Intravital Dynamic Pressure Measurements in Lumbar Discs

A study of common movements, maneuvers and exercises

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CHAPTER I

Introduction

Low back pain is a common ailment in most modern societies (35, 36, 37). The exact etiology is still obscure, but most indirect evidence points to the intervertebral disc as the site of pain origin (26, 39, 49, 77) although the former belief that disc degeneration itself (45) was the main factor has come to disrepute (21, 22). Most authors today believe that a combination of mechanical and chemical factors are of importance (7, 29, 64, 68, 80). Chemical investigation into the changes occurring with increasing age, in patients with and without pain and in herniated discs are numerous since the first studies were published by Hirsch and associates in 1952 (31, 65). The current biochemical theories have been summarized recently by among others Naylor (64) and Peyron (68).

The more obvious mechanical factor has been the subject of interest for a longer period of time (73, 74). In a majority of patients with low back pain and/or sciatica, sudden relatively severe mechanical stresses are known either to precipitate or to aggravate the symptoms (35, 39, 53, 79). The relatively small mechanical stresses of everyday movements have also been said to play an important role in the production of disc degeneration (5, 32, 45, 74, 75).

Several indirect attempts have been made to calculate the forces acting on the lower lumbar spine either theoretically (5, 52, 56, 67), from measurements of intraabdominal and intrathoracic pressures (2, 10, 11, 14, 15, 54) or from electromyographic recordings in different positions (3, 30, 55, 60, 70).

Autopsy experiments have revealed certain mechanical characteristics of the lumbar spine as a whole (6, 17), of the motion segment as a whole (12, 58, 71), the intervertebral disc proper (16, 27, 28, 38), or its different parts: the longitudinal ligaments (81), the vertebral end-plates (67), anulus fibrosus (23) and nucleus pulposus (57).

By pressure measurements in nucleus pulposus, so called discometry, it has been demonstrated (57) that nucleus in normal and slightly degenerated discs behaves hydrostatically and that the pressure in nucleus is 50% higher than the outer applied load per unit area. This phenomenon is probably due to the elastic resistance of the fibers of anulus fibrosus. Thus the normal disc can be regarded as a rubber tire with a relatively high internal pressure.

The results obtained in the in vivo experiments have been used for calculations of the load on the lumbar discs from pressures obtained in intravital discometries. Results have been published from such measurements in a number of static positions (59, 61, 62).

In this study a new type of pressure sensitive needle has been used. This pressure needle is suitable also for dynamic measurements and permits the study of some common motions, such as e.g. walking, jumping up and down on the floor, forward and sideways bending and twisting. The pain provoking effect from coughing, straining and laughing in patients with low back pain and sciatica is well-known (25, 35, 63, 75) and the pressure response during these maneuvers was also measured.

For a long time the mechanical effect of weight lifting on the lumbar discs has received attention in the literature (39, 45) and almost all regimens for low back pain patients also contain advice on "proper" lifting (7, 46, 84). The pressure difference in lifting 20 kg from a chair placed in front of the subject by stooping as compared with flexion of the knees has received particular attention in this study.

The most commonly used therapeutic procedures for low back pain patients are aimed at relieving mechanical stresses. Bed-rest with or without traction is thus widely prescribed. In the present investigation discometry was performed in supine and prone positions as well as in subjects in traction.

In almost all text-books in orthopaedics and physical medicine as well as in numerous articles on low back pain, physiotherapy in the form of various movements is recommended for these patients. Therefore measurements of intradiscal pressure during the performance of the most commonly used "back-strengthening" exercises have also been included in this study.

CHAPTER II

Previous intravital disc pressure measurements

The method used in previous in vivo experiments (62) was based on a membrane-covered needle connected to a pressure transducer. The stresses acting inside nucleus pulposus caused a deformation of the polyethylene membrane which via the liquid-filled needle was picked up by the pressure transducer, converted to electrical signals and amplified. This method had a number of limitations and drawbacks. The polyethylene membrane itself allowed only for studies of a limited number of static positions since dynamic properties of the membrane were inadequate. Also loads above 30–35 kp/cm^2 tended to give permanent deformation of the polyethylene membrane thus giving an upper limit for the measurements. This needle also had to be assembled as well as calibrated under sterile conditions, which made the measuring procedure rather troublesome and time consuming.

Nevertheless the previous in vivo measurements in the third or fourth lumbar discs of more than 30 individuals have revealed that the pressure and thus also the loads vary according to body weight and position of the subject measured (61). In Table I is given a summary of the previous findings where the total load on the disc in different positions is correlated by mathematical expressions to the weight of the subject's body above the disc level measured, calculated according to Ruff's (72) data. The total load is defined here as the load to which the lumbar disc is subjected through the vertebra above it and acting perpendicularly to its cross sectional surface area.

Table I. *Approximate formulas for load (P) on lumbar discs in different positions*

W = body weight above level measured

Position	Approximate formula	
Upright sitting unsupported	$P = 30 + 2.8\,W$	[Eq. 1]
Sitting, leaning forward α degrees	$P = 30 + 2.8\,W + 3.6\,W \sin \alpha$	[Eq. 2]
Upright standing	$P = 15 + 2.1\,W$	[Eq. 3]
Standing, leaning forward α degrees	$P = 15 + 2.1\,W + 3.6\,W \sin \alpha$	[Eq. 4]
Reclining, tilted on side, lateral decubitus	$P = (30 + 2.8\,W)/2$	[Eq. 5]

The errors that have to be taken into account in these calculations are 1) the reliability of the polyethylene membrane of the needle (57), 2) the calculation of the surface area of the disc which was made from special radiograms taken in two planes (62), 3) the relative error in Ruff's (72) data of body weights above certain levels, and 4) the factor by which the measured pressure is divided to obtain the specific pressure. In the autopsy experiments (57) this was found to vary between 1.4 and 1.6 in the relevant age groups and pressure ranges.

Due to the limitations and drawbacks of the above mentioned method it is natural that attempts have been made to achieve easier means of measuring intradiscal pressure in vivo.

The previous measurements, both in vivo and in vitro, made it possible to establish certain requirements for such a device —1) the gauge should be needleshaped and long enough to be inserted into a lumbar disc from behind, 2) the range of sensitivity should be from 1–50 kp/cm^2, 3) the gauge should be easily sterilized, 4) the gauge must have good reproducibility and 5) the gauge should also be suitable for dynamic measurements up to at least 100 Hz (Hz = cycles per second).

In the last 4–5 years so called semiconductor strain gauges in very small sizes has been manufactured and their use in biological pressure recordings, mainly for blood pressure, have been described (8). Several companies working in the bioelectrical field were asked to construct a needle with the above mentioned properties. The measurements reported in this paper were obtained using a needle type pressure transducer manufactured especially for this purpose by Toyota Research and Development Laboratories, Japan.

In this presentation the unit used for pressure has been kiloponds per square centimeter. 1 kp cm² coresponds to 14.22 pounds per square inch or 1 atmosphere (at). The internal disc pressure (p_o) is given in kp/cm² as well as the calculated load per unit of area on the disc surface (p). The body weight (W) is given in kilograms (1 kg corresponds to 2.2 lbs). The total load on the disc (P) is given in kiloponds. A kilopond (kp) is defined as the force of gravity on a mass of one kilogram.

CHAPTER III

Methods

The Pressure Transducer

The intradiscal pressures are measured by means of a subminiature pressure transducer, the operating principle of which is based on the piezoresistive effect of semiconductor strain gauges embedded in rigid resin in an elastic tube (8). When a uniaxial stress or pressure is applied to this so called strain tube in the axial direction, the applied stress is transmitted to the gauge through the rigid resin. Fig. 1 shows the structure of the transducer, in the center of which a strain tube is mounted. One end of this is fixed to the pressure sensitive diaphragm, while the other end is fixed to the inner side of the transducer. The pressure sensitive diaphragm is welded to an end of the outer tube of the transducer. To widen the effective area of the diaphragm, the outer tube is tapered as illustrated. Inside the outer tube there is an inner one, as mentioned above, to which a part of the strain tube is fixed with adhesives. These tubes are concentrically fixed as shown in the figure. A space is provided between the strain tube and the inner tube to effectively damp the unfavourable pressure effects from the side of the transducer. Further, a double tube construction will provide sufficient rigidity to the transducer, reducing the disturbance due to bending. When inserted into the pressure medium, the center of the diaphragm is displaced due to the pressure, giving a uniaxial compression stress to the strain tube and the electrical resistance of the gauges thus changes.

The transducer is connected as a Wheatstone bridge. The change in resistance due to pressure changes on the diaphragm causes an out-of-balance current from the bridge. The output from the bridge is amplified in an integrated circuit amplifier (69, 89), Fig. 2, and then connected to a recorder, Mingograph 12. The output from the bridge versus pressure is plotted in Fig. 3. The transducer is temperature compensated and Fig. 4 shows the zero drift due to change in temperature. The frequency response of the pressure needle was tested and it was found that the needle was able to measure pressure changes up to at least 5000 Hz. The frequency limit of the system is thus set by the recorder, the upper frequency limit of which is about 500 Hz.

The complete measuring equipment is placed on an instrument trolley to facilitate recording during motion of the subject (Fig. 5).

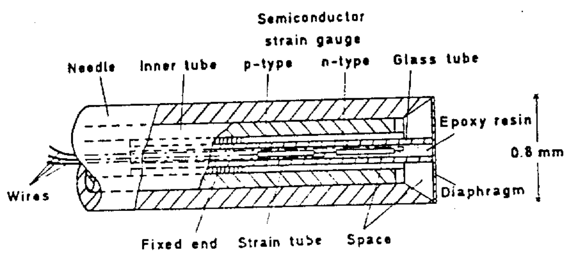

Fig. 1. Construction of the subminiature pressure transducer.

Calibration

The calibration of the transducer was performed in a specially constructed chamber filled with water and connected to a cylinder of compressed air (Fig. 6). In principle this is the same type of calibration instrument as used for the previously described discometry needle (62). The air pressure in the calibration chamber was measured with a manometer, 0–40 kp/cm^2 in range, and with a

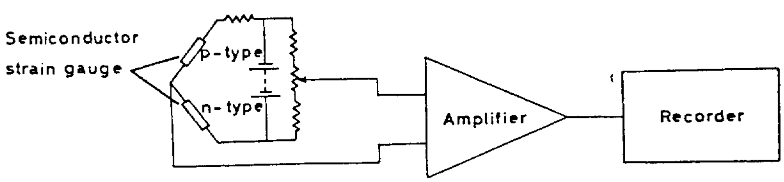

Fig. 2. Principal diagram of the pressure measuring system.

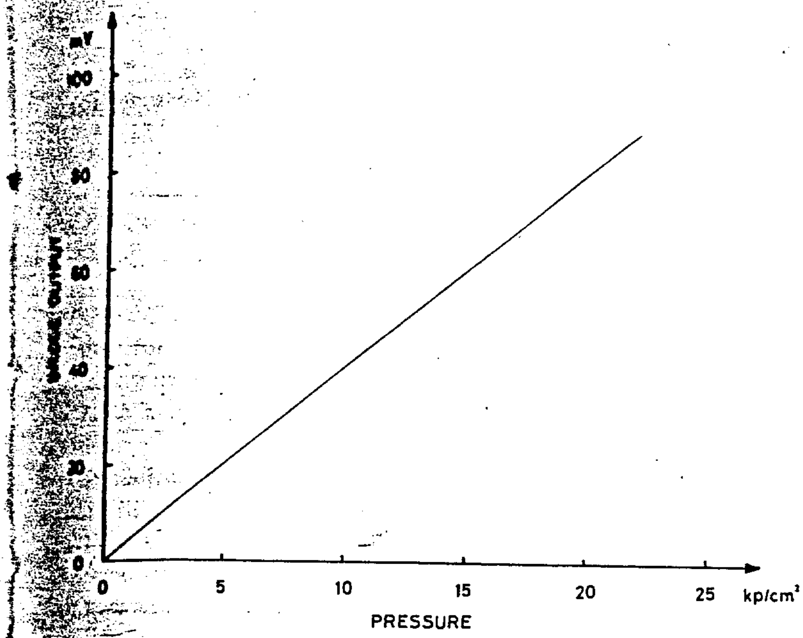

Fig. 3. Bridge output as a function of applied pressure.

scale the diameter of which was 150 mm. The accuracy of the manometer is given by the makers as $\pm 0.5\%$ of the maximum value. The transducer was calibrated before and after every experiment. The applied pressures were 0, 5, 10, 15 and 20 kp/cm² and in some instances 30 kp/cm². On no occasion was any difference noted between the values obtained at calibration before and after the experiments.

During the experiments it was observed that a slight difference in balance was obtained when the bridge was balanced with the needle in air compared with the needle in water. This is due to self heating of the transducer. In order to reach a temperature equilibrium state of the transducer, the needle has either to be zeroed in sterile water or else this drift, which corresponds to about 1.0 kp/cm², has to be taken into consideration when reading the pressures.

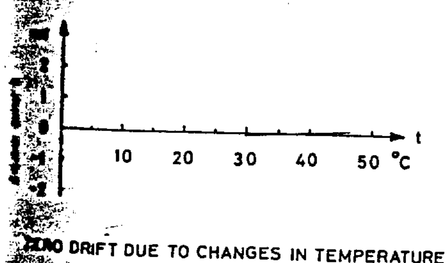

Fig. 4. Zero drift of the temperature compensated needle.

Sterilization

The wires from the transducer were covered by a PVC-tube, the length of which was about 1.5 meters, and this was sterilized together with the

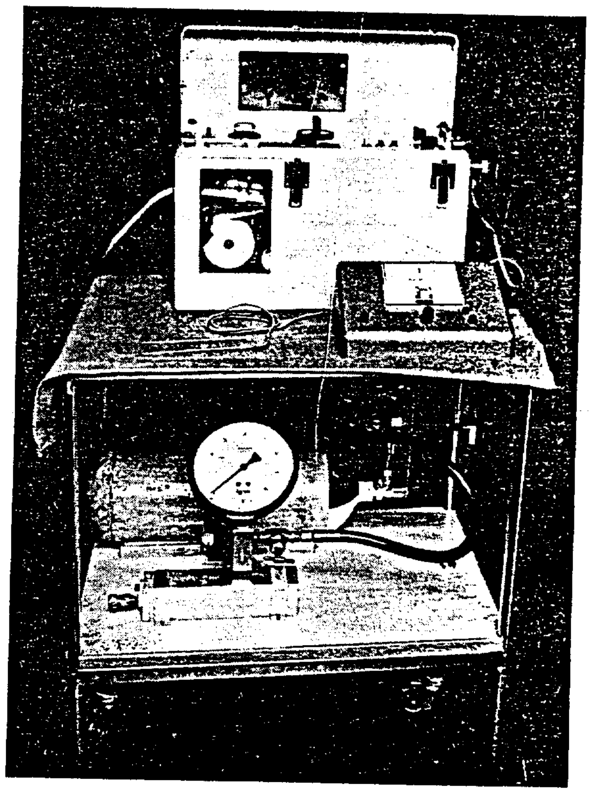

Fig. 5. The complete measuring equipment.

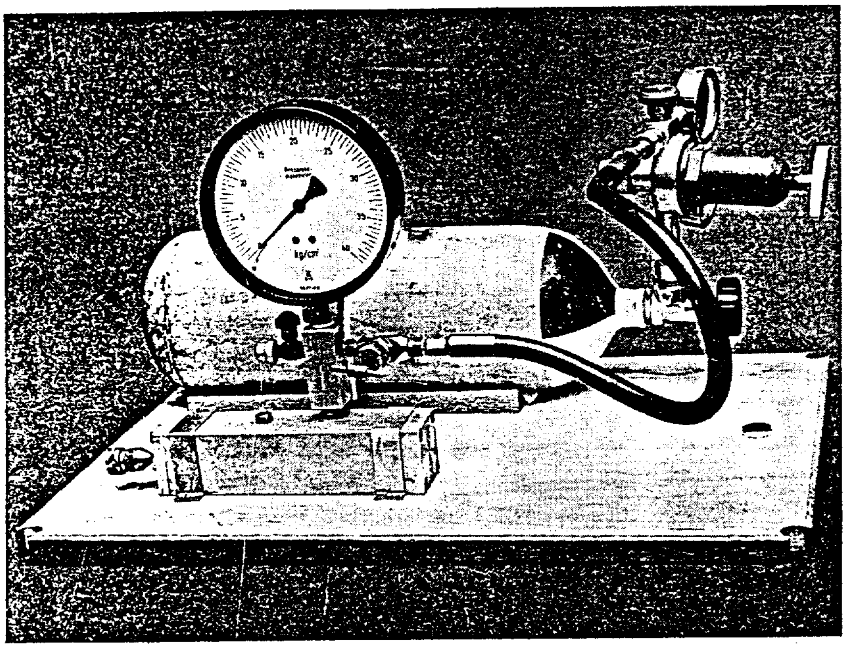

Fig. 6. The calibration system.

needle in 2.5% diglutaraldehyde solution for at least three hours (4).

In vivo Test Procedure

In order to minimize the hazard of blood pressure drop, due to vasovagal syncope sometimes noted in previous intravital discometries, the subjects were given peroral premedication of 5 mg of Effontil®. The appropriate dorsal skin area of the patient was prepared as for surgery, and using a long needle 1 mm in diameter, local anesthetic (Carbocain-Exadrin® 1%) was injected down to the disc. In either the sitting or the reclining position by use of roentgen-television equipment a needle with a pointed mandrin was inserted into the center of the disc to be measured from behind at an angle of 45 degrees of the sagittal plane. This last mentioned guiding needle, 120 mm in length and 1.2 mm wide, had inner dimensions such that the measuring needle could pass through it and when totally inserted it protruded about 1 mm in the needle-point as shown in Fig. 7.

When the subject after performing the maneuvers to be measured in one position was moved to another, the pressure needle was withdrawn and the mandrin inserted. When necessary the position of the needletip was rechecked using the roentgen-television equipment.

The discometries performed in the sitting and the standing positions have thus followed the same routine as that previously described (62).

In the reclining position a modified Tru-Trac table was used in which part of the right side of

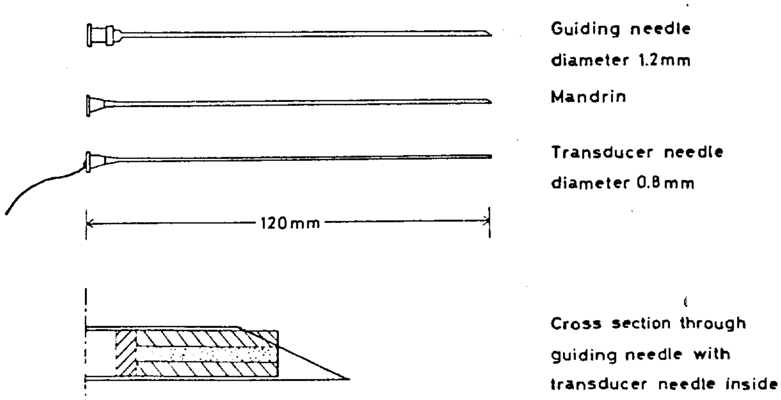

Fig. 7. Schematic drawings of the needle used.

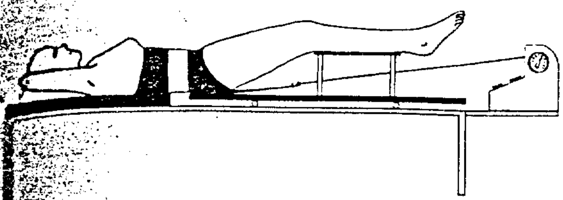

Fig. 8. Horizontally applied traction.

the lower sliding board had been removed in order to allow for the needle to project backwards. The measuring needle was inserted from behind under the table and measurements taken in the supine position.

The subjects tested in traction had this applied exactly in the same manner as recommended by Tru-Trac Co., (83) i.e. via pelvis and thoracic harnesses provided with the table (Fig. 8). The load (30 kp) was applied for 3 sec with 5 sec intervals, between 3 and 5 times.

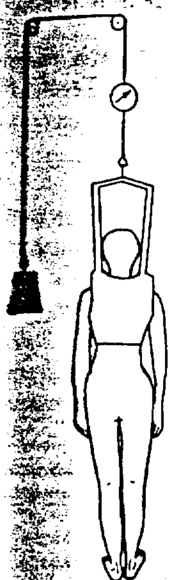

Fig. 9. Vertically applied traction.

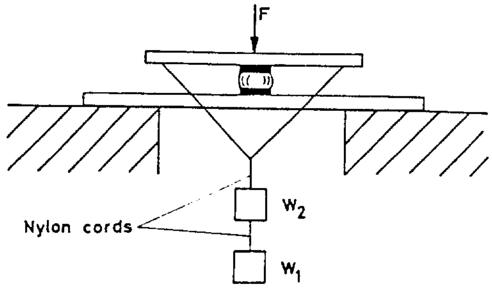

Fig. 10. Principal diagram of the method used for dynamic unloading of disc specimens.

When measuring the effect of traction in the standing position the subject with the needle already in place was fitted with a specially made thoracic harness and vertically loaded via a steel wire and bearings fastened to the ceiling. The system is shown in Fig. 9. The resulting force obtained from increasing weights applied in the other end of the wire was measured on a spring balance inserted between the harness and the wire.

In vitro Experiments

Before using the pressure needle in vivo, a number of autopsy experiments were performed on lumbar discs prepared with the halves of adjacent vertebral bodies. Static load tests were performed in a compression apparatus (57) where loads up to 100 kp were applied. The surface areas of the discs were measured with a planimeter from tracings made of the horizontally cut specimens.

Some dynamic tests were also carried out using the system shown in Fig. 10 where the specimens were loaded as seen from the figure. The weights w_1 and w_2 were given different values between 0 and 105 kg. After the disc had been loaded for two minutes the two nylon cords were burnt off, one after the other, to obtain instant unloading.

CHAPTER IV

Material

Tests were performed on 6 normal autopsy discs from three young spines (L 3 and L 4 discs). These studies included both static and dynamic loads up to about 100 kp.

The intravital measurements were made on nine individuals of whom six were young volunteers with radiographically normal L 3 and L 4 discs and no previous history of back pain. Two subjects were patients who had had either sciatica or low back pain for 2–3 months but at the time of measurement had recovered. One further patient, a young girl of 14 years, had had a thoracic idiopathic scoliosis of 60 degrees, later operated upon with the Harrington instrumentation procedure and fusion. In all the subjects the discometry was performed in the third lumbar disc, i.e. the interspace between the third and fourth lumbar vertebras.

If the age of the patient, his history or his ordinary roentgenogram led to any suspicion as to the existence of some degree of disc degeneration a discography was performed after the completion of the measurements using Urografin® 22%. On all such occasions the discograms were judged as normal or near normal (18, 49). In order to check the reproducibility of the method one volunteer (subject no. 9) was measured on two different occasions in the same disc, with an interval of four weeks.

A summary of the data on the subjects is provided in Table II.

Table II. *Summary of data on subjects*

Case no.	Age (yrs)	Sex	Weight (kg)	Height (cm)	Level	Disc condition ordinary X-ray and/or discogram*	Area (cm)	History
1	60	M	70	173	L 3	Slight* degen.	20.7	2 mo sciatica, subsiding, myelogram neg.
2	37	M	69	180	L 3	Normal*	18.3	3 mo low-back pain subsiding
3	14	F	50	174	L 3	Normal*	18.1	Idiopathic scoliosis thoracic region
4	29	F	59	170	L 3	Normal*	17.1	Volunteer, no back history
5	20	F	66	171	L 3	Normal*	17.0	Volunteer, no back history
6	24	F	57	168	L 3	Normal	16.0	Volunteer, no back history
7	23	M	61	179	L 3	Normal	16.3	Volunteer, no back history
8	20	F	58	172	L 3	Normal	16.7	Volunteer, no back history
9	24	F	58	165	L 3	Normal*	15.0	Volunteer, no back history (Measured on two occasions)

CHAPTER V

Results

Autopsy Experiments

Six autopsy discs were tested with static loads. The pressures obtained within the normal nucleus pulposus with this pressure needle were of the same magnitude as those earlier reported, i.e. the pressure inside the disc was 1.5 ± 0.1 times the outer applied load (Table III). The dynamic tests, using the system in Fig. 10, showed that the pressure needle accurately registered instant changes in the intradiscal pressure (Fig. 11). As shown in the curve the pressure change, and thus also the change in load, is damped by the disc.

Intravital Measurements

Each different position, movement or maneuver studied in the nine individuals is seen in Table IV together with the resulting intradiscal pressure. As seen from the number of different situations studied in each subject these are fewer in the first three than in the remainder due to the fact that they were measured before the exact routine was established.

In the following text the pressure in each position, movement or maneuver will be presented separately. For comparison the results are tabulated together with the pressures obtained in upright standing. The increase in pressure (and total load) in per cent are also presented.

Table III. *Autopsy experiments*

Normal discs from a 20-year-old female

Applied load (kp)	p_n (kp/cm²)	Load per unit disc area p	p_n/p
L 3-disc, area 11.7 cm²			
[illegible]	2.0	1.5	1.3
[illegible]	9.4	6.8	1.4
[illegible]	13.5	8.7	1.6
L 4-disc, area 12.3 cm²			
[illegible]	2.2	1.5	1.5
[illegible]	10.0	6.5	1.5
[illegible]	12.8	8.3	1.5

Sitting position

In seven of the nine individuals the needle was inserted in the upright sitting position and the pressure measured simultaneously. In previous experiments with the polyethylene membrane-covered needle the total load on the disc in this position could be calculated according to equation [1] in Table I. As seen from Table V the values now obtained are about the same but tend to be somewhat, but not significantly, lower. This is also seen from Fig. 12, where the previous and present loads are plotted against the weight of the body above the L 3 disc. In this connection it also should be mentioned that the presently measured subjects were not specifically asked to sit exactly upright since the object of this investigation was not to study pressures occuring in this particular position. Nevertheless the present data change the earlier obtained regression line to a rather small extent (Fig. 12).

In order to check both the validity of the previously established equation [2] in Table I and the reliability of the present needle, six of the subjects were also asked to hold 10 kg in each hand and to lean forward about 20 degrees. As is seen in Table VI the obtained pressures and calculated values of the total load correspond well to those calculated according to equation [2].

Standing position

All the nine individuals were studied in the upright standing position, which in the following text is also the basic position, the pressure of which

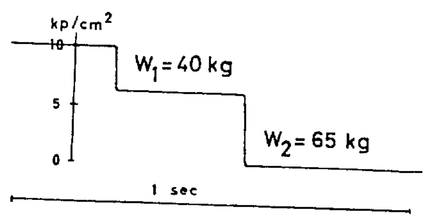

Fig. 11. Pressure response obtained from fast unloading of a normal disc specimen (L 3).

Table IV. *Summary of activities studied in the different subjects and the resulting intradiscal pressure in L[illegible] ponds per square centimeter*

Subject no. ...	1	2	3	4	5	6	7	8	9	9	Total studied
Sitting, no support			10.4	11.5	10.2	8.5	11.5	9.5	9.6		7
Sitting, leaning forward, 10 kg in each hand				18.4	20.5	21.0	23.7	21.7	23.0		6
Upright standing	5.9	5.6	5.7	8.2	7.3	7.0	9.7	7.6	7.7	7.5	9
Upright standing, 10 kg in each hand		11.8		11.1	10.7	9.5	12.7	10.9	12.3	12.0	7
Coughing	6.6	7.0		11.7		12.2	14.4	11.5	9.2		7
Straining				11.2	9.6	11.5	15.7	9.6	12.3		6
Laughing				11.2	11.5			11.8			3
Jumping	9.5		9.5	11.7	16.0	10.5	11.5	9.5	9.7	10.4	8
Walking		6.4		9.4	8.4					8.6	4
Bending forward 30°		11.4				15.0				14.2	3
Bending forward 30°, 10 kg in each hand		16.5		19.8		20.2	25.5	23.0		26.5	6
Bending sideways, 10 kg in each hand		13.4		12.9	16.1	13.5		12.1			5
(No weights)							(10.9)		(10.2)		(2)
Twisting, 10 kg in each hand				14.0		13.0		12.1	15.3		4
(No weights)							(10.9)				(1)
Lifting of 20 kg with bending of back				24.5	32.5	27.0	36.0	32.5	27.5		6
Lifting of 20 kg with bending of knees				19.2	21.5	14.5	17.0	21.0	22.6		6
Supine		3.0		3.5	4.0	4.0	4.2	4.1		4.0	7
Bilateral straight leg raising				10.4	13.0	10.5	13.4	13.4		11.5	6
Sit-up with knees extended				13.5	15.0	18.0	17.0	17.2		15.0	6
Sit-up with knees bent				14.0	14.5	18.0	18.2	17.9		15.0	6
Contract. of abd. mm. against resistance in crook-lying				10.2	10.3	12.5	13.4	9.6		9.2	6
Crook-lying relaxed						6.0	8.4			6.5	3
Prone				3.3		4.0	4.2	4.0		4.0	5
Active back hyperextension				12.9		16.0	17.0	12.1			4
Passive back hyperextension						6.0	6.8				2
Traction standing			15 kp:5.0 25 kp:4.5 35 kp:4.1						15 kp:7.2 38 kp:5.7 48 kp:4.4		2
Traction supine (30 kp for 3 sec)					2.8					3.2	2

had been compared with the different movements and maneuvers performed. In previous intravital discometries the load on the disc in the standing position was found to fall within 5–10% of the loads calculated from the equation [3] given in Table I. In a previous paper the validity of this equation was checked by increasing the weight of the upper part of the body (W) by having the subjects hold an additional 10 kg weight in each hand (59). In Table VII the intradiscal pressures in upright standing without and with 10 kg in each hand is presented. The magnitude of the loads calculated from the pressures obtained correspond well to those derived from the equation [3]. The previous and present load values in correlation to the body weight (W) is seen in Fig. 13, where the regression line based on the previous plus the new values is shown.

Straining, coughing and laughing

Straining and coughing are maneuvers that are known to increase the pain in patients with either acute low back pain or sciatica. A pressure increase on performing the Valsalva maneuver in the sitting position has previously been demonstrated (62) and varied from 5 to 35%. As seen in Tables VIII, IX and X the above mentioned maneuvers performed in the standing position also cause an increase of the same order of magnitude.

When the subjects were ordered to strain they were told to do as if defecating with obstipation. It is not possible to check the "straining force

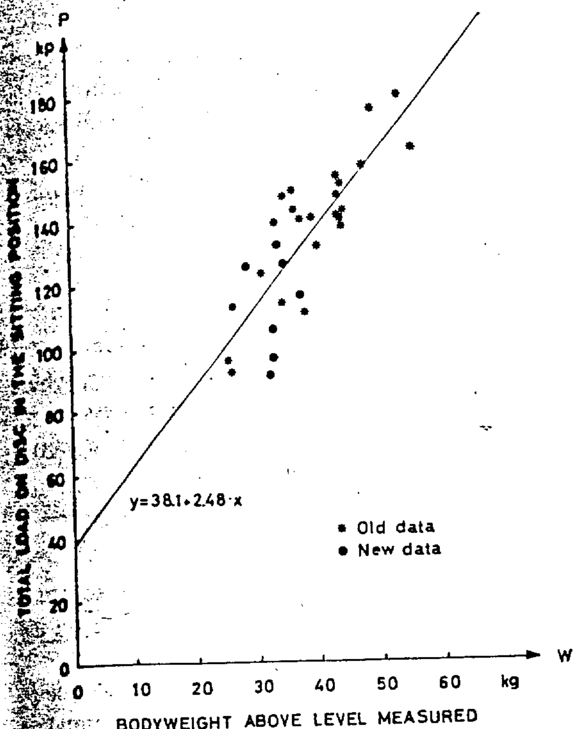

Fig. 12. Relation between total load on lumbar disc and calculated part of body weight above that level in unsupported sitting position. The slope was determined by linear regression.

or even to tell the patient to perform the maneuver exactly comparably to another subject, but as in most of the tests that are presented, they were repeated twice in each subject with similar results (Fig. 14 *a*, Table VIII).

This also is true when the subjects were asked to cough, which in some resulted in a relatively weak effort and in other subjects in a louder and probably more forceful cough (Fig. 14 *b*, Table IX).

Three subjects, although not specifically asked, happened to burst out in laughter and are reported here since recording was made in preparation for some other maneuver (Fig. 14 c). The resulting pressure responses are shown more as an interesting accessory finding (Table X). As a mean these maneuvers caused an increase of between 40 and 50 % of the pressure noted in the upright standing position, corresponding to 35–40 kp of increased load.

Walking, Sideways Bending and Twisting

These movements were performed in order to study the pressure increase that results from minor "everyday" movements.

Table V. *Sitting position*

Subject no.	Disc area (cm^2)	Body weight above level measured (kg)	Pressure (kp/cm^2)	Load (kp/cm^2)	Total load on disc (kp)	Total load on disc according to eq. $P = 30 + 2.8\,W$ (kp)
3	18.1	28.6	10.4	6.9	125	110
4	17.1	33.6	11.5	7.7	132	124
5	17.0	37.5	10.2	6.8	116	135
6	16.0	32.5	8.5	5.7	91	121
7	16.3	34.7	11.5	7.7	126	127
8	16.7	33.0	9.5	6.3	105	122
9	15.0	33.0	9.6	6.4	96	122
					$\bar{m}$ 113	$\bar{m}$ 123

Table VI. *Sitting, leaning forward ≈ 20° with 10 kg in each hand*

Subject no.	Disc area (cm^2)	Body weight above level measured (kg)	Pressure (kp/cm^2)	Load (kp/cm^2)	Total load on disc (kp)	Total load on disc according to eq. $P = 30 + 2.8\,W + 3.6\,W \sin \alpha$ (kp)
4	17.1	33.6	18.4	12.3	210	246
5	17.0	37.5	20.5	13.7	233	261
6	16.0	32.5	21.0	14.0	224	241
7	16.3	34.7	23.7	15.8	258	250
8	16.7	33.0	21.7	14.5	242	243
9	15.0	33.0	23.0	15.3	230	243
					$\bar{m}$ 233	$\bar{m}$ 247

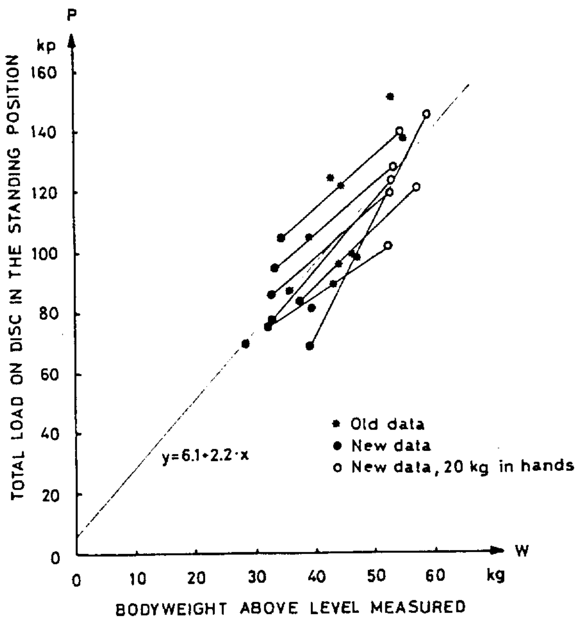

Fig. 13. Relation between total load on lumbar disc and body weight above that level in upright standing without and with 10 kg in each hand. The slope was determined by linear regression.

Walking

As seen from Table XI the increase due to slow walking is relatively small, only about 15% more than the pressure noticed in standing, corresponding to a load increase of about 10 kp.

Twisting

Twisting of the body about 45 degrees to each side also caused a relatively minor increase in pressure (Table XII). Some of these individuals performed this movement with 10 kg in each hand and the increase in pressure when twisting is compared to the upright standing pressure with the subject holding the same weights.

Sideways bending

As seen from Table XIII the results are similar to those of twisting. On sideways bending, which was in the order of 20 degrees, the pressure increases noted were about 25%, with a corresponding load increase of 30 kp.

Jumping on the Floor

This movement was included in order to study the effect of a more sudden dynamic load on the disc.

The subjects were asked to make small jumps on the floor and the pressure increase amounted to about 40% as seen from Table XIV, with a corresponding load increase of about 35 kp. Again the subjects performed differently, some making a high jump, others barely getting both feet clear of the floor. It is also obivous from Fig. 14 *d, e* and *f*, that the shock produced from the jump is completely damped inside the body.

Table VII. *Pressure and corresponding loads obtained in the upright standing position without (A) and with (B) 10 kg in each hand*

Subject no.		Disc area (cm^2)	Body weight above level measured (kg)	Intradiscal pressure (p_n) (kp/cm^2)	Load per unit disc area (p) (kp/cm^2)	Total load on disc (kp)	Total load on disc according to eq. $P = 15 + 2.1\,W$ (kp)
1		20.7	39.8	5.9	3.9	81	99
2	A	18.3	39.2	5.6	3.7	68	97
	B		59.2	11.8	7.9	145	139
3		18.1	28.6	5.7	3.8	69	75
4	A	17.1	33.6	8.2	5.5	94	86
	B		53.6	11.1	7.4	127	128
5	A	17.0	37.5	7.3	4.9	83	94
	B		57.5	10.7	7.1	121	136
6	A	16.0	32.5	7.0	4.7	75	83
	B		52.5	9.5	6.3	101	125
7	A	16.3	34.7	9.7	6.4	104	88
	B		54.7	12.7	8.5	139	130
8	A	16.7	33.0	7.6	5.1	85	84
	B		53.0	10.9	7.1	119	126
9	A	15.0	33.0	7.7	5.1	77	84
	B		53.0	12.3	8.2	123	126
						$\bar{m}$ A 82	$\bar{m}$ A 88
						$\bar{m}$ B 125	$\bar{m}$ B 130

Table VIII. *Straining*

Subject [illegible]	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure straining (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
[illegible]	17.1	8.2	11.2	3.0	2.0	34.2	37
[illegible]	17.0	7.3	9.6	2.3	1.5	25.5	32
[illegible]	16.0	7.0	11.5	4.5	3.0	48.0	64
[illegible]	16.3	9.7	15.7	6.0	4.0	65.2	62
[illegible]	16.7	7.6	9.6	2.0	1.3	21.7	26
[illegible]	15.0	7.7	12.3	4.6	3.1	46.5	60
						$\bar{m}$ 40	$\bar{m}$ 47

Table IX. *Coughing*

Subject [illegible]	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure coughing (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
[illegible]	20.7	5.9	6.6	0.7	0.5	10.4	12
[illegible]	18.3	5.6	7.0	1.4	0.9	16.5	25
[illegible]	17.1	8.2	11.7	3.5	2.3	39.3	43
[illegible]	16.0	7.0	12.2	5.2	3.5	56.0	74
[illegible]	16.3	9.7	14.4	4.7	3.1	50.5	48
[illegible]	16.7	7.6	11.5	3.9	2.6	43.4	51
[illegible]	15.0	7.7	9.2	1.5	1.0	15.0	19
						$\bar{m}$ 33	$\bar{m}$ 39

Table X. *Laughing*

Subject [illegible]	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure laughing (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
[illegible]	17.1	8.2	11.2	3.0	2.0	34.2	37
[illegible]	17.0	7.3	11.5	4.2	2.8	47.6	58
[illegible]	16.7	7.6	11.8	4.2	2.8	46.8	55
						$\bar{m}$ 43	$\bar{m}$ 50

Table XI. *Walking*

Subject [illegible]	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure walking (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
[illegible]	18.3	5.6	6.4	0.8	0.5	9.2	14
[illegible]	17.1	8.2	9.4	1.2	0.8	13.7	15
[illegible]	17.0	7.3	8.4	1.1	0.7	11.9	15
[illegible]	15.0	7.5	8.6	1.1	0.7	10.5	15
						$\bar{m}$ 11	$\bar{m}$ 15

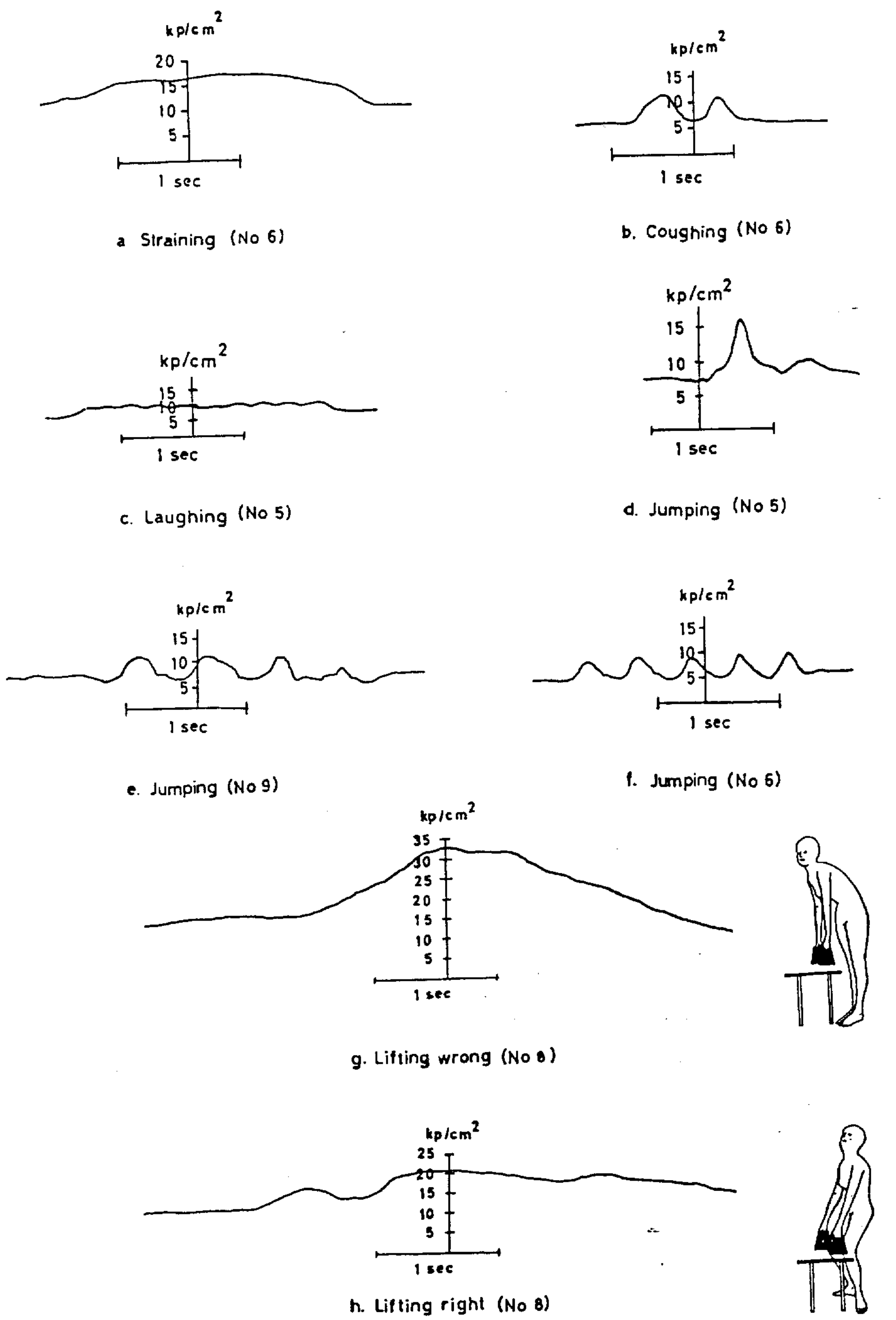

Fig. 14. Pressures measured during the performance of different movements and maneuvers in standing.

Forward Bending and Weight Lifting

In all standard texts on low back pain, the forward bending movement, and also weight lifting with bending of the back and the knees straight, is warned against. These movements have therefore been specially considered in this study.

Forward bending without and with 10 kg in each hand

As seen from Table XV three patients were asked to bend forward about 30 degrees without weights. The total load calculated from the intradiscal pressures measured during this movement corre-

Table XII. *Twisting with or without 10 kg in each hand*

Subject no.	Disc area (kp/cm²)	Pressure standing (kp/cm²)	Pressure twisting (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
[illegible]	17.1	11.1	14.0	2.9	1.9	32.5	26
[illegible]	16.0	9.5	13.0	3.5	2.3	36.8	37
[illegible]	16.3	9.7	10.9	1.2	0.8	13.0	12
[illegible]	16.7	10.9	12.1	1.2	0.8	13.4	11
[illegible]	15.0	12.3	15.3	3.0	2.0	30.0	24
						$\bar{m}$ 25	$\bar{m}$ 22

ᵃ These subjects performed the movement with weights in their hands.

Table XIII. *Bending sideways with or without 10 kg in each hand*

Subject no.	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure sideways bending (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
[illegible]	18.3	11.8	13.4	1.6	1.1	20.1	14
[illegible]	17.1	11.1	12.9	1.8	1.2	20.5	16
[illegible]	17.0	10.7	16.1	5.4	3.6	61.2	50
[illegible]	16.0	9.5	13.5	4.0	2.7	43.2	42
[illegible]	16.3	9.7	10.9	1.2	0.8	13.0	12
[illegible]	16.7	10.9	12.1	1.2	0.8	13.4	11
[illegible]	15.0	7.7	10.2	2.5	1.7	25.5	32
						$\bar{m}$ 28	$\bar{m}$ 25

ᵃ These subjects performed the movement with weights in their hands.

Table XIV. *Jumping*

Subject no.	Disc area (kp/cm²)	Pressure standing (kp/cm²)	Pressure jumping (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
[illegible]	20.7	5.9	9.5	3.6	2.4	50.0	61
[illegible]	18.1	5.7	9.5	3.8	2.5	45.3	67
[illegible]	17.1	8.2	11.7	3.5	2.3	39.3	43
[illegible]	17.0	10.7	16.0	5.3	3.5	59.5	50
[illegible]	16.0	7.0	10.5	3.5	2.3	36.8	50
[illegible]	16.3	9.7	11.5	1.8	1.2	19.6	19
[illegible]	16.7	7.6	9.5	1.9	1.3	21.7	25
[illegible]	15.0	7.7	9.7	2.2	1.5	22.5	26
[illegible]	15.0	7.5	10.4	2.9	1.9	28.5	39
						$\bar{m}$ 36	$\bar{m}$ 42

ᵃ With two 10 kg weights. ᵇ On second occasion.

…ponds well to that calculated according to equation [4] in Table I.

The same is true for the pressures obtained in the six individuals tested when bending forward holding 10 kg in each hand, Table XVI, in which situation the total load increase amounted to about 160 kp, which corresponds to an increase of 190% in pressure (and load). A comparison with the total load calculated according to equation [4] has been made in Table XVII which shows the close correlation with the measured values.

Table XV. *Bending forward* ≈ *30° without weights*

Subject no.	Disc area (cm²)	Body weight above level measured (kg)	Pressure (kp/cm²)	Load (kp/cm²)	Total load (kp/cm²)	Total load calculated according to eq: $P = 15 + 2.1W + 3.6W \sin 30°$ (kp)
2	18.3	39.2	11.4	7.6	139.1	168
6	16.0	32.5	15.0	10.0	160.0	142
9	15.0	33.0	14.2	9.5	142.5	144
					$\bar{m}$ 147	$\bar{m}$ 151

Table XVI. *Bending forward* ≈ *30° with 10 kg in each hand*

Subject no.	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure bending forward (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
2	18.3	5.6	16.5	10.9	7.3	133.6	195
4	17.1	8.2	19.8	11.6	7.7	131.7	134
6	16.0	7.0	20.2	13.2	8.8	140.8	189
7	16.3	9.7	25.5	15.8	10.5	171.2	163
8	16.7	7.6	23.0	15.4	10.3	172.0	203
9	15.0	7.5	26.5	19.0	12.7	190.5	253
						$\bar{m}$ 157	$\bar{m}$ 190

Table XVII. *Bending forward* ≈ *30° with 10 kg in each hand*

Subject no.	Disc area (cm²)	Body weight above level measured (kg)	Pressure (kp/cm²)	Load (kp/cm²)	Total load (kp)	Total load calculated according to eq. $P = 15 + 2.1W + 3.6W \sin 30°$ (kp)
2	18.3	59.2	16.5	11.0	201	246
4	17.1	53.6	19.8	13.2	226	224
6	16.0	52.5	20.2	13.5	216	220
7	16.3	54.7	25.5	17.0	277	228
8	16.7	53.0	23.0	15.3	256	222
9	15.0	53.0	26.5	17.7	266	222
					$\bar{m}$ 240	$\bar{m}$ 227

It should be noted that the subjects were asked to bend forward to an angle of about 30 degrees. This angle, however, was estimated and not measured, as was done in a previous paper (59).

Compared to the previously described maneuvers and movements, forward bending obviously increases the intradiscal pressure and thus the load on the disc to a much greater extent.

Lifting of weights

Much emphasis is placed in almost all orthopaedic or physiotherapeutic advice to the patients on how to lift weights properly. With the present method it was possible to register objectively the pressures when performing lifts in different manners. The subject was first asked to pick up two 10 kg bar-bells from a chair placed in front of him with bending of the back alone and no flexion in the knees (Fig. 14 *g*). The chair was 40 cm high and placed 30 cm in front of the subject. Recording was started with the patient standing upright and continued through the forward bending, the picking-up of the weights and when raising again back to the upright standing position. Recording was also carried out in some subjects when the patient leaned forward again to place the weights back on the chair (curve A in Fig. 15). The same subject, starting from the up-

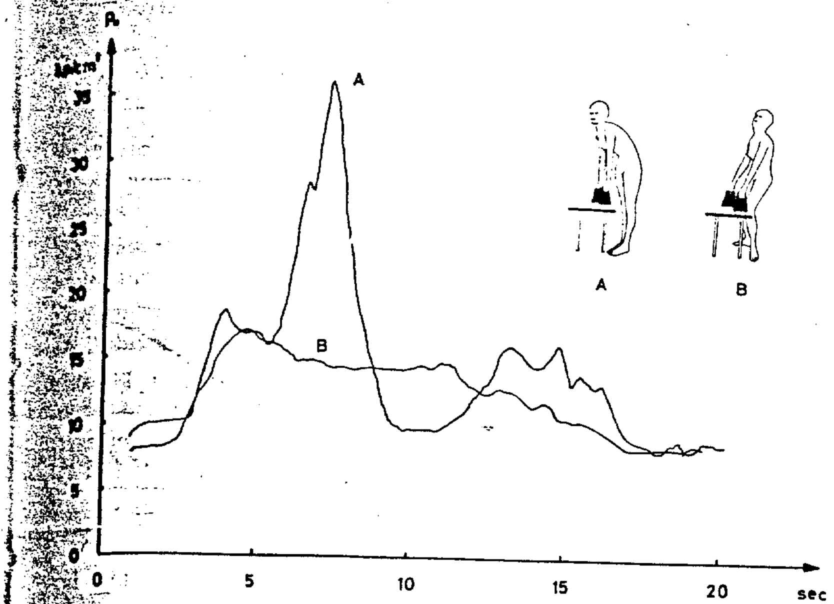

Fig. 15. Pressure recorded from the L 3 disc in subject no. 7 while lifting 20 kg. (A) With bending of back and knees straight, (B) with back straight and bending of knees.

right position, then performed the same lift but was asked this time to keep the back as straight as possible and instead flex the knees when picking up the weights (Fig. 14 *h*). Again when performing this type of lift recording started with the subject upright and continued throughout the movement and also when placing the weights back on the chair (curve B in Fig. 15). In this latter type of lift the chair with the weights was also moved 10 cm closer to the subject. As seen from Table XVIII lifting of weights causes a considerable increase in pressure and thus also load. There is, however, an obvious difference between the two manners of lifting; with the knees flexed and the back as straight as possible the load increase is considerably less than with bending of the back alone.

The pressure increase on this type of movement has been subjected to indirect calculations by different authors, among others Davis et al. (12), who by measuring of intraabdominal and intrathoracic pressures noticed a "snatch" or an abrupt increase at the moment of lifting the load, which is also clearly demonstrated in Fig.

Table XVIII. *Lifting of 20 kg with the back straight and the knees bent (A), and with the back bent and the knees straight (B) compared with upright standing with 10 kg in each hand*

Subject no.	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure lifting (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
[illegible] A	17.1	11.1	19.2	8.1	5.4	92.3	73
B			24.5	13.4	8.9	152.2	121
[illegible] A	17.0	10.7	21.5	10.8	7.2	122.4	101
B			32.5	21.8	14.5	246.5	204
[illegible] A	16.0	9.5	14.5	5.0	3.3	52.8	53
B			27.0	17.5	11.7	187.2	184
7 A	16.3	12.7	17.0	4.3	2.9	47.3	34
B			36.0	23.3	15.5	252.7	183
[illegible] A	16.7	10.9	21.0	10.1	6.7	111.9	93
B			32.5	21.8	14.5	242.2	198
[illegible] A	15.0	12.3	22.6	10.3	6.9	103.5	84
B			27.5	15.2	10.1	151.5	124
						$\bar{m}$ A: 88	$\bar{m}$ A: 73
						$\bar{m}$ B: 205	$\bar{m}$ B: 169

Table XIX. *Comparison between total load on L 3 disc in upright standing, without (A) and with 10 kg in each hand (B), in lifting of 20 kg with the back straight and the knees bent (C) and lifting of 20 kg with the back bent and the knees straight (D)*

Subject no.	A	B	C	D
4	94	127	219	279
5	83	121	243	369
6	75	101	155	288
7	104	139	184	391
8	85	119	234	362
9	77	123	227	275
	$\bar{m}$ 86	$\bar{m}$ 122	$\bar{m}$ 210	$\bar{m}$ 327

15 where the pressures also were recorded on an X-Y recorder (Hewlett-Packard) in order to present the difference more clearly.

The mean increase in load compared to that in the standing position with 10 kg in each hand is, lifting "the right way" about 90 kp, lifting "the wrong way" about 200 kp, corresponding to 70 and 170 % increase respectively.

In Table XIX comparison is made, in the six subjects measured, of the total load on the third lumbar disc in upright standing without and with 10 kg in each hand, in lifting with the back straight and the knees bent and lifting with the back bent and the knees straight. Fig. 16 gives the approximate relationship between the maximum pressures and loads obtained during these four positions and movements.

Reclining, supine and prone

The pressures obtained in these positions have in all subjects been between 3 and 4 kp/cm² as shown in Table IV, p. 14. The accuracy of these values is probably somewhat less good than in standing, where the pressure is higher. This depends on the fact that the accuracy in reading the values from the mingograph paper must be regarded as only about half a scale unit, corresponding to a pressure of about 0.5 kp/cm².

The movements performed in the reclining position have due to the above mentioned reason been compared in each particular subject with the pressure obtained in the upright standing position.

Bilateral straight leg lifting, supine

This commonly used type of exercise for hip-flexors and abdominal muscles increases the pressure about 50 % compared to that in standing as shown in Table XX and Fig. 17 *a*.

Sit-up exercises

In almost all commonly recommended programs of physiotherapy for low back pain patients special emphasis is placed on the training of the abdominal muscles (46, 84). The various reasons for this will be discussed later. In the present study the subjects were asked to perform the sit-up with knees bent as well as with the knees extended. As seen from Tables XXI and XXII the pressure compared to that in standing increased about 100 % and is similar in these two types of exercises (Fig. 17 *b* and *c*).

Isometric abdominal muscle exercise

In some types of physiotherapy programs, isometric exercises have been regarded as superior to isotonic ones (43, 44, 47, 88) and therefore the six volunteers were also tested "crook-lying" with vertical pelvis lift against resistance (Fig. 17 *d*), which is one of the isometric abdominal muscle exercises recommended (19, 47).

As seen from Fig. 17 *d* and Table XXIII the pressure increase during this muscle contraction was less than that noticed in the sit-up exercises.

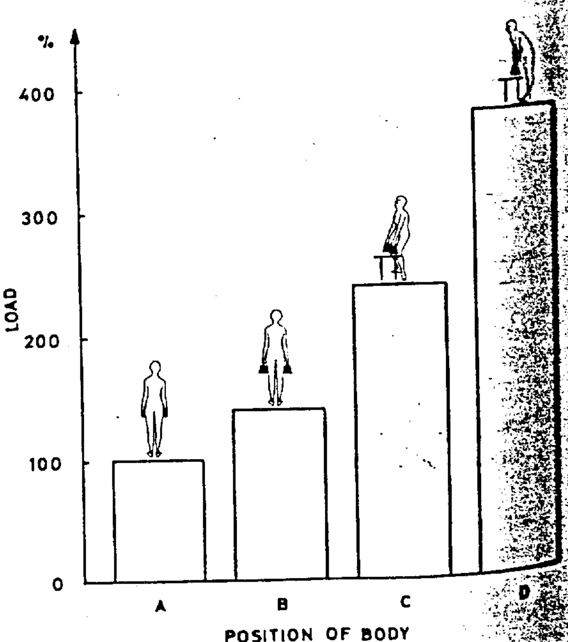

Fig. 16. Approximate relationship between load on the L 3 disc in (A) upright standing, (B) upright standing with 10 kg in each hand, (C) lifting of 20 kg "right" way, (D) lifting of 20 kg "wrong" way.

Table XX. *Bilateral straight leg raising, supine*

Subject no.	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure bilateral straight leg raising (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
4	17.1	8.2	10.4	2.2	1.5	25.7	27
5	17.0	7.3	13.0	5.7	3.8	64.6	78
6	16.0	7.0	10.5	3.5	2.3	36.8	50
7	16.3	9.7	13.4	3.7	2.5	40.8	38
8	16.7	7.6	13.4	5.8	3.9	65.1	76
9	15.0	7.5	11.5	4.0	2.7	40.5	53
						$\bar{m}$ 46	$\bar{m}$ 54

Table XXI. *Sit up exercise with knees bent*

Subject no.	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure sit up with knees bent (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
4	17.1	8.2	14.0	5.8	3.9	66.7	71
5	17.0	7.3	14.5	7.2	4.8	81.6	99
6	16.0	7.0	18.0	11.0	7.3	116.8	157
7	16.3	9.7	18.2	8.5	5.7	92.9	88
8	16.7	7.6	17.9	10.3	6.9	115.2	136
9	15.0	7.5	15.0	7.5	5.0	75.0	100
						$\bar{m}$ 91	$\bar{m}$ 109

Table XXII. *Sit up exercise with knees extended*

Subject no.	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure sit up with knees extended (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
4	17.1	8.2	13.5	5.3	3.5	59.9	65
5	17.0	7.3	15.0	7.7	5.1	86.7	105
6	16.0	7.0	18.0	11.0	7.3	116.8	157
7	16.3	9.7	17.0	7.3	4.9	79.9	75
8	16.7	7.6	17.2	9.6	6.4	106.9	126
9	15.0	7.5	15.0	7.5	5.0	75.0	100
						$\bar{m}$ 88	$\bar{m}$ 105

Table XXIII. *Isometric abdominal muscle exercise (crook-lying, vertical pelvis lift against resistance)*

Subject no.	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure isom. abd. exer. (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
4	17.1	8.2	10.2	2.0	1.3	22.2	24
5	17.0	7.3	10.3	3.0	2.0	34.0	41
6	16.0	7.0	12.5	5.5	3.7	59.2	79
7	16.3	9.7	13.4	3.7	2.5	40.8	38
8	16.7	7.6	9.6	2.0	1.3	21.7	26
9	15.0	7.5	9.2	1.7	1.1	16.5	23
						$\bar{m}$ 32	$\bar{m}$ 39

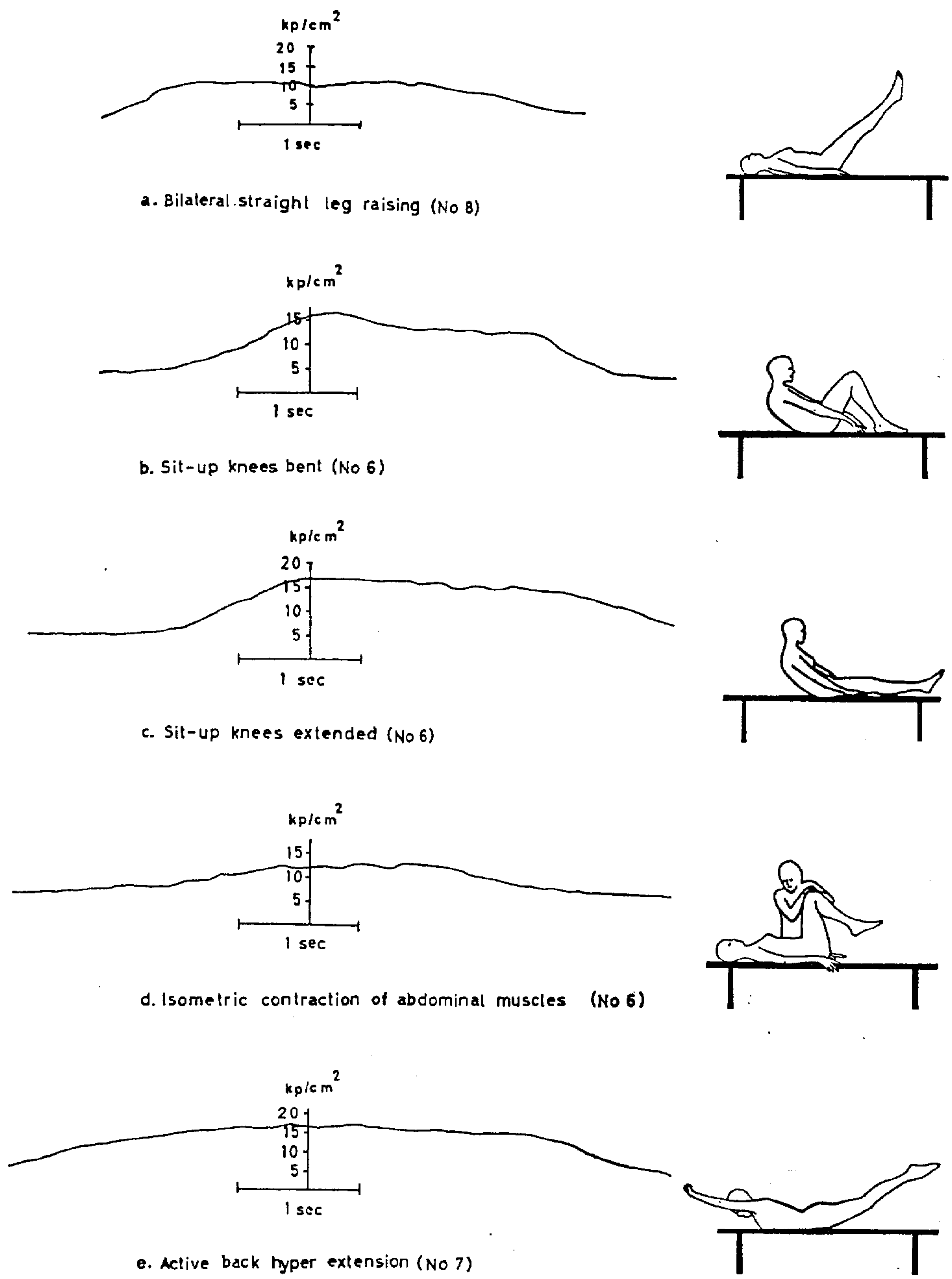

Fig. 17. Pressures measured during the performance of different exercises in recumbent positions.

Compared with the pressure in standing the increase amounted to only 40%.

In three subjects the pressure increase in relaxed "crook-lying" (Fig. 18) was also measured and found to be 6.0 kp/cm^2 in subject no. 6, 8.4 kp/cm^2 in subject no. 7 and 6.5 kp/cm^2 in subject no. 9. Compared to the pressures in standing these values are 2 and 3 kp/cm^2 lower.

Active back hyperextension

In the prone position the patients were asked to raise their heads and their feet from the table as much as they could, i.e. to actively use the back extensor muscles. As seen from Table XXIV the mean increase in pressure compared to that in standing amounted to 80%, corresponding to a load increase of about 70 kp (Fig. 17 *e*).

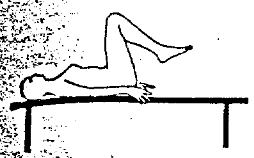

Fig. 18. Relaxed "crook-lying".

Passive back hyperextension

In two subjects lying relaxed in the prone position the back was passively hyperextended. This resulted in a moderate pressure increase from 4.0 and 4.2 kp/cm² to 6.0 and 6.8 kp/cm² respectively.

Traction

Three subjects were measured before, during and after the application of traction. Subjects no. 3 and no. 9 were measured with vertical traction applied as described earlier (p. 11) and the reduction in pressure from the stepwise increasing loads are seen in Table IV (p. 14) and in Fig. 19. Traction applied vertically in the standing position reduces the pressure to a moderate extent. It is seen from the figure that traction with about 60% of the body weight is needed to reduce the pressure by 25%. In the supine position traction was applied as described on p. 11, up to 30 kp for three seconds in two individuals (nos. 5 and 9) with a reduction from the supine pressure of 1.2 and 0.8 kp/cm² respectively (Table IV, p. 14).

Table XXIV. *Active back hyperextension (prone)*

Subject no.	Disc area (cm²)	Pressure standing (kp/cm²)	Pressure active back hyper-extension (kp/cm²)	Increase: Pressure (kp/cm²)	Increase: Load on disc (kp/cm²)	Total load increase (kp)	Increase in pressure and load (%)
4	17.1	8.2	12.9	4.7	3.1	53.0	57
6	16.0	7.0	16.0	9.0	6.0	96.0	129
7	16.3	9.7	17.0	7.3	4.9	79.9	75
8	16.7	7.6	12.1	4.5	3.0	50.1	59
						$\bar{m}$ 70	$\bar{m}$ 80

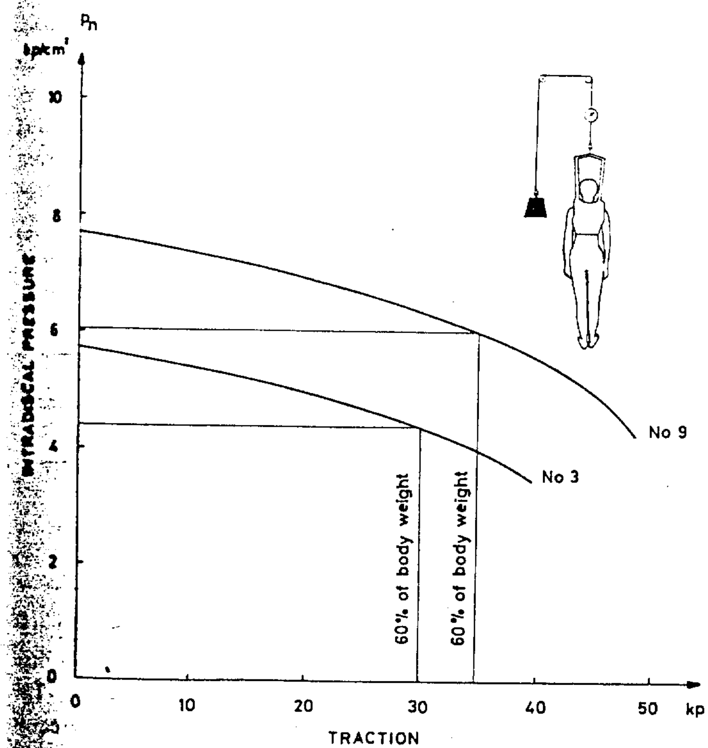

Fig. 19. The effect of vertical traction on the intradiscal pressure in two subjects (nos. 3 and 9).

CHAPTER VI

Comparison of the various pressures obtained

From the results presented in Chapter V it is obvious that some positions, movements and maneuvers increase the intradiscal pressure more than others. The mean change in pressure compared to that obtained in the upright standing position is graphically presented in Fig. 20, where all the positions etc. evaluated in three or more subjects have been compared. The statistical analysis of the intradiscal pressures is based upon paired differences where the pressure in upright standing or the pressure in upright standing with 10 kg in each hand is used as a reference. The statistical analysis was performed only in those positions that were studied in 4 or more individuals.

The mean values of the differences are tested by Student's t-test:

$$t = \frac{\bar{d}}{S_{\bar{d}}}; \text{ degrees of freedom} = n - 1;$$

$$\text{where } \bar{d} = \frac{\Sigma(x_i - y_i)}{n} = \frac{\Sigma d_i}{n}$$

$S_{\bar{d}}$ = standard error of the mean,
x_i = the pressure for the ith subject in a certain activity,
y_i = the reference pressure for the ith subject.
n = number of subjects.

Significant mean differences are marked *.

The following mean differences from upright standing with 10 kg in each hand are obtained:

	Mean diff.	t	n
Coughing	0.5 kp/cm²	0.5	5
Straining	0.5 kp/cm²	0.7	6
Jumping	0.4 kp/cm²	0.3	6

None of the mean differences are significant; the pressures for these activities are equal to the pressure obtained in standing with 10 kg in each hand. The differences from upright standing *without* weights are, of course, all highly significant.

Sideways bending and twisting gave similar pressure increases but the statistical analysis showed that twisting only gave significantly higher values than standing with 10 kg in each hand. ($d = 2.8$, $t = 5.2$*, $n = 4$). There was, however, the same tendency in sideways bending ($d = 3.0$, $t = 2.8$, $n = 4$). The increase compared to the upright position in percent is smaller than for straining etc. as seen in Fig. 20 and Tables VIII–X, XII, XIII.

For bending and lifting the analysis gave the following results:

	Mean diff.	t	n
Forward bending 30°, 10 kg in each hand	11.7 kp/cm²	12.3*	6
Lifting of 20 kg, bending of back ("wrong way")	18.8 kp/cm²	11.5*	6
Lifting of 20 kg, bending of knees ("correct way")	8.1 kp/cm²	7.0*	6

All the mean differences are significant; that is, all these activities give a higher intradiscal pressure than upright standing with 10 kg in each hand.

Comparing lifting the "wrong" way with lifting the "right" way shows that the difference between 18.8 kp/cm² and 8.1 kp/cm² is significant (t = 5.0*, $n = 6$).

The mean differences from upright standing with 10 kg in each hand are for the following positions:

	Mean diff.	t	n
Bil. straight leg raising	0.9 kp/cm²	1.5	[illegible]
Sit up with knees extended	4.9 kp/cm²	5.6*	[illegible]
Sit up with knees bent	5.3 kp/cm²	5.9*	[illegible]
Isometric contr. of abd. muscles	−0.3 kp/cm²	−0.4	[illegible]
Act. back hyperextension	3.5 kp/cm²	−2.8	[illegible]

Sit up with knees extended and sit up with knees bent give both a significantly higher pressure than upright standing with 10 kg in each hand. The other activities in this group give pressures equal to the pressure in upright standing with 10 kg in each hand.

All activties give of course significantly higher pressure than upright standing, as the difference between upright standing and upright standing with 10 kg in each hand, 3.3 kp/cm², is significant, $t=4.2$*.

The isometrically performed abdominal muscle exercise, however, also gave a significantly less pressure increase than the sit up exercises, and a probably smaller increase than straight leg raising and active back hyperextension.

CHAPTER VII

Discussion of the measuring procedure

This study introduces a new device for intravital pressure recording within lumbar discs. The reliability of the pressure needle presented was tested in repeated static as well as dynamic autopsy experiments and was found to be good. Also in one subject (no. 9) pressures were measured on two different occasions with small deviations (Table IV).

To be able to register the static pressures the metering equipment has to be a DC-coupled system. As all DC-amplifiers have a certain zero-drift due to temperature changes, the base-line drift might cause trouble. If however the equipment is turned on about one hour in advance, this zero-drift could be neglected in comparison with that of the pressure transducer itself. As the bridge current causes a slight heating of the transducer it is important to balance the bridge with the pressure needle in a liquid with about the same thermal conductivity as the disc with surrounding tissues. The use of sterile water or 0.9 % saline is convenient and has proved to give a satisfactory result. If the temperature of the liquid used is about 37°C (98.6°F) when the bridge is balanced even the zero-drift due to the temperature sensitivity of the transducer can be overlooked.

Calibration was performed before and after every experiment as described on p. 8. The accuracy of the manometer used for calibration is given as ± 0.5 % of maximum value or ± 0.2 kp/cm^2 and the accuracy in reading the values of the mingograph recordings can be estimated to half a scale unit which corresponds to a pressure of 0.5 kp/cm^2 at the amplification used. The maximum measuring fault can thus be estimated to ± 0.7 kp/cm^2.

The possible errors when calculating the total load on the disc from these measurements have already been discussed in Chapter II. These errors are, however, omitted in the comparison and calculation of the increase in per cent of the pressure in the different positions compared to standing within the same subject.

As noted from the results the pressures in the different individuals performing the same movement, maneuver or exercise have varied to a relatively large extent, although the relation of the pressures within the same person is closely alike and with a few exceptions is that seen in Fig. 20, (p.x).

The variation in pressure in different subjects performing the same movement could be due to: 1) The probable variability of the body weight above the level measured. 2) The surface area of the disc. 3) The fact that the described measurements are experiments on humans where all precautions and considerations must be taken with the volunteers. With the pressure needle in the disc some of the volunteers dared to perform the movements more forcefully than others. The personal differences in performing a task under the given circumstances must naturally differ. Some subjects had to be stopped from exaggerating a movement in order not to risk fracture of the needle, while others had to be asked to increase the movement. 4) Another factor that could influence the results is the bending of the needle. The previous polyethylene covered discometry needle did not allow for more than about 20° of bending without impairing the results. The presently used device allowed for a distortion of 35°–40° without change in pressure response.

When the results from the present series are compared with those previously published as was done in Tables V, VI, VII, XV and XVII, it is clear that in the upright sitting and standing positions there are rather small differences which have already been discussed in Chapter IV, p. 12.

The approximate equations (Table I, p. 6) calculated from previous discometries have been corroborated by the present results at the same time as the possibility of intravital discometry with this pressure needle was ascertained.

The experiments performed on autopsy specimens also served the same purpose, as well as providing a check on the dynamic properties of the needle. This investigation was planned on ten individuals but had to be interrupted in one volunteer before measurements were carried out, because the subject displayed a vasovagal syncope, which was quickly relieved when the guiding needle was withdrawn and the subject lay down. In two other subjects signs of blood pressure drop in the beginning of the procedure were prevented by a few minutes rest and breathing of fresh oxygen. No other untoward effects were noted, either during the procedure or within 18 months following it. In this connection it should also be mentioned that of the more than thirty intravital discometries previously performed, with an observation time now between two and six years, no late ill effects have been reported.

CHAPTER VIII

Discussion of the results obtained in the different positions, maneuvers and movements studied

It is well-known that most of the patients with low back pain and/or sciatica experience more pain from various movements and situations that increase the stress on the lumbar spine. In 50–70 % of the cases some types of movements, such as lifting, twisting and sudden change in position, have been said to precipitate the initial pain attack (35, 36, 37). Pressure increase between 5 and 35 % when performing the *Valsalva maneuver* in the sitting position has previously been demonstrated (62). In the present material the increase, when the straining was performed in the standing position, was about 50 %. The present results seem to support the view that the pain experienced during the performance of this maneuver by many of the patients with extradural cause of their symptoms is most likely related to the increased mechanical load on the lumbar spine produced by muscle activity in contrast to those with an intraspinal tumor where radiating pain from prolonged straining is due to increased intraspinal pressure (63). The pressure response was always noted within 0.5 sec. Compared to the pressure in upright standing position, however, the increases noted in *straining, coughing* and *laughing* were all of about the same magnitude and amounted to about 40–50 %, corresponding to some 40 kp of increased load.

On the other hand it has been demonstrated by Hirsch and Nachemson (32) that on lumbar discs already loaded by 75 kp a further load increase of 40 kp will increase the lateral bulge of anulus only about 0.2 to 0.3 mm. Obviously load increases of this magnitude in some instances cause increased pain. In subjects with definite disc hernias this is conceivable but since the pain increase occurs also in subjects without any demonstrable direct impressions on the nerve, it automatically raises the question of the excitation of pain receptors located in anulus fibrosus (30, 34, 40).

Walking, sideways bending and twisting are all relatively common, minor everyday movements that have been said by some authors, e.g. Schmorl (74), Keyes & Compere (45), Spurling (78), de Sèze (75), to be sufficient to cause disc degeneration. In the present study the recorded pressures were relatively low, the smallest increase having been noted on walking while sideways bending and twisting induced stresses of about the same magnitude, i.e. around 25 % increase from the standing pressure. Few patients experience any pain in walking nor is this a frequent complaint in the latter movements (1). From a purely mechanical point of view the loads arising from these movements are relatively small compared to those arising from e.g. forward bending and weight lifting and are well below those known to cause permanent changes in the disc (6, 17, 33, 67).

Almost all authors who have tried to calculate the load on the lower lumbar discs either theoretically (5, 52), or indirectly from pressure measurements inside the abdomen (2, 10, 11, 14, 54), have made particular reference to the load in *forward bending and weight lifting*. The results have differed widely, from more than 1000 kp (52) to 300 kp (10, 11). In prior intravital discometries the load was found to be around 200–300 kp when a subject holding 10 kg in each hand bent forward 20° by hip flexion. In this study the previously calculated approximate equation (Eq. [4] in Table I) has been further confirmed by measurements in forward flexion of 30°.

From intraabdominal and intrathoracic pressure measurements and from cyclophotograms (14, 17) it has been demonstrated that when lifting there is initially an increase in load, a so called "snatch pressure". In the present study this was verified (Fig. 15, p. 21) and under the present test conditions amounted to about 300 kp for some tenths of a second. The highest pressure noted in this particular study was 37 kp/cm² in subject number 7 when lifting 20 kg, which corresponds to a load of about 350 kp.

When the subjects lifted with the back straight and knees bent significantly less pressure and load on the disc was noted than in lifting with knees straight and bending of the back. In the present study the difference was found to be as a mean 10.5 kp/cm² of intradiscal pressure, corresponding to a mean load increase of about 120 kp. The values obtained varied to some extent in this series, which is probably due to both the relative variation in height among the individuals and also to the fact that the volunteers did not always perform the lifts as they were told. The degree of knee flexion particularly differed, which meant that the forward flexion of the spine in the hip-joints had to be increased in some individuals more than in others. This was most obvious in subject no. 9, where the quadriceps muscle on the right side was weakened due to blocking of the fourth lumbar nerve root because of the local anesthetic injected.

In spite of this, the significant difference in load demonstrated between the described manners of weight lifting, stresses the importance of ergonomic advice to patients with low back pain problems, which obviously should be given more generally if one believes in the importance of mechanical stresses for the production or maintaining of these pain syndromes.

Compression tests on autopsy discs have demonstrated that the motion segment withstands 300-700 kp of vertical load before being permanently changed or fractured (6, 14, 16, 67). There is a definite trend of lessened resistance to load with increasing age (67).

In previous autopsy studies it was calculated that due to relatively high internal pressure of the normal disc, the anulus fibers are subjected to relatively low vertical stress while the horizontal or tangential tensile stress will be high, in some parts up to 5 times the vertical load applied (57, 58).

These calculations were recently confirmed by the findings of Galante (23) and Tkaczuk (81) who studied the tensile strength of the anulus fibers and the dorsal longitudinal ligament respectively. Galante (23) demonstrated that anulus fibers with slight degenerative changes have a rupture load of around 100 kp/cm². Some of the subjects of the present study, while lifting 20 kg the "wrong" way exhibited short pressure increases above 30 kp/cm² which corresponds to more than 120 kp/cm² of tensile stress in anulus. Obviously there are situations and movements that might impose stresses and strains in different parts of the disc that are sufficiently large to cause permanent changes, as observed in load tests in older and slightly degenerated autopsy specimens.

Bed-rest is the most commonly used primary treatment for patients with low back pain and is strongly recommended by almost all authors on low back pain, e.g. Armstrong (1), Cailliet (7), Williams (84), Pearce & Moll (66), Stevens (80), Young (87). In this study the pressures obtained in both the supine and prone positions have been the same and were between 3 and 4 kp/cm² and lower than in any of the other positions tested. They are, however, higher than the ones found in anesthetized individuals in complete muscle relaxation where values of 1.5–2 kp/cm² have been recorded, but again lower than when lying on the side (lateral decubitus position) previously reported (62) where the pressures were between 5 and 6 kp/cm².

Next to bed-rest, *physiotherapy* is most commonly prescribed for patients with low back pain problems. Due to the unknown etiology of the problem it is natural that a number of different theories are used to justify the varying types of programs that exist. Some authors, such as Lucas (50) and Troup (82), advocate back strengthening exercise for the extensor muscles alone while others try to increase the mobility of the spine (24, 25). Of the current programs the one most commonly used is Williams' (84) back flexion exercise program or its modification (46). Postural exercises alone are also advocated (66). Much emphasis is usually placed on training of the abdominal muscles both by different isotonic exercises like sit-ups (84) or isometric ones in "crook-lying" (43, 44, 88). As seen from the results obtained in this study (Table XXV), all the commonly recommended isotonically performed exercises resulted in intradiscal pressures that were higher than those measured in standing and even in straining and jumping. The sit-up exercises gave significantly higher pressures than the other two types tested and the values obtained were similar to those noted when the subject bent forward 20° with loads of 10 kg in each hand (Fig. 20). In most instances the same authors who advocate these types of exercise also stress the importance that the patient should avoid carrying weights or bend forward due to the high load it imposes on the disc (46, 84).

In the present material the isometrically performed abdominal muscle exercises induce a sta-

Table XXV. *Total load on L 3 disc in upright standing (A) without and (B) with 10 kg in each hand compared to exercises in supine and prone position*

Subject no.	A		B		Bilat. straight leg raising		Sit-up, knees extended		Sit-up, knees flexed		Isometric abd. exer.		Active back hyperext.	
	Pressure (kp/cm^2)	Load (kp)	Pressure (kp/cm^2)	Load (kp)	Pressure (kp/cm^2)	Load (kp)	Pressure (kp/cm^2)	Load (kp)	Pressure (kp/cm^2)	Load (kp)	Pressure (kp/cm^2)	Load (kp)	Pressure (kp/cm^2)	Load (kp)
4	8.2	94	11.1	127	10.4	118	13.5	154	14.0	159	10.2	116	12.9	147
5	7.3	83	10.7	121	13.0	148	15.0	170	14.5	165	10.3	117		
6	7.0	75	9.5	101	10.5	112	18.0	192	18.0	192	12.5	133	16.0	171
7	9.7	104	12.7	139	13.4	145	17.0	184	18.2	197	13.4	145	17.0	184
8	7.6	85	10.9	119	13.4	149	17.2	190	17.9	199	9.6	107	12.1	135
9	7.5	75	12.3	123	11.5	115	15.0	150	15.0	150	9.2	92		
Mean	7.9	86	11.2	122	12.0	131	16.0	173	16.3	177	10.9	118	14.5	159

tistically significant smaller load on the lower lumbar spine than the other types tested.

Active back hyperextension and bilateral straight leg raising induced pressures that were equal to or higher than those obtained in upright standing with 10 kg in each hand.

Although the literature on physiotherapy for low back pain patients is abundant, the number of studies on the clinical effect, performed in a controlled manner, is small. To the authors' knowledge there exist only two such studies (43, 88) which have tried to evaluate different methods of physiotherapy and also of no treatment at all. In both these series it was shown that programs containing mainly isometrically performed exercises seem to be superior to the other types examined.

Measurements made in "crook-lying" alone and in passive hyperextension of the back also have demonstrated that the main pressure raising factor is dependent on muscular forces, rather than passive movements of the spine itself. In relatively relaxed "crook-lying" the pressure increased by 3 kp/cm^2 compared to the relaxed supine position, while the passive hyperextension increased

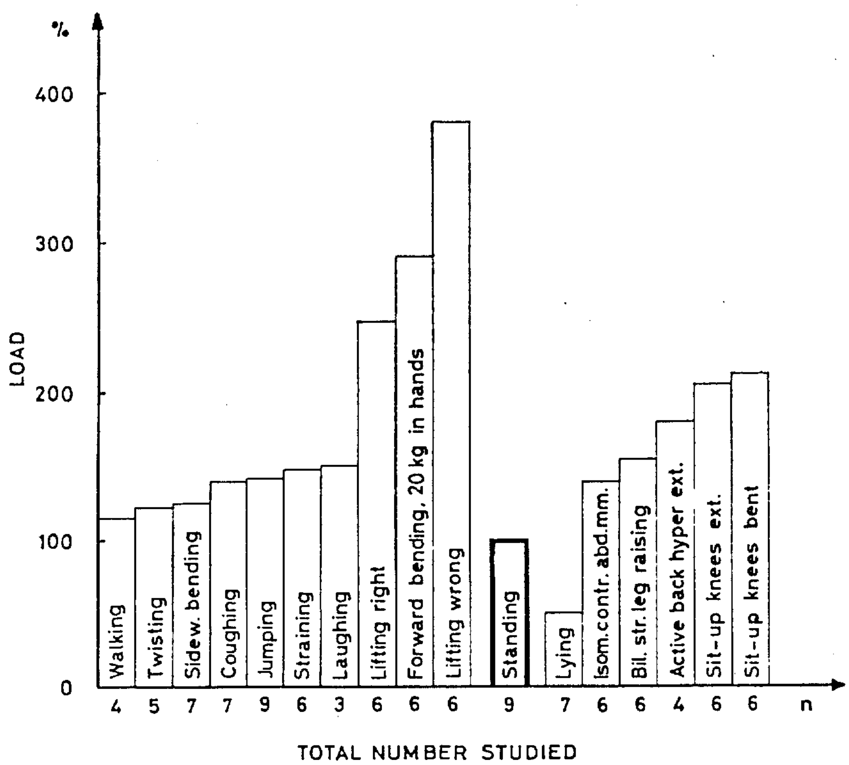

Fig. 20. Mean change in load (%) compared to that obtained in the upright standing position.

the pressure about 2 kp/cm^2. With active muscular contraction in these same positions the increases noted were 7 kp/cm^2 and 10 kp/cm^2 respectively.

Traction for low back pain patients is considered by a number of authors to be beneficial e.g. Worden & Humphrey (85), Judovich (41), de Sèze & Levernieux (76), Youel (86). The effect is said to depend on the possibility to produce a constant pull to overcome muscle spasm and to provide rest and immobilization. It has also been suggested to allow for a reduction of a disc hernia by the pull of the dorsal longitudinal ligament (9, 51).

De Sèze & Levernieux (76) and Judovich & Nobel (42) have maintained that traction has to be applied with rather large weights to overcome the friction resistance of the body and Judovich (41) has calculated that at least about 30% of the entire body weight is needed to allow any stretch in the lumbar area. In the present series traction in the supine position was applied in two subjects with about 50% of the body weight on a sliding table (Tru-Trac table) which allows for motion of the lumbar part of the body. In these volunteers traction was applied for three seconds with 30 kp. The reason for the small number of subjects tested, as well as for the relatively low traction force, is that some distortion of the needle might occur because of the different elasticity of the body segments pierced by the pressure needle (skin, fascia, muscles and disc) and also the fact that traction injuries have been reported (87). In the two subjects there was a pressure decrease of 1 kp/cm^2, which corresponds to a decrease of about 25% of the pressure in the supine position.

Already Hippocrates, quoted from de Sèze & Levernieux (76), applied traction in the vertical position and it has since been advised to low back pain patients (48). In the two subjects tested as described on p. 11, a load of about 60% of the body weight was needed to reduce the standing pressure by about 25% (Fig. 19, p. 25). In these subjects the traction was applied for at least three minutes, with no obvious change in the recorded pressures.

If the purpose of traction is a decrease of intradiscal pressure or load on a lumbar spine it is, according to the results presented, best applied in the supine position.

In earlier attempts to evaluate the *dynamic or damping properties* of the disc, measurements were made on autopsy specimens (27, 32) and it was demonstrated that a disc specimen subjected to a sudden blow starts to oscillate at frequencies around 10 Hz. Evaluations of the damping properties have also been made indirectly in tractor ride research where the spine was noted to have a resonant frequency of about 4 Hz (13).

In the present study the recordings of jumping and other sudden movements did not show obvious oscillations in the intradiscal pressure in the living body although it was possible for the system as a whole to record frequencies up to about 500 Hz.

This in vivo observation is also confirmed by the dynamic in vitro tests.

CHAPTER IX

Summary and conclusions

The etiology for low back pain is still obscure. Presently the discussions are centered around chemical changes occuring in the lumbar discs and different mechanical factors to which these are subjected. In the various types of treatments recommended the mechanical factors are most commonly considered.

Thus although the importance of the mechanical stress is widely recognized, our knowledge of the load on the lumbar discs hitherto has been limited to a number of static positions. This study was performed in order to elucidate by intravital measurements the pressure in nucleus pulposus, not only in a number of static positions, but also in some common movements, maneuvers and exercises used in different programs of physiotherapy for low back pain.

Previous intradiscal pressure measurements both in vitro and in vivo have demonstrated that nucleus pulposus of the normal or nearly normal disc behaves hydrostatically when subjected to loads in the vertical direction, i.e. it distributes pressure evenly to anulus fibrosus and to the vertebral endplates.

Due to the special anatomical arrangement of the disc the pressure in nucleus is 50% higher than the outer applied load per unit of area. Theoretically this also means that the tensile stresses in some parts of anulus can be approximately 4 to 5 times the outer applied load.

The previous in vivo measurements have provided some data on the intradiscal pressure in a number of static positions of the body, such as upright standing and sitting, forward leaning of 20° and reclining. Since the previous method, besides being rather time consuming and cumbersome also was limited to static measurements, the need for developing a better pressure needle became evident.

In the present study a device built on the semiconductor strain gauge principle was used and found suitable for this purpose, i.e. it accurately measured both static and dynamic pressures in vivo.

The possible errors of the method consist mainly in those occuring when reading the recorder. The errors in the calculation of the total load on the lumbar discs from the presures obtained in nucleus are the variability of the factor by which the measured value is divided to obtain the load per unit disc area and the possible error in measuring the surface area of the disc.

Experiments were performed on six normal autopsy discs. The static loading tests in these confirmed the previous finding that the pressure inside nucleus is 1.5 ± 0.1 times that of the outer applied load, while dynamic tests confirmed the accuracy of the device up to 500 Hz. Dynamic tests also showed that instant changes in intradiscal pressure, and thus also changes in load, are perfectly damped by the disc.

This pressure needle was then used in pressure measurements in the third lumbar disc of nine individuals, one of which was measured on two different occasions with similar results.

Three of the subjects were patients with either low back pain (2 subjects) or scoliosis of a relatively mild degree (1 subject). Six were young volunteers. All were measured in a normal disc, as judged from the roentgenograms. In some cases a discography was also performed to confirm the normal state of the nucleus.

The following *static positions* were measured: upright standing without and with 10 kg weights in each hand, forward leaning of 30° without and with 10 kg in each hand, sitting without support, sitting leaning forward 20° and with 10 kg in each hand, supine and prone recumbency.

The following *maneuvers* were studied: straining, coughing, laughing, crook-lying, passive back bending.

The following *movements* were studied: walking, jumping, twisting, sideways bending, forward bending 30° without and with 10 kg in each hand. Particular studies were made of the pressures when weight lifting with the back straight and the knees bent and with the back bent and the knees straight.

In the supine recumbent position the following *exercises* were studied: bilateral straight leg raising, sit-up exercises with knees bent and with knees extended, isometric abdominal muscle exercises in "crook-lying" with vertical pelvis lift against resistance and active back hyperextension in the prone position.

In addition two subjects were studied when standing subjected to increasing vertical *traction*. Two subjects had traction applied in the supine position using a Tru-Trac table.

The results obtained in the static positions tested corroborate previously empirically established equations for the load on the lumbar disc in these different positions which can be approximately calculated from the body weight of the subject.

In the sitting position the mean load calculated from the pressures obtained was 113 kp, while the mean load calculated, according to the equation ($P = 30 + 2.8W$) previously obtained (by regression), was 123 kp. With the new values included the equation for the regression line was $P = 40 + 2.5W$. (P = Load on the disc, W = Body weight above level measured.)

Also when sitting and leaning forward 20° and holding 10 kg in each hand the present measurements showed close correlation with those calculated according to the previous ecquation for the load in this position, 233 kp and 247 kp, respectively.

In the upright standing position without and with 10 kg in each hand the mean load calculated from the pressures obtained were 82 kp and 125 kp, respectively. The mean loads, calculated according to the equation ($P = 15 + 2.1W$) previously obtained (by regression), were 88 kp and 130 kp respectively. With the new values included the equation for the regression line was $P = 6 + 2.2W$.

Such maneuvers as straining, coughing and laughing, performed in standing, increased the pressure, and thus also the load, by 40% (coughing) and 50% (straining). The load increase amounted to 30–40 kp.

The increase in pressure noted in ordinary slow walking was only 15% coresponding to an increase in total load of 10 kp.

Sideways bending (20°) and twisting (45°) increased the pressure by 25% and 22% respectively, corresponding to load increases of about [illegible] kp.

Jumping on the floor increased the pressure by [illegible]% and the recordings made during this and other sudden movements did not show any obvious oscillations in the intradiscal pressure in vivo. The shock produced from the jump was completely damped inside the body.

From a mechanical point of view, with regard to both pressure and load, slow walking induces less stress than sideways bending and twisting and these in their turn less than straining, coughing, laughing and jumping.

Again from a mechanical point of view forward bending movements create significantly higher pressures inside the disc.

In the present study recordings were made, in the same individuals, when lifting 20 kg in two different ways. Lifting with bending of the back and with the knees straight increased the pressure noted in upright standing by 22.1 kp/cm^2 (range 16.3–26.3 kp/cm^2), or by nearly 300%. Lifting with bending of the knees and with the back as straight as possible caused a significantly smaller increase in pressure than the just mentioned manner of lifting. Compared to standing the increase was 11.6 kp/cm^2 (range 7.5–14.9 kp/cm^2) or 150%. The mean difference between lifting the "wrong" and the "right" way was 11 kp/cm^2 of pressure, corresponding to approximately 120 kp of load.

These figures demonstrate the value of ergonomic advice to patients with low back troubles.

The pressures measured in recumbent positions, both supine and prone, were about 50% of those in the standing position.

Tests performed in passive static positions such as crook-lying and passive backwards bending showed increases of 2–3 kp/cm^2 while active muscular contraction in the same positions as a mean increased the pressure by 7 kp/cm^2 and 10 kp/cm^2, respectively.

These observations as well as those in the standing position such as e.g. straining, coughing, sideways bending, twisting and forward bending demonstrate the importance of muscular forces for increasing the intradiscal pressure and load on the disc.

In the recumbent position the exercises tested demonstrated that isometric abdominal muscle training in crook-lying gave significantly lower pressures than the commonly recommended sit-up exercises.

The latter types induced pressures ($\overline{m} = 16.2$ kp/cm^2, range 13.5–18.2) and loads ($\overline{m} = 175$ kp) similar to those seen in forward bending 20° with 10 kg in each hand. The mean pressure in the isometriç exercises was 10.9 kp/cm^2 corresponding to a load of 120 kp.

Bilateral stright leg raising and active back hyperextension gave mean pressures of 12.0 kp/cm^2 and 14.5 kp/cm^2 respectively, with corresponding loads of 130 kp and 160 kp.

Since the advocates of physiotheraphy all consider the mechanical factor in their approach to the back problem, the pressure increases noted in the most commonly used exercises should serve as an observandum against their uncritical use in patients with low back pain.

In the two subjects measured with traction applied vertically while standing, a load of about 60% of the body weight was necessary to reduce the "standing" pressure by 25%. In the supine position, where traction was applied repeatedly on a sliding table, with 30 kp for 3 sec, the decrease from the "supine" pressure of 4 kp/cm^2 was 1 kp/cm^2, which also was the lowest value noted in this study. It is higher, however, than that noted previously in subjects completely relaxed under anesthesia.

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