

NEW OBSERVATIONS ON THE MECHANICAL BEHAVIOR OF LUMBAR DISCS

By

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INTRODUCTION

It must be admitted that we still do not know how, or from what sites, lumbar pain arises in lumbago. In spite of the literature on the subject containing detailed morphological descriptions of structural changes in the lumbar discs—changes which we are only too ready to associate with lumbago—no one has succeeded in finding out what happens pathophysiologically behind an acute or chronic lumbar pain.

Since the origin of the pain has not been elucidated, it is of importance for the purpose of continued research that the problems confronting us shall not be “pegged” to certain given tissue elements only—it may still be pointed out that, not only the discs can be made responsible but also the intervertebral joints, perhaps the ligamentous apparatus, and possibly other mesenchymal tissues around the vertebral column as well. And why not nerves?

If, then, the very foundations of our pathophysiological thinking in regard to lumbago are so indeterminate, our treatment is also bound to suffer from a high degree of inaccuracy; we are fully justified in surveying with a critical eye the results of the measures we adopt—otherwise our researches run the risk of not receiving the right clinical stimulus that is so essential if work on this branch of orthopaedic surgery is to continue to bear fruit.

There are many reasons why surgery of the back may be said to find itself in a dilemma. The action taken is mainly concentrated upon experimenting with various methods of immobilizing large or small portions of the lumbar region. It may be considered on good grounds

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however, that these operations have not as yet yielded entirely satisfactory results. The performance of an osteosynthesis is still a form of treatment that does not invariably cure the patient.

It is natural, perhaps, that our mode of thinking in regard to lumbar back pains should concentrate on mechanical disturbances, viewed nowadays in the light of structural changes in the intervertebral discs. As we are unable to restore the disc to normal, our therapy aims instead at an attempt to immobilize completely one or more segments. As long as we are compelled for lack of further insight into the subject to adopt mechanically orientated views we are justified in seeking to increase our knowledge of how the lumbar region reacts when subjected to various kinds of strain.

PLANNING THE INVESTIGATION

It is a well-known fact that, if the height of the intervertebral disc is reduced, the X-ray reveals structural changes, i.e. that changes in the disc tend to bring the vertebral bodies closer together. This may be assumed to result from reduced resistance to mechanical strain. It is also known, however, that this lowering of the height of the disc does not occur until considerable structural changes have arisen in the intervertebral disc. It has been clearly demonstrated that advanced changes may exist without this fact necessarily being disclosed in the X-ray. A comparison between the presence of annulus ruptures, for instance, and X-ray changes shows that the former arise much earlier than can be revealed by the X-ray, unless this latter source of information is supplemented by nucleographical means (Lindblom). Since, moreover, the occurrence of annulus ruptures coincides in time with an increasing frequency of clinical symptoms of lumbago (Friberg, Hirsch and Schajowicz), the question arises as to whether the presence of the ruptures does not lead to so severe an undermining of the entire disc's power of resistance to mechanical strains that it is here that we have to seek the causes of lumbago. This view has been held by Knutson, who has demonstrated the instability in the lumbar spine, and Friberg and Hirsch have been able to prove the same thing after experiments on autopsy material.

In the light of the observations made here we have contemplated trying to study in greater detail the reaction of different lumbar intervertebral discs to increasing mechanical strains. An inquiry of the kind we have planned seems now much more feasible and worthwhile owing to the fresh progress which has been made by means of the improved measuring technique which experts have placed at our disposal.

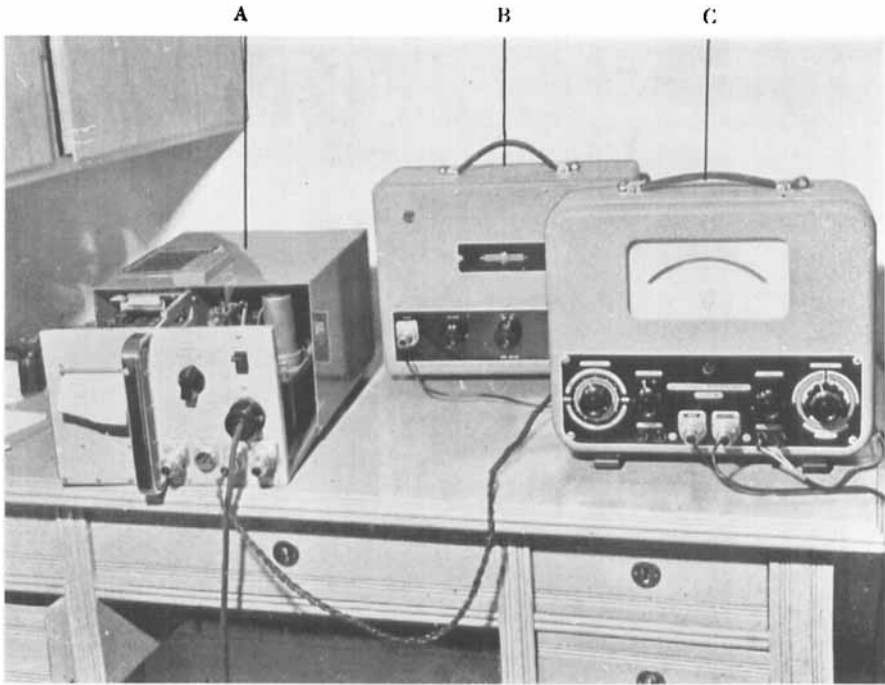


Fig. 1.

The devices for measurement. A. Direct reading measuring bridge. B. Pre-amplifier. C. Kelvin and Hughes four pen recorder.

MATERIAL

Fresh lumbar spines taken from autopsy material have been used. As a rule, only a few hours have elapsed between death and the carrying out of the experiments. Generally the second and fourth lumbar discs, and in exceptional cases others, have been tested. Prior to each experiment the clinical notes have been examined and cases involving tuberculosis or tumors have been excluded in order to avoid any suspicion that the discs may have been affected by these changes.

All musculature has been removed from the spines, while skeletal and ligamentous parts have been carefully preserved intact. Then a disc with half the upper and half the lower vertebral body, together with the intervertebral joints, has been sawn off. The surfaces of the vertebral bodies have been levelled off with a file so as to make the surfaces parallel, and placed against a flat horizontal base, made absolutely horizontal with a spirit level. All the specimens have been X-rayed before any further treatment. The size of the material and the grouping by ages will be seen in the annexed table (Fig. 2).

TECHNIQUE OF MEASUREMENT

Our conception of the tolerance of tissues when subjected to mechanical pressure was formerly based on a system of *static* registration, i.e. measuring certain changes of shape after a given period of pressure. This method of measuring has given us valuable information about the elasticity of cartilage, bone, ligament etc. But the static method—even after having been improved by a more widespread use of sensitive indicators, covering in addition very small fields of measurement—does not permit us to observe what happens within very short intervals of time; it gives no *dynamic* registration. The speed with which tissues change their form when rapid mechanical pressure is exerted is a decisive factor in enabling us to make correct evaluation of the strains to which such tissues are subjected.

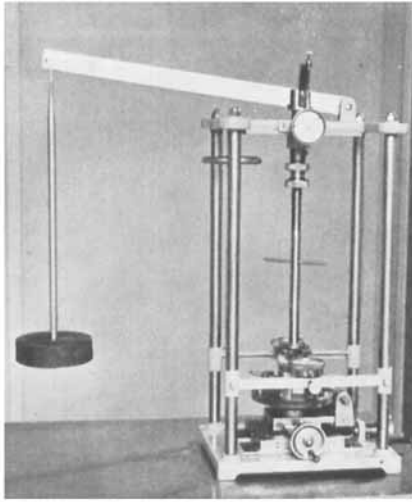
During the 1940s considerable progress was made in the field of measuring technique. The so-called strain-gauge principle had made it possible to take more adequate measurements, both *static and dynamic*, of deformations down to 1/1000th of a millimetre. By means of a fine thread, which is connected to a measuring bridge with a high degree of sensitivity, an electric current is applied. If the thread is subjected to even the slightest tension, its electrical resistance is changed and the measuring instruments indicate the degree of the tension and record it on a moving strip of paper, the speed of which can be varied. This is one method of obtaining a dynamic picture of a mechanical process, although it takes place in a fraction of a second.

Another method is to use an inductive displacement pick-up, consisting of two spools, one outside the other. The inner one is in contact, via a piston, with the material whose change in form within a given section is to be registered. According to whether the inner spool is moved into or out of the outer one, the strength of the current changes in the latter. The measuring instruments, (fig. 1) are connected up with this system and register the variations in form.

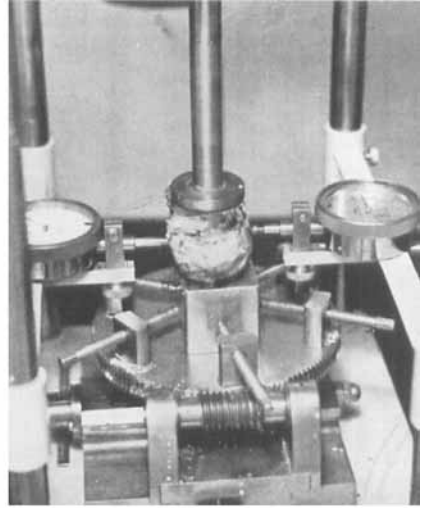
Fig. 2.

Table showing distribution of discs according to age and anatomical site.

Disc. level	No. of discs.	Age group								
		0—10	11—20	21—30	31—40	41—50	51—60	61—70	71—80	81—90
L I	1				1					
L II	49	1	6	2	10	12	9	3	4	2
L III	4				2	1	1			
L IV	40	1	6	2	8	8	8	3	3	1



A



B

Fig. 3.
Compression apparatus.

STATIC REGISTRATION

After the caudal vertebra has been fixed in a metal base, from which a number of pins have penetrated into the vertebra without reaching the intervertebral disc, the preparations are mounted in a compressing apparatus (previously described by Hirsch).

From this apparatus sturdy metal arms are moved so as to clasp those parts of the disc whose variations of form it is desired to study. A dial indicator is screwed firmly on to the end of one of these arms in such a way that by suitable pressure the ball of the indicator can be brought into contact either with a small area of the outer edge of the intervertebral disc or with the cranial vertebral body (fig. 3 and 4). The dial indicators that have been used have permitted measurements to be taken with an accuracy of 1/100th of a millimetre.

The same intervertebral disc is first loaded with a certain number of kilogrammes. When equilibrium is attained, i.e. when the indicators show a more or less stabilized value, readings are made. Absolute equilibrium never arises (see Fig. 5).

However, the deformation of the disc takes place rapidly during the first few seconds, after which the elasticity curve asymptotically approaches a certain equilibrium, which, however, is not attained for some hours. After five minutes an adequate value is obtainable. The intervertebral discs are measured from different directions. It is found that those values which are obtained ventrally are quite as useful as

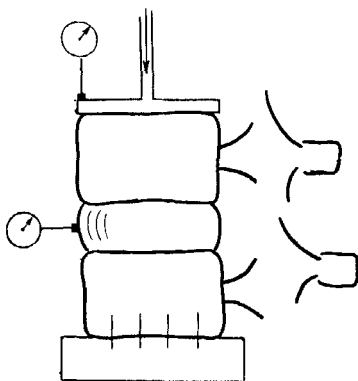


Fig. 4.

Diagram to illustrate method of placing indicators.

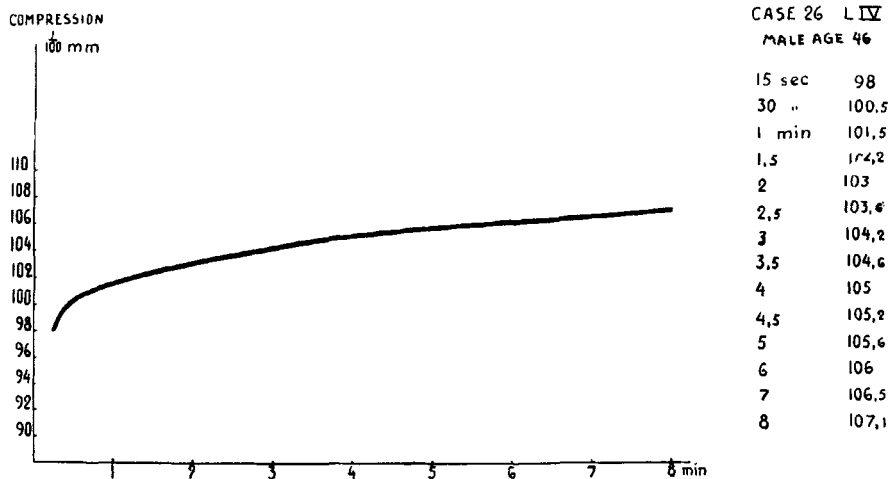


Fig. 5.

Graph to illustrate relationship between the degree of compression obtained by a load of 100 kg over a given period of time (disc elasticity curve).

Case no. 26. L IV-disc. Male age 46.

those obtained from other areas in the course of comparative experiments. That is the reason why in this work we have only indicated the anterior expansion values. At the same time as readings are made registering the anterior expansion, the degree of compression is also measured. We have thus found by measurements how much a given disc bulges anteriorly, and how much it allows itself to be compressed as the load increases. The weights used have been 40, 70 and 100 kg., i.e., they have been kept within physiological limits.

It is true that in this connection there were reasons for investigat-

ing even greater loads. That this was not done was due to special circumstances. We were anxious not to damage the preparations since they were to be used for more experiments. It was found during our first preparatory investigations that the deformation which a given disc showed was reversible to stresses up to 130 kg, if the load was not allowed to act for more than a maximum of about 5 minutes. If this limit were considerably exceeded in both time and weight, an intervertebral disc took longer to recover. However, there is always a certain permanent change of shape, though it is very small, below the indicated limit. The decisive factor in this connection is the time which the load rests on the preparation.

Within the limitations stated we have considered it permissible to carry out several experiments on one and the same preparation. Accordingly, each case was subjected to 3 experiments, the first with arches intact, the second with hemilaminectomy, and the third after total laminectomy.

After load experiments had been carried out the discs were sectioned and were then divided into a healthy and a degenerate group. Those which showed ruptures within the annulus fibrosus were placed in the latter group. All the preparations were photographed, after which they were fixed in formalin for subsequent microscopical analysis.

In the diagrams reproduced below, series A represents intact arches, series B hemilaminectomized and series C totally laminectomized preparations.

CHANGES IN THE FORM OF LUMBAR INTERVERTEBRAL DISCS AFTER BEING SUBJECTED TO STATIC LOADS

The following observations may be made on the values obtained. The compressibility of healthy discs is somewhat greater in the fourth than in the second lumbar disc. In the case of a 40 kg load it amounts to just under 1 mm. For a person weighing 70–80 kg, 40 kg is the approximal weight that the vertebral column bears when in an upright position. If the load is increased to 100 kg, the compression increases to about 1.4 mm. Within the stated limitations of load, the compression is proportional to the size of the stress.

Within a small section the lateral expansion is of course smaller than the total compression. Anteriorly, it amounts in the case of healthy discs to 0.5 mm with a pressure of 40 kg rising to approximately 0.75 mm with a pressure of 100 kg. Posteriorly, values of the

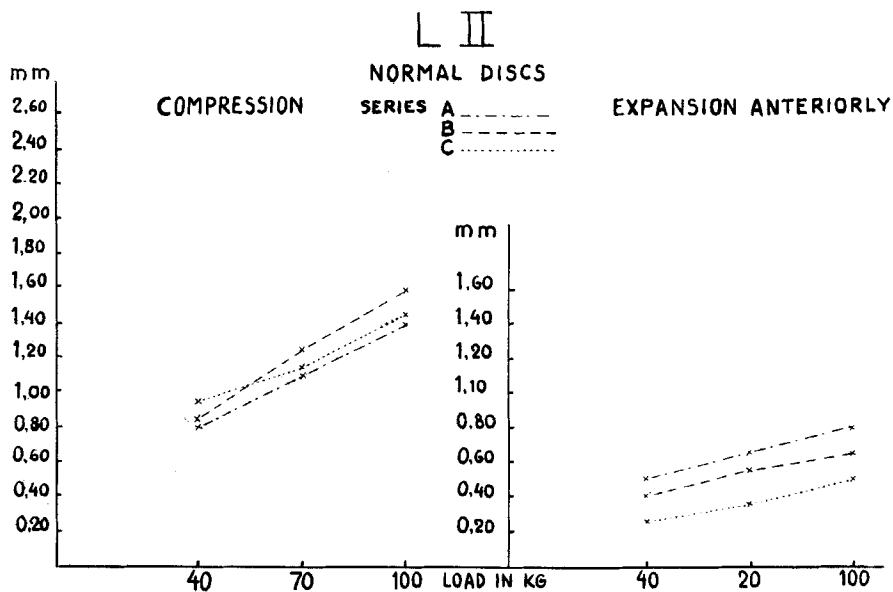


Fig. 6.

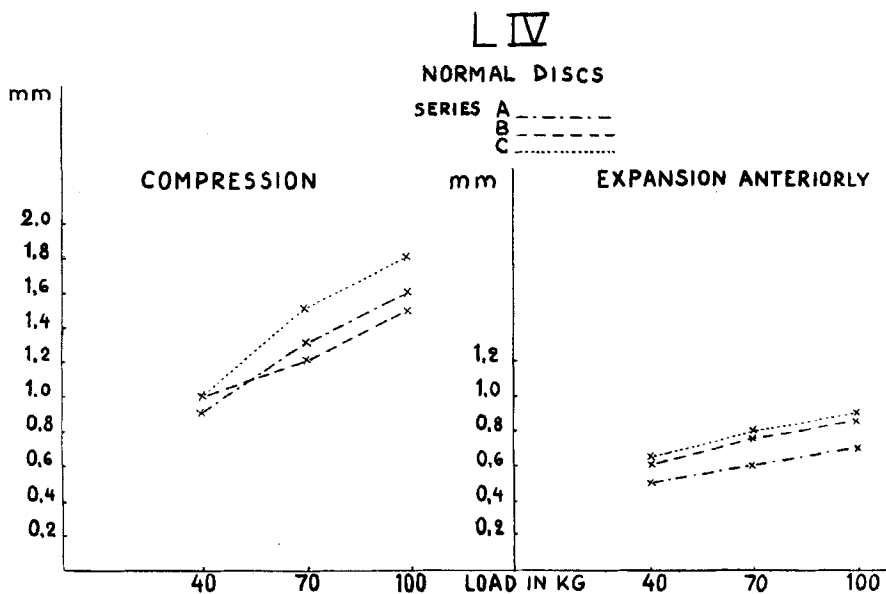


Fig. 7.

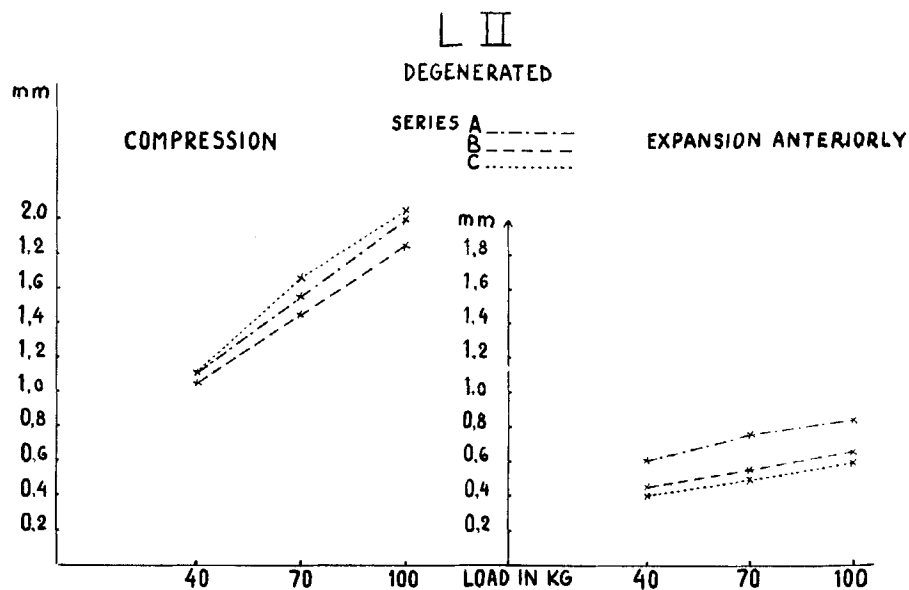


Fig. 8.

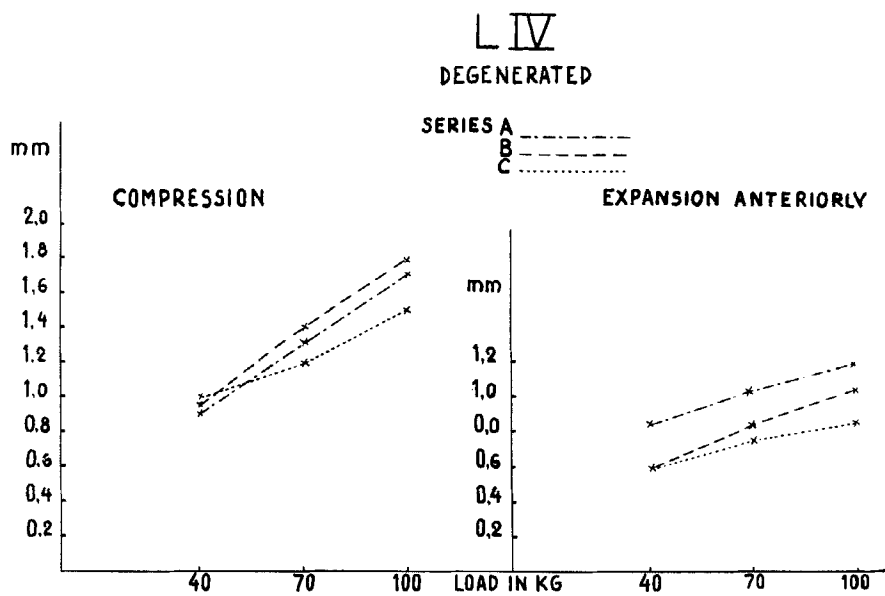


Fig. 9.

same magnitude were obtained. Here, too, the change of form is a function of the size of the load.

It is striking to note how small are the changes of form that arise with loads of up to 100 kg and how perfectly the disc appears to be constructed to carry loads.

In the case of healthy discs neither a hemilaminectomy nor a total laminectomy leads to any appreciable disturbances in the behaviour of the intervertebral discs. The magnitude of the deformations is the same throughout. The investigations offer no support to the idea that factors other than the discs themselves play any part in carrying loads applied *vertically* to a cross-section through the vertebral column.

Figs. 8 and 9 indicate the values obtained from degenerated discs. In all these cases the preparations have been specially selected insofar as roentgenologically advanced cases have been weeded out. The reason for this is that osteophytes and highly fibrous discs, for example, might interfere with measurement, giving such wide variations in different sections that the expansion would either prove difficult to register or might occur too much at random. It is clear that such cases are bound to be difficult to judge, and they have therefore been excluded in this paper.

Degenerated discs can be more easily compressed than healthy discs and are more sensitive to an increasing load. The degree of compression rises more rapidly as the load increases. Thus, the difference in sensitivity is more distinctly apparent the greater the load. At 40 kg about the same value was obtained as in healthy discs, but at 100 kg the reading showed approximately 2 mm as against 1.5 mm for healthy discs. The anterior expansion likewise shows a marked difference.

In the case of the degenerated discs neither hemilaminectomy nor total laminectomy appears to have any appreciable effect on the ability of the discs to stand *vertical* mechanical strain (see Figs. 8 and 9).

Our experiments may be open to many objections. They give no true idea of the physiological conditions, primarily because no account can be taken of what may happen if the preparations are subjected to load in oblique positions or if the preparations are in motion. There are, however, reasons for assuming that the above measurements are very largely magnified at the precise moment when the back passes from being a firmly mounted preparation into being a dynamic system in which a given mechanical point of departure can be entirely altered from one moment to another. However, there can be no doubt as to the importance of the intervertebral disc as a simultaneously governing, stabilizing and bearing factor. Structural changes within it lead to disturbances in its mechanical functions.

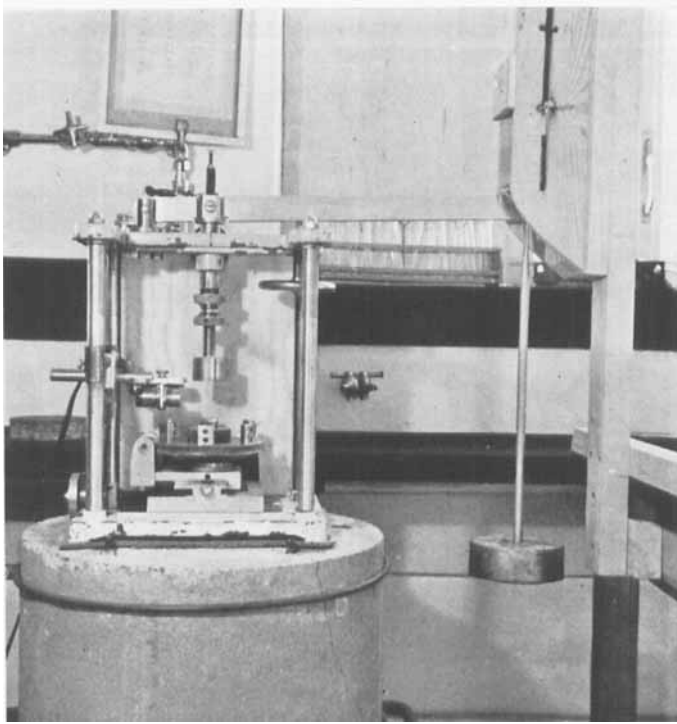


Fig. 10.

Close up view of compression chamber with laminated wood partially removed.

DYNAMIC REGISTRATION

The very fact that the vertebral column, like most other parts of the body, seldom assumes a static equilibrium but is in a more or less mobile state means that static measurements are bound to have a limited value. Obviously, therefore, the aim must be to try to investigate those changes which are reflected mechanically in the intervertebral discs during very short periods of time. In this respect the new principles of measurements to which reference has been made in the section entitled "technique of measurement" have proved very useful to us.

EXPERIMENTAL DEVICES

We soon found that the electrical instruments were so sensitive that our compression apparatus could not be used. Even small vibrations in or within the vicinity of our apparatus were at once recorded by the oscillograph in such a way that it was impossible to gauge the deformations in the intervertebral disc.

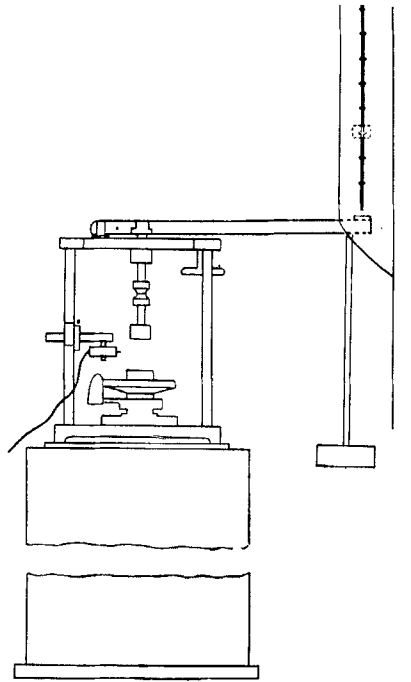


Fig. 11.

Diagram of compression apparatus with falling weight attachment on the right.

The compression apparatus was therefore mounted on a concrete pillar 1 metre high with a diameter of 60 cm, and firmly fixed to it with four metal bolts. The concrete pillar had to be isolated from the floor by a slab of cork, 2.5 cm thick. A cork base, 1 cm thick, had to be placed between the compression apparatus and the concrete pillar. Pieces of laminated wood were inserted between the bearing columns of the apparatus. The cork and wooden sheets served to eliminate vibration. See Figures 10 and 11.

To enable us to transmit force to the intervertebral discs within a very short space of time we adopted a method of "dealing blows" by letting weights fall from various heights. Fig. 12 shows the experimental devices and the table (Fig. 13) indicates how the forces are estimated. Thus, the degree of violence can always be determined in respect of each specific experiment. The weight of the blows has varied between 6 and 30 kg because of the magnification, given by the metal lever. For technical reasons we have not been able to go higher, as our apparatus could not stand any greater strain. When the limit was exceeded, a number of bearings tended to get loose and there were disturbing vibrations.

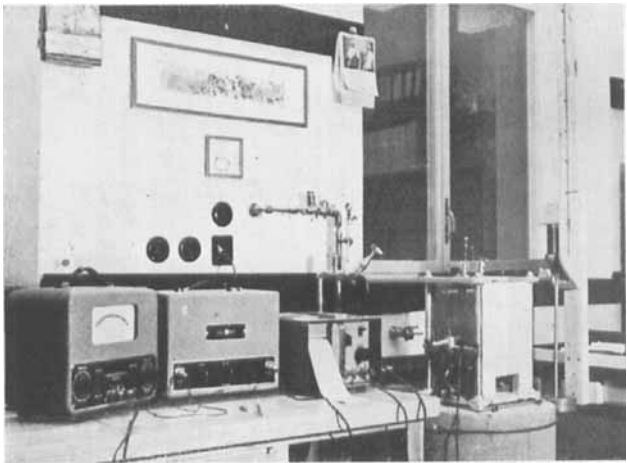


Fig. 12.
Apparatus mounted and ready for use.

Before any “blows” were delivered the intervertebral discs were loaded with weights varying between 10 and 130 kg, and the preparation was allowed to assume its static equilibrium. The shocks were then administered with increasing force.

All the discs have been compressed between two vertebral bodies, with joints and arches intact, and the direction of the force applied has invariably been *vertical*. Only the expansion of the disc laterally, at right angles to the direction of force, has been recorded in the cases described here. In certain experiments several sections within one and

Fig. 13.
Table showing relationship between height of fall, amount of weight and kinetic energy generated.

Height of fall	Duration of fall	Kinetic energy falling weight	
		of 1 kg	of 2 kg
10 cm	0.141	1 kp	2 kp
20 "	0.200	2 "	4 "
30 "	0.245	3 "	6 "
40 "	0.283	4 "	8 "
50 "	0.316	5 "	10 "
60 "	0.346	6 "	12 "
70 "	0.374	7 "	14 "
80 "	0.400	8 "	16 "
90 "	0.424	9 "	18 "
100 "	0.447	10 "	20 "

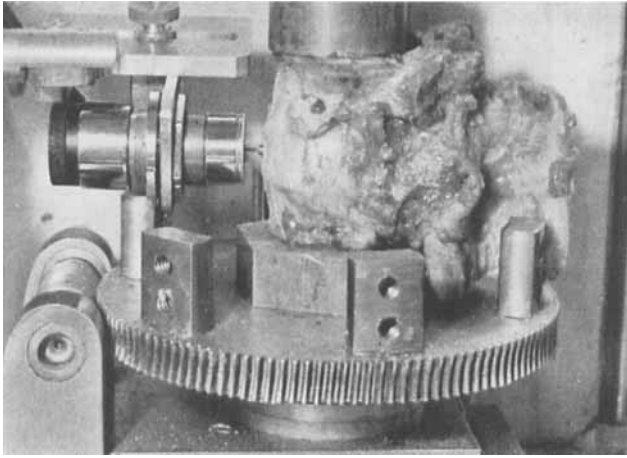


Fig. 14.

Disc under compression with the pick up attached.

the same disc were studied. As we have had access to only one inductive displacement pick-up we have not been able to make synchronous determinations and this limits the value of the investigation (Fig. 14).

The electrical measuring system is such that if the pelote which lies in contact with the intervertebral disc is shifted in either direction, the oscillograph will give a reading that can be directly transmitted in a path of motion in mm or in fractions of a mm.

The apparatus permits the measuring of distances down to $1/1000$ th of a mm and is easily adjustable to various degrees of sensitivity. Our static measurements gave us the size of the deformations that arose, and in conformity with the areas of measurement thus obtained the electrical registration further showed that a degree of accuracy of 0.1 mm was the most suitable. We therefore adopted this figure from the outset.

In the course of our researches it appeared that this degree of accuracy of 0.1 mm in this, our first survey work, was not absolutely necessary, but that for the time being we could confine ourselves to 0.3 mm of sensitivity and yet obtain an adequately clear picture. Only for the purpose of certain detailed studies have we used a greater degree of sensitivity—especially as for the present we do not consider ourselves in a position to survey the experimental sources of error that are still bound to exist. In other words, we are not yet prepared to carry our measuring technique too far when studying a biologically heterogeneous body of material in which we are *a priori* aware that the heterogeneity is of the highest grade.

TEST ON WOOD

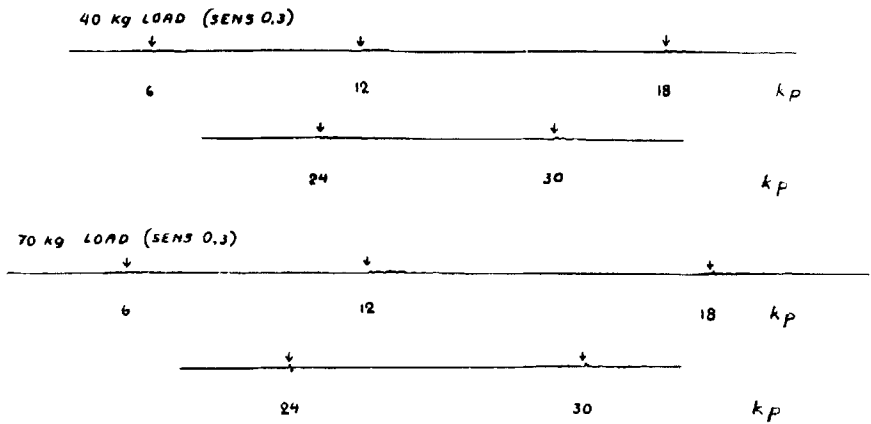


Fig. 15.

TEST ON BRASS

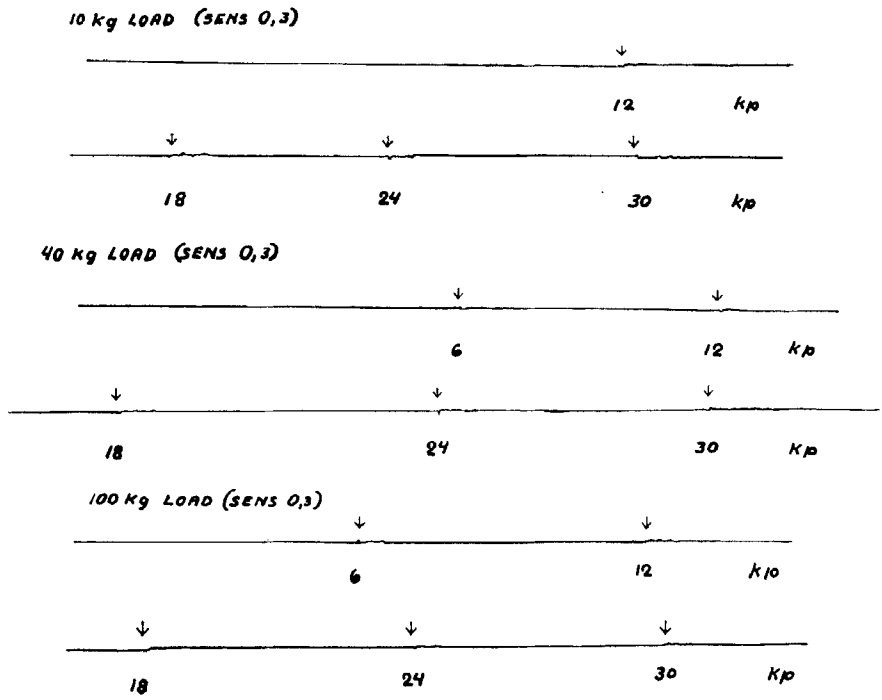
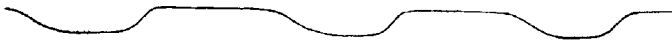
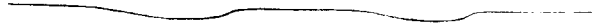
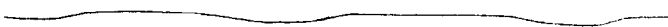


Fig. 16.

CASE 86 MALE AGE 48 L₃ EXPANSION ANTERIORLY**10 kg LOAD (SENS 0,3)****40 kg LOAD (SENS 0,3)****70 kg LOAD (SENS 0,3)****100 kg LOAD (SENS 0,3)****130 kg LOAD (SENS 0,3)***Fig. 17.*

Elasticity curve for varying loads. Case no. 86. L II-disc. Male age 47.

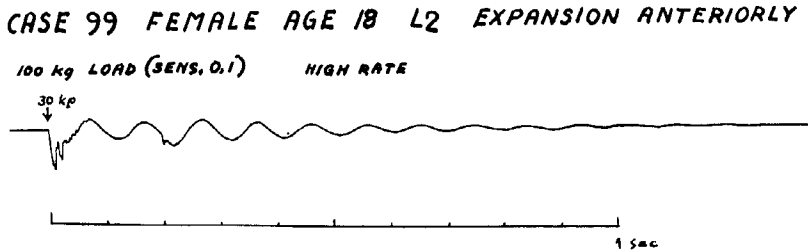
As a rule, the variations of form which it has been possible to observe in the course of the load experiments have been transferred to specially treated strips of paper, which have unrolled at a speed of 5 cm per second; in exceptional cases the speed has been brought up to 15 cm per second,—i.e. we have been able to follow what was taking place within an interval of 1/5th and 1/15th resp. of a second.

Before we started to apply our apparatus to intervertebral discs we tested its reliability on metal and wood. It will be seen from the examples we reproduce here in curves of the various test pieces that stresses in the form of pressure and shocks do not give readings with the indicated degree of accuracy. See Figs. 15 and 16. Indeed, with our knowledge of the physical properties of these materials, there is no reason to expect any readings at all, or conversely, since no readings have been obtained, the experimental devices possess stability.

DYNAMIC MEASUREMENTS OF INTERVERTEBRAL DISCS

If an intervertebral disc with its surrounding vertebral bodies, joint arches and ligaments is subjected to a load lasting 1–2 seconds, a certain compression occurs and, at the same time, a lateral bulge, which entirely disappears at the very moment at which the load ceases to be applied. Since the strains last for so short a time, even with

heavy loads the intervertebral disc retains practically its entire elasticity. This applies both to healthy and to degenerated discs of the kind we have used. Compression experiments of this nature can be repeated any number of times without disturbances being observable in the elasticity of the discs. This fact is an essential condition if we are to be able to attach any value to the experiments for which we are accounting here. The intervertebral disc gives an elasticity curve of the



Graph showing the oscillations obtained in a normal L II-disc. Drawing from the original curve without magnification. The measurements were taken with a sensitivity of 0.1 mm. The disc was loaded with 100 kg before a blow of 30 kp struck the preparation. The paper on which the graph was recorded ran at a speed of 15 cm/sec.

same type as that obtained in regard to a normal hyaline articular cartilage.

If, first of all, we load a disc with a certain number of kgs and let it assume its static equilibrium, and if after that we subject it to a brief increasing strain, it will still show a reversible change of form, that is to say, it immediately resumes the form it had before the additional load was brought to bear on it. In other words, the disc possesses, so far as we have been able to ascertain, an extraordinary power of adaption to different mechanical stresses and adjusts itself, whenever a more or less permanent (static) strain is exerted, to assume an equilibrium in which it is subsequently able to maintain perfect elasticity, i.e. it is quite capable of enduring further brief strains, having a retentive capacity for absorbing shock.

However, the greater the load applied to the disc from the outset, the less capacity will remain in the disc for any further change of form should it be subjected to a still greater load—in other words—the elasticity curve becomes “flatter”. The disc’s total change of form within the limit of its elasticity can be read from the curve at any point. The disc adapts itself uniformly to the same kind of stress (see Fig. 17).

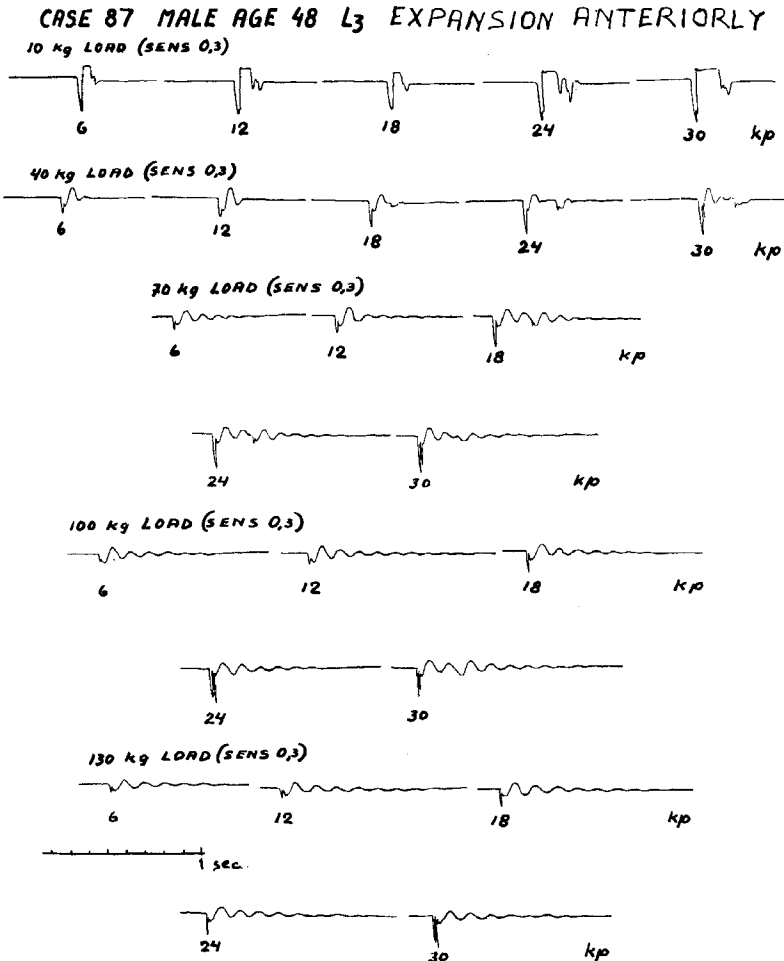


Fig. 19.

Graphs illustrating vibrations obtained with increasing loads.
 Case no. 87. L III-disc. Male aged 48.

If we subject the disc to violence to which it reacts rapidly it will begin to *oscillate*, see Fig. 18 and 19. One blow has the effect of making the entire disc start to vibrate.

As we have mentioned above, we have let weights fall against a lever, which in turn has acted upon our preparations. If at the very moment when the violent blow is struck we let the inductive displacement pick-up absorb the movements at a point on the surface of the disc—it makes no difference which point we contact—we observe how a number of oscillations arise in the course of one-fifth to two-fifths of a second. Under different conditions the frequency and amplitude

of the oscillations may vary as an expression of how a given disc behaves or reacts to the specific force to which it has been subjected. The reaction of the disc is constant under the same circumstances and can be repeated indefinitely.

If the disc is loaded with a certain number of kg (in our experiments these weights have varied between 10 and 130 kg) so that it is allowed to assume its static equilibrium and is then subjected to blows of a weight up to 30 kg vibrations will arise which are invariably the same in respect of a given degree of violence. The same experiment can be repeated many times with the same result.

When primary loads *below* 40 kg are applied the oscillations due to blows or shocks become more irregular. Only after the disc has been subjected to a certain degree of compression does it exhibit a greater resistance to shock.

Rapidly acting traumata—irrespective of their size—invariably start an intervertebral disc oscillating rapidly, but the oscillations, irrespective of the strength of the blow, are always of shortlived intensity.

If the experiment is repeated, the same type of oscillation is invariably obtained as reaction to a similar amount of force.

SUMMARY

1. The aim has been to study the mechanical behaviour of lumbar intervertebral discs when subjected to stresses.
2. Experimental devices have been constructed. This has made it possible to follow movements and changes in shape in discs within very short periods of time.
3. The mechanical behaviour of the disc differs according to how fast the stresses set in. If a disc is kept loaded a certain amount of compression occurs until an equilibrium is reached. If a disc is subjected to a short momentary load it starts to *oscillate*.
4. Diagrams are presented showing the amount of compression as well as the lateral expansion that occur after increasing loads up to 100 kg in both normal and degenerated lumbar discs. It is striking to see how little the discs are deformed. 100 kg gives a compression in a normal disc of about 1.4 mm and an expansion of 0.75 mm. In a degenerated disc, i.e. when the annulus fibres are ruptured, a compression of 2 mm was the effect of a 100 kg load.
5. There was no difference in the bearing capacity, whether the arches were intact, or a hemilaminectomy or a total laminectomy

was performed. This supports the idea that the discs themselves play by far the most important role in carrying loads.

6. Loads lasting seconds give perfect elasticity curves of the same shape as in the hyaline articular cartilage. Compression of this nature can be repeated any number of times without disturbances in the mechanical response of the disc.
7. If the disc is under load and has assumed an equilibrium and is then subjected to an increasing strain for a short period of time, it resumes the form it had before the additional load was brought on. The disc has the power of *adaptation* to mechanical stresses. However, the greater the load applied the less will be the capacity for shock absorbing.
8. When an intervertebral disc is subjected to rapidly acting forces it starts to oscillate.
9. Oscillations have been registered while the disc has been under a static load from 10 to 130 kg. This means that, even if a disc has reached a static equilibrium, additional rapid forces can increase deformations to a very great extent, even if these forces are relatively small. Because the deformations occur frequently during a short period of time (tenths of seconds), this means a hitherto unknown stress of considerable magnitude.
10. The smallest trauma can produce great stress in a low back if the force acts rapidly. The changes in shape in a disc are of such intensity and frequency that it is hardly believable that muscular reaction can stabilize and protect a back from these variations in form. They are entirely due to the biophysical construction of the disc material itself.

DISCUSSION

It has previously been considered that, in consequence of its solid construction, an intervertebral disc reacted slowly, that it could be compressed or could change shape, relatively speaking, fairly gradually. Further, it was assumed that, having reached a certain equilibrium, it retained that position until the strain upon it was relaxed. The intervertebral disc was said to have what was called an elastic quality, a fact which our investigations described here have confirmed. The disc has a capacity for *statically* adjusting itself to different mechanical demands.

In addition, however, to these slow ways of reacting there are also extremely rapid changes in form, oscillations which arise quite irrespective of the point of static equilibrium at which the disc may find itself. Thus an intervertebral disc represents a *dynamic* system in

which the disc's mass is constantly in motion. Even very small rapidly exerted strains induce shiftings of the mass that are measurable in tenths of a millimetre. Measurements of the movements of the disc with a greater degree of accuracy show that those forces which are required in order to induce such rapid movements at all may be extremely small. Seeing that the body is never in a, mechanically speaking, absolute state of rest, we cannot expect that any such state of rest will arise in an intervertebral disc either. The more frequently the strains are brought to bear, the higher the frequency of the oscillations.

We are here concerned with biomechanical phenomena, or changes in tension, in the material which occur within fractions of a second—phenomena that are merely a consequence of the physical properties of the material. It has been possible to register movements that are far more rapid than we have previously had any cause to take into account.

It is possible, indeed probable, that other tissues also show similar conditions.

In the light of the observations made here the authors may perhaps be permitted to look back a moment. In earlier writings the frequency of injury to intervertebral discs in quite early years has been pointed out from the experiences of this clinic. It has been possible to demonstrate how disturbances in the histo-chemical structure of the intervertebral discs can be traced at an early stage and how they can subsequently be followed by injuries to the tissue, changes in the nuclear content of polysaccharides, by a decrease in water content, by a disproportion arising between polysaccharide and albumen, by rupture in the annulus fibrosus, by the ingrowing of granulation tissue etc.—all signs that we are here concerned with complicated histo-chemical processes in which mechanical forces could not possibly play any essential part.

It need not necessarily be quite irrelevant any longer to reintroduce biomechanical factors into the discussion. Mechanical movements of such rapidity as are here described and of an order of magnitude that is undoubtedly bound many times daily to exceed anything that we have hitherto computed, may at any rate conceivably exert an influence on the biological phenomena that arise in the intervertebral discs.

ZUSAMMENFASSUNG

1. Es war bezweckt, die mechanische Funktion der lumbalen Zwischenwirbelscheiben zu untersuchen, wenn diese Druck unterworfen werden.

2. Es wurden Experimentierapparate konstruiert. Diese gestatteten, die Bewegungen und Formänderungen der Scheiben in sehr kurzen Zeitperioden zu verfolgen.
3. Die mechanische Funktion der Scheibe wechselt mit der Schnelligkeit, mit der der Druck beginnt. Behält man die Belastung der Scheibe, so lässt sie einen gewissen Kompressionsgrad zu bis ein Gleichgewichtszustand erreicht wird. Wird die Scheibe einem kurzen plötzlichen Druck unterworfen, so beginnt sie zu oscillieren.
4. Es werden Diagramme vorgelegt, die den Grad der Kompression sowie die seitliche Expansion bei allmählicher Erhöhung der Belastung bis zu 100 kg sowohl für normale wie für degenerierte Scheiben zeigen. Es ist überraschend festzustellen, wie wenig sie deformiert werden. 100 kg ergeben bei normalen Scheiben eine Kompression von ca. 1,4 mm und eine Expansion von 0,75 mm. Bei degenerierten Scheiben, d.h. bei solchen, die Annulus fibrosus Rupture hatten war eine Kompression von 2 mm das Ergebnis einer Belastung von 100 kg.
5. Es bestand kein Unterschied in der Tragkraft in den Fällen, in denen die Bögen der Wirbeln unversehrt waren und in denen eine Hemilaminectomy oder eine vollständige Laminectomy vorgenommen worden war. Es zeigt sich also, dass die Scheiben selber die grösste Rolle beim Tragen der Belastungen spielen.
6. Belastungen mit einer Dauer von Sekunden ergeben Kurven für völlige Elastizität mit der gleichen Form wie bei Gelenkknorpel. Eine Kompression dieser Art kann eine unbegrenzte Anzahl Male wiederholt werden, ohne dass Störungen der mechanischen Reaktion der Scheibe hervorgerufen werden.
7. Wenn die belastete Scheibe einen Gleichgewichtszustand gefunden hat und dann wachsenden Druck während eines kurzen Zeitintervalls unterworfen wird, nimmt sie wiederum die Form an, die sie vor Anbringung der zusätzlichen Belastung gehabt hatte. Die Scheibe besitzt das Vermögen, sich mechanischen Drücken anpassen zu können. Indessen ist das Stossabsorptionsvermögen desto geringer je kräftiger die angewendete Belastung ist.
8. Wenn eine Wirbelscheibe schnell wirkenden Kräften unterworfen wird, beginnt sie zu oscillieren.
9. Es wurden die Schwingungen aufgezeichnet, während die Scheibe statischen Belastungen von 10 kg bis 130 kg unterworfen war. Dies besagt, dass schnelle zusätzliche Kräfte Deformierungen in sehr hohem Grad steigern können, auch wenn die Scheibe einen statischen Gleichgewichtszustand erreicht hat und auch in den Fällen,

in denen diese Kräfte verhältnismässig klein sind. Da die Deformationen zahlreich in einem sehr kurzen Zeitintervall (Zehntel-Sekunde) entstehen, zeigt dies, dass die mechanische Reaktion von einer bisher unbekannten Kraft ist.

10. Das geringste Trauma kann grosse Beanspruchungen im unteren Rücken hervorrufen, wenn die Kräfte schnell wirken. Die Formänderungen einer Scheibe haben eine solche Intensität und Frequenz, dass kaum eine Muskelreaktion den Rücken gegen diese Formänderungen stabilisieren oder schützen könne. Sie beruhen einzig auf der biophysischen Konstruktion des Scheibenmaterials selbst.

DISKUSSION

Man hat früher angenommen, dass eine Intervertebralscheibe infolge ihrer festen Konstruktion langsam reagiere, dass sie sich komprimieren lasse oder dass sie ihre Form verhältnismässig langsam ändern könne. Man hat weiterhin angenommen, dass sie nach Erreichung einer gewissen Gleichgewichtslage diese bis zur Beendigung der Beanspruchung beibehalte. Die Intervertebralscheibe sollte eine sogenannte elastische Eigenschaft besitzen. Dies haben unsere Untersuchungen, über die wir hier berichten, bestätigt. Die Scheibe besitzt ein Vermögen, sich verschiedenen mechanischen Forderungen *statisch* anzupassen.

Ausser diesen langsamen Reaktionsweisen kommen jedoch auch äusserst schnelle Formveränderungen vor, es treten Schwingungen völlig unabhängig von der statischen Gleichgewichtslage der Scheibe auf. Eine Intervertebralscheibe stellt somit ein *dynamisches* System dar, in dem die Masse der Scheibe sich ständig in Bewegung befindet. Bereits sehr kleine, schnell eintretende Beanspruchungen rufen Verschiebungen hervor, die in Zehntel mm messbar sind. Mit grösserer Genauigkeit ausgeführte Messungen der Bewegungen der Scheibe zeigen, dass die zur Hervorrufung solcher schnelle Bewegungen erforderlichen Kräfte äusserst gering sein können. Da sich der Körper niemals in einer mechanisch absoluten Ruhe befindet, kann man auch nicht damit rechnen, dass eine derartige Ruhe in einer Intervertebralscheibe eintreten werde. Die Schwingungsfrequenz wird um so grösser je dichter die Beanspruchungen eintreten.

Wir haben es hier mit biomechanischen Erscheinungen oder Spannungsänderungen im Material zu tun, die sich in Bruchteilen von Sekunden abspielen und nur eine Folge der physikalischen Eigenschaften des Materials sind. Man hat Bewegungen aufzeichnen können, die viel schneller sind als man früher Anlass hatte anzunehmen.

Es ist möglich, ja wahrscheinlich, dass auch andere Gewebe sich ähnlich verhalten.

Auf Grund dieser Darlegungen gestatten sich die Verfasser einige Ausblicke. In früheren Aufsätzen ist von dieser Klinik auf die Häufigkeit von Intervertebralscheibenschäden bereits in jungen Jahren hingewiesen worden. Es hat nachgewiesen werden können, wie Störungen der histochemischen Struktur der Intervertebralscheiben zeitig festgestellt werden können und wie auf diese dann Gewebeschäden, Veränderungen im Nucleusgehalt von Polysacchariden, Herabsetzung des Wassergehalts, Disproportion zwischen Polysaccharid und Eiweiss, Bruch im annulus fibrosus, Einwachsen von Granulationsgewebe etc. folgen; alles dies deutet darauf hin, dass wir es hier mit komplizierten histochemischen Prozessen zu tun haben, bei denen mechanische Kräfte keine grössere Rolle spielen können.

Es dürfte nicht allzu fernliegend sein wieder die Biomechanik in die Diskussion hereinzubringen. Es ist denkbar, dass mechanische Prozesse mit einer solchen Schnelligkeit, die hier dargelegt wurde und von einer solchen Grössenordnung, wie sie sicherlich täglich vielfach das übersteigen muss, mit dem wir bisher gerechnet haben, die biologischen Erscheinungen in den Intervertebralscheiben jedenfalls beeinflussen.

CONCLUSIONS

1. Le but a été d'étudier quelques points du fonctionnement mécanique des disques intervertébraux lombaires quand ils sont soumis à des pressions.
2. On a construit des modèles expérimentaux. Ils ont permis de suivre les mouvements et les changements de forme des disques dans des périodes de temps très courtes.
3. Le fonctionnement mécanique du disque diffère suivant la rapidité avec laquelle la pression commence. Si on maintient la charge sur le disque, on obtient un certain degré de compression jusqu'à ce qu'un équilibre soit atteint. Si le disque est soumis à une courte pression instantanée, il commence à *osciller*.
4. On présente des diagrammes qui montrent le degré de compression ainsi que l'expansion latérale qui se produisent après des charges augmentant successivement jusqu'à 100 kilos, tant pour des disques lombaires normaux que pour des disques lombaires dégénérés. Il est frappant de remarquer combien les disques se déforment peu. 100 kilos donnent sur des disques normaux une compression d'environ 1,4 mm. et une expansion de 0,75 mm. Sur des disques dégénérés, c'est-à-dire dans lesquels les fibres de l'anneau sont

rompues, une compression de 2 mm. a été l'effet d'une charge de 100 kilos.

5. Il n'y a pas eu de différence de la force portative dans les cas où les arcs étaient intacts et dans ceux où une hémilaminectomie ou une laminectomie totale avaient été exécutées. On est d'avis que les disques eux-mêmes jouent de beaucoup le rôle le plus important pour porter les charges.
6. Des charges d'une durée de quelques secondes donnent des courbes d'une parfaite élasticité de la même forme que dans le cartilage articulaire. Une compression de cette nature peut se répéter un nombre indéfini de fois sans provoquer de troubles dans la réaction mécanique du disque.
7. Si le disque étant sous charge a trouvé un équilibre et qu'il soit alors soumis à une pression croissante pendant un court laps de temps, il reprend la forme qu'il avait avant l'application de la charge supplémentaire. Le disque possède le pouvoir *d'adaptation* aux pressions mécaniques. Cependant, plus la charge appliqué est forte, moins grande est la capacité d'absorption du choc.
8. Quand un disque intervertébral est soumis à des forces agissant rapidement, il commence à osciller.
9. On a enregistré les oscillations pendant que le disque était sous des charges statiques de 10 à 130 kilos. Cela signifie que, même si le disque a atteint un équilibre statique, des forces additionnelles rapides peuvent augmenter les déformations à un très haut degré, dans les cas également où ces forces sont relativement petites. Etant donné que les déformations se produisent fréquemment pendant un laps de temps très court (dixième de seconde), cela indique qu'il y a une pression d'une grande force inconnue jusqu'ici.
10. Le plus petit trauma peut produire de grandes pressions dans un dos bas, si les forces agissent rapidement. Les changements de forme d'un disque sont d'une telle intensité et d'une telle fréquence qu'aucune réaction de muscle ne peut stabiliser ni protéger le dos de ces variations de forme. Elles sont dues uniquement à la construction biophysique du matériel du disque lui-même.

DISCUSSION

On a considéré auparavant qu'un disque intervertébral, par suite de sa construction ferme, réagissait lentement, qu'il se laissait comprimer et pouvait changer de forme d'une manière relativement lente. On a de plus supposé qu'après avoir atteint un certain équilibre, il le conservait jusqu'à ce que la charge cessât. Le disque intervertébral

aurait ce que l'on appelait une qualité d'élasticité. Ceci a été confirmé par nos recherches exposées ici. Le disque a la faculté de s'adapter *statiquement* aux diverses exigences mécaniques.

A côté de cette manière de réagir, il se produit cependant des changements de forme extrêmement rapides, des oscillations qui se manifestent indépendamment de la position d'équilibre statique dans laquelle le disque peut se trouver. Un disque intervertébral représente donc un système *dynamique* dans lequel la masse du disque se trouve en mouvement continu. Déjà des charges très petites appliquées rapidement provoquent des déplacements qui peuvent se mesurer en dixièmes de millimètre. Des mesures plus exactes des mouvements du disque montrent que les forces nécessaires pour pouvoir déterminer de tels mouvements rapides peuvent être extrêmement petites. Etant donné que le corps ne se trouve jamais, au point de vue mécanique, dans un état de repos absolu, nous ne pouvons pas non plus prévoir que cet état de repos puisse s'établir dans un disque intervertébral. Plus les charges se succèdent rapidement, plus grande est la fréquence des oscillations.

Nous sommes ici en présence de phénomènes biomécaniques ou changements de tension du matériel, qui ont lieu dans l'espace de fractions de seconde, et qui sont seulement une conséquence des caractères physiques du matériel. On a pu enregistrer des mouvements beaucoup plus rapides que ceux que l'on avait pris en considération auparavant.

Il est possible, et même probable, que ces conditions sont les mêmes pour d'autres tissus également.

Sur la base des observations relatées ici, les auteurs se permettent d'exprimer quelques points de vue. Dans des publications antérieures émanant de cette clinique, on a signalé la fréquence des lésions de disques intervertébraux déjà chez des individus jeunes. On a pu montrer que des troubles de la structure histochimique des disques intervertébraux peuvent se découvrir déjà de bonne heure et qu'ils sont accompagnés par la suite de lésions des tissus, de changements de la teneur en polysaccharides du nucleus, d'une diminution de la teneur en eau, d'une disproportion entre le polysaccharide et l'albumine, d'une rupture de l'anneau fibreux, de la pénétration de tissu de granulation, etc., signes que nous sommes ici en présence de processus histochimiques compliqués, dans lesquels les forces mécaniques ne pouvaient pas jouer de rôle important.

Il n'est plus nécessaire maintenant de considérer comme entièrement exclue la possibilité de ramener la biomécanique dans la discussion. Il est permis de penser que des phénomènes mécaniques de la rapidité qui a été démontrée ici et d'une amplitude qui doit sûrement

dépasser journellement bien des fois les calculs faits jusqu'ici, peuvent, en tout cas, influencer sur le processus biologique dans les disques intervertébraux.

CONCLUSIONES

1. El objeto ha sido estudiar algunos puntos del funcionamiento mecánico de los discos intervertebrales lumbares cuando son sometidos a presiones.
2. Han sido construídos modelos experimentales que permiten seguir los movimientos y cambios de forma de los discos en periodos de tiempo muy cortos.
3. El funcionamiento mecánico del disco difiere según la rapidez con que empieza la presión. Si se mantiene cargado el disco, admite un cierto grado de compresión hasta que se alcanza un equilibrio. Si el disco es sometido a una corta presión instantánea, empieza a *oscilar*.
4. Se presentan diagramas mostrando el grado de compresión así como la expansión lateral que se producen después de unas cargas aumentadas sucesivamente hasta 100 kgs., tanto en los discos lumbares normales como en los discos lumbares degenerados. Es interesante observar qué poco varían los discos. 100 kgs. dan sobre discos normales una compresión de unos 1,4 mm. y una expansión de 0,75 mm. Sobre los discos degenerados, es decir en los que las fibras del anillo han sido rotas, una compresión de 2 mm. ha sido el efecto de una carga de 100 kgs.
5. No ha habido diferencia de capacidad portativa en los casos en que los arcos estaban intactos y en los que una hemilaminectomía o una laminectomía total habían sido ejecutadas. Se es de la opinión que los discos mismos juegan con mucho el papel más importante en el transporte de los pesos.
6. Cargas de unos segundos de duración producen curvas de una elasticidad perfecta de la misma forma que en el cartílago articular hialino. Una compresión de esta naturaleza puede repetirse un número de veces indefinido sin provocar trastornos en la reacción mecánica del disco.
7. Si el disco, bajo carga, ha encontrado un equilibrio y es entonces sometido a una presión creciente durante un corto espacio de tiempo, vuelve a recobrar la forma que tenía antes de la carga suplementaria. El disco posee el poder de *adaptación* a las presiones mecánicas. Sin embargo, cuanto más fuerte sea la carga aplicada, menor es la capacidad de absorción del choque.

8. Cuando un disco intervertebral es sometido a fuerzas que actúen rápidamente, comienza a oscilar.
9. Han sido registradas las oscilaciones mientras el disco estaba bajo cargas estáticas de 10 a 130 kgs. Esto quiere decir que, aun cuando el disco haya podido alcanzar un equilibrio estático, fuerzas rápidas adicionales pueden aumentar las deformaciones en un alto grado, en los casos en que de la misma forma estas formas son relativamente pequeñas. Teniendo en cuenta que las deformaciones se producen en un espacio de tiempo muy corto (décimo de segundo), esto quiere decir que existe la presión de una gran fuerza hasta aquí desconocida.
10. El más pequeño trauma puede producir grandes presiones en una espalda baja, si las fuerzas actúan rápidamente. Los cambios de forma de un disco son de tal intensidad y frecuencia que ninguna reacción muscular puede estabilizar ni proteger la espalda de estas variaciones de forma. Son debidas a la construcción biofísica del material del propio disco.

DISCUSIONES

Ha sido anteriormente considerado que un disco intervertebral, como consecuencia de su construcción firme, reaccionaba lentamente, se dejaba comprimir y podía cambiar de forma de una manera relativamente lenta. Se ha supuesto además que después de haber alcanzado un cierto equilibrio lo conservaba hasta que se acababa el cambio. El disco intervertebral tendría una llamada propiedad de elasticidad. Esto ha sido comprobado por nuestras investigaciones aquí expuestas. El disco tiene la propiedad de adaptarse *estáticamente* a las diversas exigencias mecánicas.

Junto a esta forma de reaccionar, se producen sin embargo cambios de forma extremadamente rápidos, y oscilaciones que se manifiestan independientemente de la posición de equilibrio estático en que el disco pueda hallarse. Un disco intervertebral representa, por lo tanto, un sistema *dinámico* en el que la masa del disco se encuentra en movimiento continuo. Ya algunos cambios muy pequeños, aplicados rápidamente, provocan unos desplazamientos que pueden medirse en décimas de milímetros. Medidas más exactas de los movimientos del disco muestran que las fuerzas necesarias para poder determinar tales movimientos son extremadamente pequeñas. Teniendo en cuenta que el cuerpo no se encuentra nunca, bajo el punto de vista mecánico, en un estado de reposo absoluto, tampoco podemos prever que este estado de reposo pueda establecerse en un disco intervertebral. Cuanto mayor

sea la rapidez con que las cargas se suceden mayor es la frecuencia de las oscilaciones.

Estamos aquí ante la presencia de unos fenómenos biomecánicos o cambios de tensión del material, que tienen lugar en el espacio de fracciones de segundo y que son sólo una consecuencia de los caracteres físicos de la materia. Han sido registrados movimientos mucho más rápidos que los que antes habían sido tomados en consideración.

Es posible, e incluso probable, que otros tejidos muestren también tales condiciones.

En base a las observaciones aquí relatadas, los autores se permiten exponer ciertos puntos de vista. En los anteriores escritos procedentes de esta clínica, ha sido señalada la frecuencia de lesiones en los discos intervertebrales ya en individuos jóvenes. Ha sido mostrado que los trastornos de la estructura histoquímica de los discos intervertebrales pueden ser descubiertos muy pronto y que están acompañados, como resultas de lesiones en los tejidos, de cambios en el contenido de polisacáridos del núcleo, de una disminución del contenido de agua, de una desproporción entre el polisacárido y la albúmina, de una ruptura del anillo fibroso, de la penetración de tejido de granulación, etc., prueba de que estamos ante la presencia de un proceso histoquímico complicado, en el que las fuerzas mecánicas no pueden desempeñar un papel importante.

Ya no es necesario considerar ahora como enteramente excluida la posibilidad de hacer entrar la biomecánica nuevamente en discusión. Puede pensarse que los fenómenos mecánicos de la rapidez que ha sido demostrada aquí y de una amplitud que seguramente sobrepasa a diario buen número de veces los cálculos hechos hasta ahora, pueden, en todo caso, influir sobre el proceso biológico en los discos intervertebrales.

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