulus decreases.

An attempt was made to calculate the tangential stress in the different parts of the annulus fibrosus. It was found that the tangential stress in the narrower, dorsal part of the annulus fibrosus is 3–5 times the applied external load per unit of area. Thus for a static load of 10 kp/cm^2 the tangential stress in this part of the annulus is 30–50 kp/cm^2. Radial stresses set up in the end-plate will, however, tend to lower these figures.

Into the discussion concerning the mechanical behaviour of the lumbar intervertebral discs, the question has often been introduced what part the intervertebral joints play in the force-bearing of the spine. Ten disc preparations were tested with the pedicles and facets still attached. These specimens were loaded and the resulting pressures recorded. The measurements were then repeated after removal of the posterior bony elements. In these specimens the force-bearing capacity of the facets was roughly 20% of the total load applied to the vertebrae.

The method used for intradiscal pressure measurement is not quite satisfactory for measurements in discs with severe macroscopic changes (group 4). Nevertheless, since the investigation was designed along lines which included experiments on a number of such discs, some results are available. It was found that the values obtained in different directions in these discs show considerable variations from specimen to specimen. Furthermore, the values are lower in group 4 than those obtained in the remaining groups (1–3). Even though the heterogeneous structure of such discs makes measurements by the present method not entirely dependable, it can be said that these discs no longer show hydrostatic behaviour. In some of the severely degenerated discs, however, the values obtained in the different directions did not vary significantly. In these specimens, the pressure values were found to be lower than the corresponding values in intact or moderately degenerated discs. It would seem, therefore, that the annulus in a severely degenerated disc is subjected to a relatively higher vertical stress than in a healthy disc, and, furthermore, to lower tangential stress.

A point of discussion in the literature has been whether damage to the end-plate or the underlying spongiosa influences the intradiscal pressure and thus the entire mechanism of the disc. It could be demonstrated that such mechanical disturbances arise following experimental fractures of the vertebrae. A loss of nucleus pulposus substance through the end-plate has been found to result in a deterioration of the hydrostatic behaviour of the nucleus pulposus. This loss of tissue implied that lower values were obtained for the compressive stresses inside the disc, as compared to conditions before the specimen was fractured. Similarly to what has been stated with regard to severely degenerated discs, this implies an increase of the vertical stress on the annulus fibrosus combined with a decrease in the tangential stress.

The experiments in this investigation were made on post-mortem specimens. For practical reasons, the specimens could not be used until some time following death, and were therefore prior to the experiments stored either in a deep-freezer or in a refrigerator, depending on the length of the interval between their removal at post-mortem and the experiment.

An analysis of the experimental results was made to determine whether the manner of storage might have a distorting effect. The result shows that the conclusions drawn were not influenced by the manner in which the specimens were stored prior to the experiments.

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