ACTA ORTHOPAEDICA SCANDINAVICA · SUPPLEMENTUM No. XXV

From the Orthopaedic Department of Karolinska Institutet, Stockholm

Chief: Professor Sten Friberg

FRACTURE OF THE VERTEBRAL END-PLATE IN THE LUMBAR SPINE

AN EXPERIMENTAL BIOMECHANICAL INVESTIGATION

By Olof Perey

STOCKHOLM 1957

English translation by

C. A. GRANT

Ivar Hæggströms Boktryckeri AB

Stockholm 1957

Contents

Preface

My chief, Professor Sten Friberg, suggested this study of the behaviour of the disc under stress. I am deeply grateful for the stimulating interest he has shown towards this work. His knowledge and wide experience in this field were of inestimable value.

I should also like to thank Docent Carl Hirsch most heartily for many stimulating and valuable discussions and his practical help in making apparatus available.

Professor Knut Lindblom has shown much interest in my work and kindly helped me with tomography of specimens and patients.

Professor John Lind and Professor Karl Wegelius have greatly assisted me by generously allowing me to make use of apparatus and facilities in the Wenner-Gren Research Laboratory of Norrtulls Hospital.

Prosektor Hans Jörgen Hansen has assisted me with the histological examinations.

Valuable assistance with the technical calculations has been given by Teknol. Dr. Bertram Broberg and Civ.ing. Jan Boman.

Miss Karin Lundin has helped with all the photographic work, Miss Eva Schultz with the preparation of many of the microscopic specimens, and Konstnär Sven Henriksson with the drawings.

Some of the preliminary work was carried out at Georg Schönanders AB where the chief engineer, Teknol. Dr. Erik Ledin, showed great interest in the solution of the technical problems.

The dynamic investigations were carried out with the aid of an image-amplifier and camera which, together with technical personnel, were kindly placed at my disposal by Philips Svenska AB.

The Gustav V Institute for Scientific Research provided me with working quarters for a long period of time.

The costs of the investigation were defrayed in part by Karolinska Institutets Reservationsanslag för Medicinsk Forskning, Landsfiskal Pontus Nohres Stiftelse, and Flyg- och Navalmedicinska nämnden.

I welcome this opportunity to express my profound gratitude to all the individuals and institutions whose generous help and support enabled me to complete my task.

Stockholm, febr. 1957.

OLOF PEREY

Introduction

The minor accident cases which lead to prolonged back pain often give rise to conflicts between the patient, physician, and insurance companies because the incapacity to work often extends over long periods. Radiographic survey of the vertebral column seldom presents evidence of recent damage and after the acute stage has subsided, clinical examination cannot always confirm the patient's description of pain. There is a continuous effort, therefore, to increase our skills and diagnostic resources in order to be able to assess these patients as fairly as possible.

Most countries require obligatory insurance for employees to cover injuries received as the result of accidents while at work. The interpretation of the phrase "accident while at work" varies somewhat from country to country.[1]

[1] Private accident insurance came into existence as long as five hundred years ago when shipowners insured their captains against accidents while at sea. During the eighteenth century, the Dutch republic insured its volunteer soldiers against accidents. The first Swedish insurance company was formed in 1881. Employers in certain industries were compelled by a Swedish law of 1901 to assume responsibility for injuries received at work and obligatory accident insurance for workers was introduced in 1916.

There are wide differences between private and social insurance inasmuch as private insurance represents an agreement between the insured and the insurer by which the latter can reduce the risk by exempting certain forms of injury.

The social accident laws can be divided on the whole into two groups according to the people who are covered by the insurance. There are laws which limit the insurance to certain specified activities as is the case in France, Germany, Italy, Norway, and Switzerland. Under other regulations, workers are insured while in the paid employment of another person as is the case in Britain, Denmark, Finland, Holland, Sweden, and the USA. As the laws are widely applicable in most countries, difficulties arise in defining the terms "employer" and "employee" in certain cases.

Regulations concerning compensation for accidents occurring at work have been made by most countries although in some, the law is limited to certain categories of workers. The term "accident" is not generally defined in the laws but has received somewhat varying interpretations through legal precedent. In Germany, it is considered that "an event must occur which is injurious and sudden". Every unintentional and unexpected occurrence leading to injury or material loss is considered to be an accident in Britain. The French concept is defined in a law of 1898 stating that every injury which is caused by or arises from work performed, even the customary, is considered to be an accident while at work.

The phrase "while at work" has in a similar fashion been interpreted differently as certain countries use the terms "beginning of work" and "end of work" in an extended sense. Insurance in Austria, Germany, Finland, and Sweden covers accidents occurring on the way to and from the place of work. In Switzerland, the obligatory insurance even covers accidents outside working hours. Only if an employer has ordered travel by a certain means does insurance come into the picture in France. In Britain, it is considered that an accident must occur because of and during the course of work before a justifiable claim for compensation can be lodged. Accidents which occur in connection with activities in the worker's

France applies a generous interpretation of the term "accident" which even includes under the law certain diseases which occur after strain. In Sweden, "bodily injury must have been caused, it must have occurred suddenly of some external cause, and it must have been incurred involuntarily" (Nordin). In the case of patients with back pain, strain associated with an accident such as occurs in slipping while lifting is often given as the cause. With the diagnostic resources at our disposal, it is not always possible to determine whether or not an accident has actually occurred according to the legal definition. It can be pointed out that up to the present, the general practice of the Supreme Insurance Council of Sweden in assessing claims for compensation arising out of this type of accident is to grant compensation under the insurance law as soon as it is made clear by clinical examination that the insuree's back tissues were injured during work even although the circumstances under which the accident occurred cannot be more closely determined. Only in those cases in which it is considered likely that the injury in question was basically caused by previous lesions such as disc degeneration is compensation refused.

When no radiographic changes can be detected, the diagnosis lumbago traumatica is often made. This diagnosis largely reflects the physician's opinion of the cause of the patient's difficulties.

In order to establish, if possible, more reliable criteria for the assessment of this type of accident, my chief, Professor Sten Friberg, proposed an experimental investigation of the changes occurring within the vertebral disc during motion and weight-bearing. The physiology of the nucleus during movement was first investigated. Discography was performed on all the discs in specimens consisting of the entire lumbar and sacral regions. Extreme movements were made in various directions and recorded on Röntgen plates while the sacra were held fixed. Loads of up to 30 kp were placed on these specimens while both moderate and extreme movements were carried out. The specimens were so arranged that the discs were horizontal and the pressure applied from above. In no instance could changes in the contrast medium within the nucleus be noticed. This method was not sufficiently accurate to allow precise investigations to be made of the centres about which movement took place in various stages of degeneration. These experiments were carried out within normal load limits and in order to simulate an accident experimentally, a dynamic force was applied in the longitudinal direction of the spine, the same direction in which forces act in the case of a fall on the sacrum. As events took

own interest, for example during the lunch rest, are excluded from coverage by German regulations.

The Swedish interpretation of accident while at work can be considered one of the most extensive in practice.

place rapidly during these experiments, a special chymograph was constructed which enabled plates of a portion of the specimen to be made with an exposure time of 0.003 sec. and with an interval between exposures of 0.01 sec. In assessing the resulting plates, the assumption was made that the intervertebral discs were elastic shook-absorbers and that the vertebral bodies were quite firm and unaffected by the forces used. Under these conditions, it was possible to estimate the compression of the discs in a number of instances. It was, however, impossible to calculate the forces applied to the long specimens as they tended to bend. This undesirable movement resulted in the Röntgen series not being sufficiently accurate. It proved to be technically difficult to solve this problem satisfactorily. Experiments using various types of clamps, encasing in Wood's metal and in plaster-of-Paris, with and without gauze reinforcement, gave poor fixation since fractures occurred around the base. The method which provided the best fixation was not suitable for experiments in which force was applied in a direction other than at right-angles to the cross-sectional dimension of the disc.

When these problems were solved, the way was open for an experimental investigation of the changes occurring within a vertebral disc exposed to a dynamic force such as occurs in a fall onto the tip of the sacrum or in a disc acted upon by a static force as in the case of heavy lifting. As it proved necessary during the course of the experiments to know the resistance of the end-plate and the vertebral body, these were investigated in a material-testing apparatus. Finally, as a practical application of the investigations reported here, an attempt has been made on the basis of the values obtained in these studies to calculate the maximum allowable forces during expulsion from an aircraft in an ejection seat.

Survey of the literature

1. Historical survey

During the last fifteen to twenty years, many facts have come to light which indicate that disc degeneration is the most common cause of lumbago. It can be confidently stated that when any or several of the radiological changes which occur as a result of disc degeneration can be detected, the stage is set for the occurrence of lumbago.

Since Bantu negroes and some mongol peoples such as Koreans and Japanese seldom show disc degeneration, it has been widely speculated whether or not a high standard of living and "modern" life has injurious effects. But even our ancestors had spondylosis deformans which may be considered as a sequel to disc degeneration. If one examines the skeletons preserved in the Historical Museum in Stockholm, it is possible to find pronounced exostoses on the lumbar vertebrae. A skeleton dating from the Viking period, that of a man estimated to be in his twenties, shows a small exostosis on L_4. An advanced spondylosis can be seen in the skeleton of a middle-aged man belonging to the Stone Age. Fig. 1.

Until the end of the last century, rheumatism served as a collective term for all types of painful conditions in muscles and joints. Painful conditions of the lumbar region were early differentiated into spondylosis deformans, tuberculous spondylitis, syphilis, fracture of the vertebra, and spondylarthritis anchylopoetica. It is difficult to establish a diagnosis of fracture of the vertebra without the aid of a Röntgen plate, and even although the patient shows gibbus and the anamnesis clearly indicates an accident, tuberculous spondylitis or syphilis cannot be definitely eliminated. This was especially difficult in the days when these diseases were much more common than they are now as can be seen from Henle's 1896 article. H. Kümmell can be considered as a pioneer in the study of vertebral fractures with his 1895 article giving a general clinical account entitled "Über die traumatischen Erkrankungen der Wirbelsäule". As late as 1911, Imbert & Vial wrote about "la spondylite traumatique" or "la maladie de Kümmell-Verneuil". When it became possible to visualise the vertebral column radiographically, it was apparent that "traumatic diseases of the vertebrae are very common" (Schantz, 1910). Treatment of vertebral fractures rapidly came into the centre of attention and many methods have been described. All these strive towards good radiological reduction

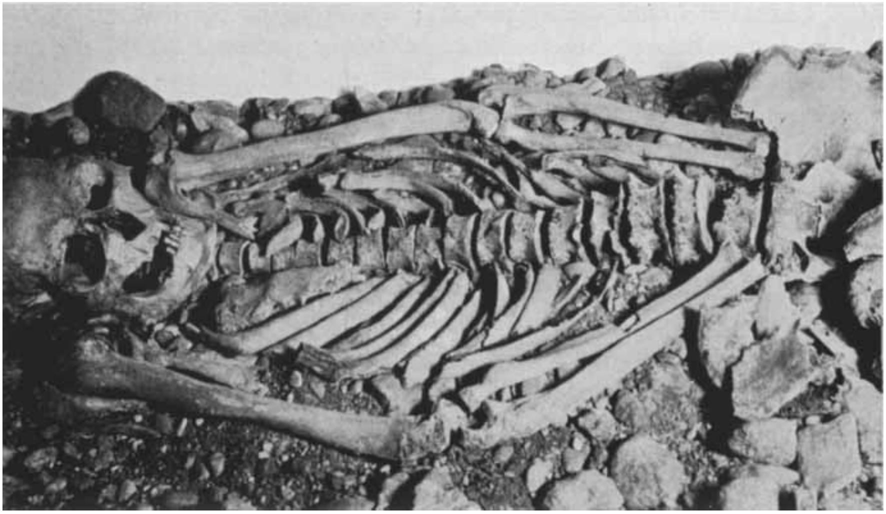


Fig. 1. Skeleton from grave 9 at Västerbjärs in Gothem parish, Gotland. This man, middle-aged, 170 cm, tall, and of nordic type, is believed to have lived during the middle neolithic period (2200—1800 B.C.) The skeleton is well preserved because of the high calcium content of the soil. Large, circular exostoses on both the upper and lower borders of the vertebral bodies can be seen.

by means of hyperextension. Wallace was the first to demonstrate the value of effective hyperextension treatment. Davis, Dunlop & Parker, and Ryerson, among others, have described various methods of achieving hyperextension but none is as reliable and simple as the one described by Watson-Jones. Compression fractures can be reduced under local anaesthesia without trained assistance or special apparatus and with the patient ambulatory. At the international orthopedic conference in 1948, Nicoll advocated functional treatment of stabile fractures. Up to that time, it had been customary to direct attention entirely towards the deformation of the vertebral body in examining fracture cases and to pay little attention to disc damage or malposition of the intervertebral joints. According to Nicoll, functional treatment gives better results than fixation in plaster-of-Paris. It seems that fractures should not be assessed solely on the grounds of their stability, but that attention should also be paid to the discs. Landoff has demonstrated that there is a definite difference in prognosis depending upon whether or not the disc has been damaged. Patients with fractures but no primary disc injury fully recovered in 100 per cent of the cases, while those with disc injuries fully recovered in between 55 and 77 per cent of the cases depending upon other features of the fracture. Many writers consider that disc lesions occur in 75 to 80 per cent of all vertebral fractures (Olin, Hellner). As for localisation of vertebral fractures, Jefferson collected

2,006 cases and found the highest frequencies in the cervical region and at the junction between the thoracic and lumbar portions. Over 20 per cent of the entire series showed fractures of Th_{12} and L_1.

No systematic pathological investigations of vertebrae and discs were made before 1927 when Putschar and Schmorl, working independently, described their findings. In both series, intraspongious herniation was the most widely remarked discovery. Among seventy-two cases, Putschar found "Knorpelinseln" in fifty-four, none of which was a subject under fifteen years of age. Eighteen of these herniations, however, were microscopic only. It was his opinion that a herniation must be at least 1 mm deep in order to be macroscopially visible. Putschar's investigations were, however, overshadowed by Schmorl's since the latter had much more material at his disposal. After their first publication, Schmorl and his colleages continued with their examinations of the vertebral column at the Friedrichstädter Krankenhaus in Dresden and compiled a series of 7,000 representing all the autopsies performed between 1925 and 1930. Prolapse of the nucleus pulposa into the spongiosa of the vertebral body ("Knorpelknötchen") was found in 38 per cent of 3,000 backs. The sex distribution was approximately equal.

Schmorl did not deny that trauma to the back could give rise to intraspongious disc herniation through shattering of the end-plate but he did not believe that the majority of these lesions occurred so abruptly. He was never able to detect such lesions in cases of reduced compression fractures or other recent back injuries. Most of the intraspongious disc herniations were considered to arise through rupture of an already damaged end-plate. Damage to the end-plate was chiefly attributed to degenerative changes but the possibility of its arising through trauma was not altogether eliminated. Trauma, as interpreted by Schmorl, included the minor traumata which always occur during heavy manual labour and sport as well as single trauma. A photograph showing pronounced haemorrhage and intraspongious herniation is published in the third edition of the book "Die gesunde und die kranke Wirbelsäule in Röntgenbild und Klinik" by Schmorl and Junghanns (1933).

Übermuth considers that degenerative changes are the basic cause of intraspongious disc herniation and that trauma as a cause is encountered less often. "Degeneration" is interpreted as a physiological phenomenon and the conclusion is drawn that the greater the demands made on a back, the earlier degeneration appears. According to this writer, these changes may not be considered as indications of disease.

Böhmig & Prévot believe that the persistent blood vessel channels in the osseous plates form weak points through which the nuclear pulp may be pressed.

Galvé & Galland, on the other hand, advance the proposal that a weakness in the end-plate exists at the site of the notochord. They express themselves very cautiously and point out that intraspongious disc herniation is "a most curious disease". A defect in the end-plate can always be found at the site of herniation according to these writers. The defect is the primary change and appears in adults as the result of degeneration in the plate while in children, the disease represents a particular form of developmental error.

Putschar believes that injuries of the end-plate occur in every individual during life. These injuries give rise to an increased vascularisation which in turn leads to resorbtion of the end-plate. In addition, he advances the question whether the nucleus pulposus is pressed into the spongiosa or whether it grows in. In his opinion, support for both of these possibilities can be drawn from his microscopic material.

"Light physiological traumata" including manual labour and sport are considered by Beadle to play a decisive rôle in fracture of the end-plate.

Schantz believes that trauma is the cause of intraspongious disc herniation and that many of these lesions occur as the result of a pressure wave.

Once the occurrence of intraspongious herniation had been demonstrated pathologically, investigations were begun in order to clarify the pathogenesis and clinical signs of the lesion. Most of these studies used radiological techniques instead of being based on pathological material as before.

Brandes has shown that the ratio between the incidence of disc herniation in the lumbar region to that in the thoracic region is 29 to 18 and that the most commonly affected region is from Th_{12} to L_3. Compression fractures are also most frequently encountered in this region. After dividing his material into cases with trauma and those without, Brandes came to the conclusion that an association between herniation and trauma was doubtful in most cases but the possibility that trauma played some part could not be eliminated.

Wissing examined Röntgen plates from 421 patients with various clinical diagnoses. Intraspongious disc herniation, detectable radiologically, was found in 13.5 per cent. All of these patients complained of back pain following an accident. As a control series, 147 Röntgen plates taken during examinations of healthy individuals were used. Intraspongious disc herniation was found in 16 per cent. Wissing also claims to have found intraspongious disc herniation in individuals who absolutely deny having been involved in an accident.

Rose & von Mentzingen examined a series of 800 Röntgen plates including eighty cases of vertebral fracture. Intraspongious disc herniation was found in 0.5 per cent. They describe four patients who were undeniably involved in accidents and for which Röntgen plates made at the time of accident showed no changes. Plates made two to five months after the accidents, however, showed distinct intraspongious disc herniation.

A similar case has been described by Joplin. Radiological examination of a patient who fell twenty feet showed only a fracture of Th_{12}. Three months later, intraspongious disc herniation was demonstrated at L_1 and L_2.

A similar case has also been described by Buisson who drew the conclusion that large intraspongious disc herniations are the result of trauma but that it is not clear whether or not the smaller herniations have the same aetiology.

In the German publications of the 1930's, it was often stated by, among others, Schmorl and Schneider that the "Knorpelknötchen" lacked clinical significance and that their pathogenesis was therefore of no importance. Interest in Schmorl's "Knorpelknötchen" declined but attention had been directed to the clinical significance of the discs.

The discussion of disc rupture and its significance stimulated Mixter, Barr, and Ayer to reappraise the operation which they carried out to relieve root pressure. They came to the conclusion that the material which they excised was herniated or ruptured disc tissue and not, as was believed earlier, enchondromata. Following this announcement, interest in diseases of the back greatly increased and exhaustive investigations have been carried out in all parts of the world where back diseases are a problem.

Investigations have been carried out for many years in Sweden in an attempt to clarify the significance of the discs in back diseases, to increase diagnostic accuracy, and to extend the range of therapeutic measures. Much of this work has been directed by Friberg. He also made a detailed study of spondylolistesis and in 1941 published the results of an extensive anatomical and clinical investigation of low back and sciatic pain caused by intervertebral disc herniation. In collaboration with Hirsch, Friberg has contributed towards the clarification of disc degeneration in the lumbar region. Hirsch has also carried out a number of mechanical investigations such as measurement of compression and bulging of the disc under various loads. Together with Sylvén, Paulsson, & Snellman, he has investigated the biophysical properties of the disc. The innervation of the discs and the longitudinal ligament has been studied by Wiberg. Arnell developed myelography and Knutsson subsequently contributed some valuable observations. A critical evaluation of myelography in relation to clinical symptoms and operation findings has been made by Friberg & Hult. Lindblom first carried out discography and thereby made it possible to obtain information about early changes within the discs in vivo. Another method of diagnosing early disc degeneration in certain cases has been described by Knutsson who pointed out the instability between two vertebrae which may be seen in lateral view. Unander-Scharin carried out an experimental investigation and a clinical follow-up of lumbar fusion. Hult made a field investigation of back pain in more than 1,500 men between twenty-five and fifty-nine years of age taken from a normal population sample. Of these, 60 per cent had experienced lumbago (sciatica) at some time or other. Sixty per cent of these individuals could not associate the occurrance of back pain with any known external cause. In 20 per cent of the cases, back pain dated from the time of an accident. In the remaining 20 per cent, back pain began in association with heavy lifting which could not ordinarily be described as an accident.

The Swedish investigations have thus attacked back problems from various aspects in an attempt to extend our knowledge of these conditions. The present experimental investigations represent a part of this effort to contribute to the knowledge of back diseases.

II. Embryology and anatomy of the lumbar spine

The embryological development of the vertebral column and particularly the origin of the notochord and the discs was first described by von Luschka in 1858. Bardeen (1905) and Williams (1908) have described the development of the spine in detail while Schmorl, Calvé, Galland, and Beadle as well as others have extended these studies.

The primitive, paired vertebrae are formed from the segmented column of mesenchyme cells which collects around the notochord. Ingrowth of the intersegmental arteries marks the cephalic and caudal faces of the segments. Those cells which lie nearest the arteries show a more rapid differentiation, possibly because of better nutrition, and give rise to the primordia of the vertebral bodies which gradually unite while the notochord disappears from these regions.

The tissue between the embryonal vertebral bodies which lies farthest from the intersegmental arteries remains undifferentiated to become the primordia of the discs. Squeezed between the developing vertebral bodies, the notochord enlarges to become the primordia of the nucleus pulposus. A cartilage plate is derived from the annulus fibrosus to form the border between the nucleus pulposus and the adjacent vertebral body. Keyes & Compere consider it rather remarkable that the disc remains avascular during the entire development and life. Other writers such as Böhmig and Coventry, Gormley, & Kernohan believe that during embryonal development and childhood, the disc is supplied with blood through vessels originating from the vertebral body. These vessels are obliterated rather early in life although some consider that they do not disappear until after the third decade.

At the end of the fourth month of gestation, all the vertebral bodies are present in rudimentary form. The vertebral body of a newborn infant is quite rounded and appears egg-shaped in lateral view on a Röntgen plate. The radiological appearance of the vertebral body rapidly changes and relatively soon the shape is more rectangular with collar-like grooves circling both the cephalic and caudal surfaces. These collars, consisting of cartilage, are known as the epiphysial rings (Schmorl's knorpelige Wirbelkörper-randleiste). During the first seven years of life, an osseous plate with a number of fine holes develops on the cephalic and caudal surfaces of the vertebral body. In the early stages, this osseous plate occupies a position adjacent to the nucleus and has received the name pressure-absorbing plate (Druckaufnahmeplatte, Schmorl). Vessels pass through holes in this pressure-absorbing plate or the bony part of the end-plate. According to Coventry, Ghormley & Kernohan, these vessels have completely disappeared by ten years of age although Beadle believes that they may persist until twenty years. Fibrous and cartilaginous tissue obliterate these channels but the traces persist throughout life. According to many writers, these constitute weak spots in the end-plate. The loosely attached cartilage-plate covers the entire osseous plate with the exception of the compact peripheral portions.

At the end of the embryonal period, the disc is largely composed of hyaline cartilage with remnants of the notochord occupying the centre. Continous differentiation takes place during the first year of life. The greater portion of the disc is occupied by the annulus fibrosus which consists of fibrous and fibro-cartilaginous lamellae, ten to twelve in the lumbar region (Eckert & Decker, Joplin). The anterior longitudinal ligament is much more intimately associated with the annulus than the dorsal.

At birth, the nucleus pulposus contains chord cells but these gradually disappear until, at maturity, such cells can no longer be demonstrated (Übermuth). By this stage of development, the nucleus consists of a loose net of cartilage cells and fibroblasts in a semigelatinous matrix. The moisture content of the nucleus is high, but becomes less with increasing age. Püschel states that the moisture content of the nucleus of the newborn is 88 per cent, that of an eighteen-year-old, 80 per cent, and that of a seventy-seven-year-old, 69 per cent. Similar figures are given by Keyes & Compere. Investigations have been carried out in Schmorl's institute to compare the moisture content of the annulus fibrosus with that of the nucleus pulposus. A newborn infant has a moisture content in the annulus about 10 per cent lower than that in the nucleus. The difference increases with increasing age.

It is of considerable clinical importance to know whether or not sensory nerves can be found in the annulus. Opinions on this question are divided.

Nerve fibres have been demonstrated by, among others, Fick and Roofe while Hirsch & Schajowicz and Wiberg, on the other hand, have not found any nerves. There is general agreement on the presence of nerves in the longitudinal ligament. These were first demonstrated by Jung & Brunschwig.

Since a vertebra develops from several different centres, malformations of various types can occur. Only those malformations which directly involve the parts of the vertebral body concerned in these studies will be briefly mentioned. These malformations must be recognised in order to be able to assess, for example, tomographic plates correctly. A not altogether uncommon type of malformation is Spina bifida anterior. Individuals with only a fine cleft dividing the two halves can lead a relatively normal life unaffected by the leison.

The notochord may persist in various stages of development. If the entire notochord persists between two discs, the vertebral body is perforated centrally and the nuclei pulposi of both adjacent discs are united. Remnants of the notochord within a vertebral body can give rise to defects there without affecting the end-plates. Schmorl believes that it is difficult to diagnose notochord malformations from routine Röntgen plates.

Bulging of the disc into the vertebral body in the region of the nucleus is considered by Schmorl to be of considerable clinical significance. This convexity of the end-plates on both sides of the disc is easily visible on Röntgen plates and, according to Schmorl, when it is detected in young persons, they ought to be warned against overexertion.

Spondylolysis, a defect which does not directly involve the vertebral bodies or discs, may be of congenital or traumatic origin, or it can be the result of re-modelling. This lesion is associated with a change in the segment of movement (Junghanns). Because of the mobility of the arches, normal exertion leads to the formation of small fissures in the disc lying below. These fissures become larger and disc degeneration is the result.

III. Physiology of the lumbar spine

Intervertebral discs function partly as the joint between two vertebrae and partly as a supporting structure between two vertebral bodies. von Luschka described the disc as "halbgelenke" in which the nucleus was the joint space, the annulus the joint capsule, and the cartilage-plate the articular cartilage. Mobility between two vertebrae was considered by Junghanns to take place as an unit and he coined the phrase "Bewegungssegmente" to include the disc, the corresponding intervertebral articulation, and the interspinous ligament. On this basis, a segment of movement is obtained between every vertebra with the centre of movement being situated in the nucleus pulposus (Steindler). In a degenerated disc, the centre of movement is moved dorsally to the intervertebral joints according to Compere & Keyes. The possible range of movements is greatly limited by the annulus fibrosis and strong ligaments. The intervertebral joints chiefly serve to restrict and direct mobility. Rotation of the lumbar region is greatly reduced by this arrangement.

Alvik has investigated the mobility in the lumbar spine of healthy individuals with an average age of thirthy-three years.

	Frontal plane	Sagital plane
L_1—L_2	11.6°	13.4°
L_2—L_3	14.2°	15.7°
L_3—L_4	15.1°	16.4°
L_4—L_5	10.2°	18.3°
L_5—S_1	2.3°	18.7°
L_1—L_5	51.1°	63.8°

The discs must be strong and stable since they are responsible not only for the mobility between the vertebrae but also for the bearing of weight. The entire weight of the upper body rests upon the lower lumbar vertebrae and during manual labour, pressure on the disc can be quite great. When the body is bent forwards 90°, the pressure on the lower lumbar discs is about ten times greater than the weight lifted. This weight is distributed over the entire surface of a normal disc. Even without any additional loading, most writers consider that the nucleus is under a certain amount of pressure. Petter has estimated this pressure to be 14.5 kg on the average. If this is true, then the pressure from the end-plate is distributed partially over the annulus and partially over the nucleus. The pressure absorbed by the nucleus is hydrostatically distributed partially over the end-plate and partially along the internal borders of the annulus. Pathological processes within the disc drastically alter its normal rôle by weakening the structures which maintain the integrity of the nucleus or by involving the nucleus itself. Disc degeneration, nowadays considered by many to be a normal sign of ageing, is such a pathological process. The changes which the disc undergoes during the course of life alter its functional properties. A cross-section of a senile disc gives a dry, homogeneous, relatively hard, yellowish surface. Mobility in such a disc, normal for its age, is reduced and pressure is transferred from vertebra to vertebra more or less uniformly by a large portion of the disc. But the greater the degree of degeneration in the central tissues of the disc, the greater is the proportion of the pressure to be transferred by the remaining annulus.

IV. Definition of the technical nomenclature

Few investigations of the elasticity and strength of the human vertebra have been carried out. Robert (1855) was the first to investigate the strength of vertebrae. He subjected spine specimens to the effects of great force and found that the articular processes were the most resistant portions of the vertebral body. No specific measurements were made. Rauber (1876) and Messerer (1880) subsequently measured the resistance of vertebrae. It was not until 1902 that the next publication on the subject appeared, the elasticity and resistance experiments carried out by Lange. The results of similar mechanical investigations were published by Göcke in 1928 and 1931. Table 8 summarises the results obtained by the various writers. Disc elasticity has been investigated by Virgin (1951), Hirsch & Nachemson (1954), and Hirsch (1955).

Biomechanics may be defined as the study of those phenomena in the living body which are basically of a mechanical nature. The techniques and terminology which are used in such studies are identical with those used to analyse similar phenomena in inanimate materials and constructions.

One of the basic concepts of mechanics is force. This may be of three different types—compression, extension, and shearing. If a fixed object is subjected to the effects of an external force, it develops internal stresses and may undergo changes in form. Changes in form depend upon the degree of elasticity shown by the material. Material which resumes its original form after the effects of force have ceased is fully elastic. Material which completely or nearly completely retains its deformity following the removal of force is termed plastic. Stress which occurs within the material may be directed at right-angles to the cross-sectional dimension and in that case is called normal stress or σ-stress. This type is seen in extension, compression, bending, and buckling. Stress may also be directed parallel to the cross-sectional dimension and as such is called tangential stress. Examples of this type are seen in shearing and twisting. See fig. 2.

If the external force is increased, stress within the material is also increased. This can be taken only to a certain limit beyond which the material cannot withstand greater stress. This limit is called the breaking-point. The breaking-point (σ_B) can vary for the same material and the same type of force depending upon whether the force is static (slowly increasing) or dynamic (rapid changes in strength). Blows, vibration etc., if often repeated, as well as rapid change-over between extension and compression (exhaustion) can be deleterious even although the stress values, calculated as force per unit surface area, are not particularly high.

If a squat object is subjected to compression, both compression stresses

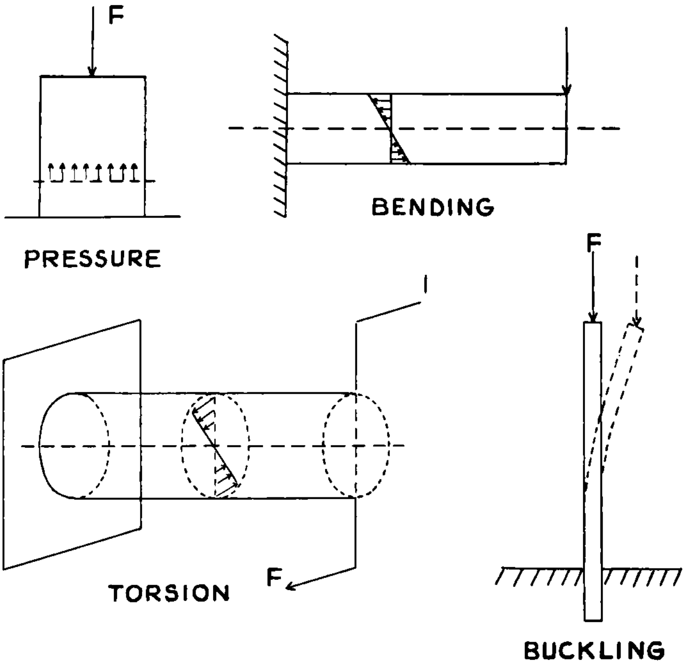


Fig. 2. When force is applied at right angles to the cross-sectional dimension of an object, the effective forces give rise to pressure, bending and buckling. A normal stress arises within the material. In the case of torsion, the force acts parallel to the cross-sectional dimension and tangential stress arises in the material.

and changes in form occur so that the object becomes shorter and wider. If, on the other hand, the difference between the length and the width of an object is great, the object will buckle.

Force and deformity can be represented by a curve such as can be obtained by using a material-testing apparatus (fig. 23). Forces and change in form are directly proportional in the first portion of the curve. The point where this relationship ceases is called the limit of proportionality. The greatest possible value for stress which will not result in permanent deformity after removal of the applied force is called the limit of elasticity. The limit of elasticity is often not distinct and it is consequently difficult to give exact values. It is usually close to but somewhat less than the limit of proportionality. (The value is generally 0.8—0.9 σ_B for steel and metals in general.)

The crushing-point is that value for stress at which the material is compressed without any increase in stress. The crushing-point is not available for many materials such as wood.

The breaking-point is the greatest value for stress which can be obtained before the material breaks.

The spring-constant can also be obtained from the curve. This is a theoretical value which expresses the force required to compress an object per unit of length. The value is related to the inclination of the straight portion of the curve which lies below the limit of proportionality.

Present investigations

Material

The specimens used in these investigations were obtained from the pathology departments of two Stockholm hospitals. Specimens were taken from all cadavers whose age at the time of death did not exceed fifty-five years. During certain predetermined periods, all available specimens were taken regardless of age. Specimens were not taken from patients dying of tuberculosis or in those cases in which the pathologist considered it necessary to examine the vertebral column or the spinal chord. No specimens from children have been obtained. It would have been desirable to use only specimens obtained from individuals who died suddenly as the result of an accident or suicide. It was impossible, however, to establish such narrow criteria as it was sufficiently difficult to obtain an adequate number of specimens within the upper age limit of fifty-five years.

The specimens were removed from the cadavers without injuring the vertebrae or discs. The entire lumbar region, a portion of the sacrum, and in some cases, the lower thoracic vertebrae were included. During the interval between autopsy and the carrying-out of the experiments, the specimens were kept in plastic bags in order to reduce dehydration. These specimens were usually prepared for use on the same day that they were removed. In those cases in which it was impossible to do this, the specimens were placed in a freezer at —20° C. Before being used in an experiment, the specimens were kept in plastic bags at room temperature for eight to ten hours.

When prepared for the experiments, the specimens consisted of either two or three entire vertebrae with the intervening discs or of vertebral bodies alone. The disc tissues were excised from the upper and lower surfaces of all specimens so that these surfaces were formed by the end-plates only. This measure was especially important for those experiments on the single vertebral bodies in which the resistance of the bodies or the end-plates was to be measured. The annular and nuclear tissues were removed as carefully as possible with a small, curved knife. Special care was taken to avoid damaging the cartilage-plate.

The experiments were carried out at room temperature (between 20° and 22° C) with the specimens protected against dehydration by means of a wet towel.

The force applied has, in every experiment, been directed at right-angles to the largest surface of the discs, i.e. in the longitudinal direction of the spine. Force has been applied very suddenly and rapidly reduced to zero, i.e. dynamic stress, or has been increased to a maximum during one to two minutes, i.e. static stress.

I. Dynamic stress due to compression

a) Apparatus

The experiments were carried out with the aid of an image-amplifier and a 35 mm camera.[1] With this camera it was possible to take forty-eight individual plates per second with an exposure time of 1/96 sec. The field was sufficiently large to enable exposures to be made of two vertebrae and the intervening disc. The large number of plates which could be exposed in a short time made it possible to register any reversible changes which may have occurred as well as to obtain an exposure immediately following the first blow and before the falling weight rebounded and struck the specimen again, an interval of about 0.15 sec. Ordinary still plates were made in a number of instances as the quality of such plates is better. It was still possible to follow the course of events by using the image-amplifier. These plates were made without altering the focus so that entirely comparable images could be obtained before and after the blow. Under these circumstances, it was possible to measure the height of the discs on Röntgen plates and make accurate comparisons before and after the blow.

The specimens were placed in a hammer apparatus similar to the one shown in fig. 3. In order to obtain as much stability as possible, the apparatus was mounted on an iron plate weighing 60 kg. A smaller iron plate, screwed to the base plate, was studded with a large number of sharp points, 3 mm in height, upon which the specimens were fastened. Two polished iron rods, 1.5 m long, were mounted on each side of the specimen and along these, a weight of desired size could descend onto the specimen.

Discography using 35 per cent Umbradiol (Astra) was carried out in every experiment. Methyl red was added to the contrast medium in most instances in order to be able to ascertain after the experiment which of the fissures had been filled by the contrast medium. The contrast material was injected through needles with an external diameter of 0.5 to 0.6 mm. Injection was made from the ventral surface and the amount used never exceeded 0.5 ml. The ventral approach was chosen in order to avoid unnecessary traumatisation of the tissues lying dorsally in the disc.

[1] The dynamic experiments were carried out in the Wenner-Gren Research Laboratory at Nortulls Hospital in Stockholm. The image-amplifier and camera were constructed by Philips.

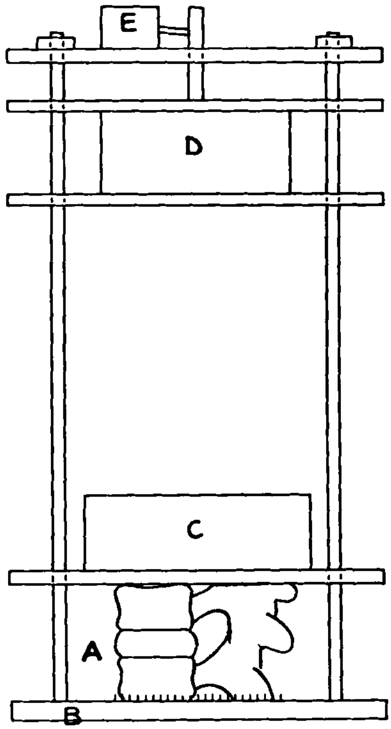


Fig. 3. Apparatus used to produce a dynamic force on a spine specimen by means of a blow. A. Specimen. B. Base plate with a large number of small pointed studs which hold the specimen steady. C. Weight varying between 10 and 25 kg which is used to apply pressure to the specimens for at least ten minutes before the experiment. D. Falling weight ranging between 15 and 18 kg. E. Electric release for the falling weight.

It was not considered necessary to make Röntgen plates of the specimens before the injection of the contrast medium since no additional information could be gained which would not be obtained in conjunction with discography. Before being exposed to a falling weight, the specimens were placed under a static load for ten minutes in order to eliminate some of the elasticity of the disc. The experiments have been divided into four groups according to the weight combinations which were used.

Group	Static weight kg	Falling weight kg	Approximate maximum force during 0.006 sec. kp
A	25	15	1050
B	25	18	1200
C	15	15	1250
D	10	15	1350

In each instance, the falling weight was dropped 50 cm.

b) Material

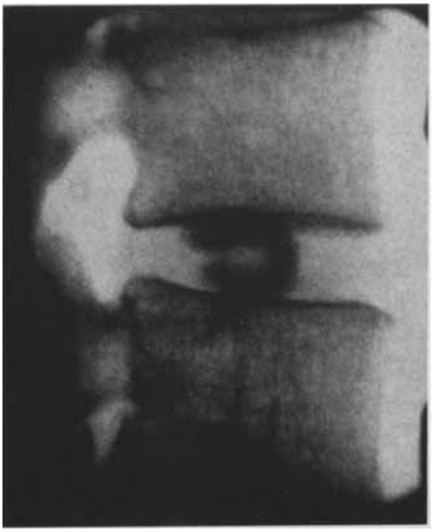
The specimens used in these experiments consisted of two lumbar vertebrae with the intervening disc. The arches with the intervertebral joints and the spinal processes with their ligaments were undisturbed. Various combinations of vertebrae have been used and in seven instances, the twelfth thoracic vertebra has been included in order to be able to investigate the upper end-plate of L_1.

The sex distribution for the whole series was F/M = 26/39.

The discs have been divided into three groups according to the degree of degeneration. Assessment was made partly on the basis of the Röntgen plates and partly after examination of the cut surface. The Röntgen plates were examined for the height of the disc and possible reactions shown by the vertebral bodies and especially for the results of discography. A "normal" disc was of usual height, lacked signs of reaction on the bordering vertebral bodies, and had a nucleographic appearance showing the contrast medium occupying a horse-shoe-shaped space when seen in lateral view, and showed no signs of the contrast medium having flown out into fissures (fig. 4 a). The cut surface of a "normal" disc was a light yellowish-white colour and the nucleus was firm, moist, and bulged above the cut surface. The "moderately degenerated" group includes those specimens in which the disc was of normal height and no reaction was displayed by the bordering vertebral bodies but in which the contrast medium occupied an irregular, central space which in lateral view did not take up more than 60 per cent of the width of the entire disc or those in which the contrast medium occupied small fissures. The cut surface of such discs was drier than normal, the nucleus bulged over the surface, and within the nucleus, it was possible to distinguish firmer but not completely separated portions. If the disc was obviously compressed, if spondylotic exostoses or sclerosis of the end-plate were present, if the contrast medium occupied large fissures which extended any great distance peripherally, or if the cut surface of the disc was yellowish, dry, and lacked a distinctly demarcated nucleus, the disc was considered to be "degenerated".

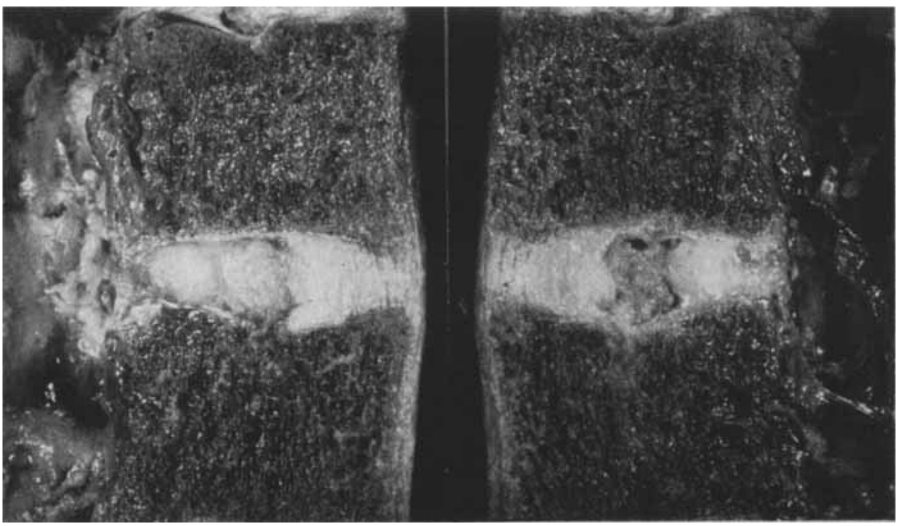
c) Results

The results of the seventy-six experiments which were carried out in the manner described above are shown in tables I A to D. After the experiments were completed, the arches were removed in most cases to facilitate inspection of the entire periphery of the discs. Special attention was directed towards the prediliction sites for disc herniation. Macroscopic lesions confined to the central or peripheral portions of the disc were detected in only two instances (nos. 16 and 60).



A

B



C

Fig. 4. Specimen 1. L_3—L_4, male, 59 years. Röntgen plates taken with a Philips camera at the rate of 48 per sec.

A. Appearance of the specimen before the experiment showing a normal discographic picture.

B. Plate taken after the experiment in which no fracture of the vertebral bodies or end-plates can be detected. Some of the contrast medium appears in the spongiosa of the vertebral body as a sign of end-plate fracture.

C. Specimen sawn longitudinally through the centre of the vertebral bodies. The portion of the lower end-plate which borders onto the nucleus bulges downwards and the end-plate is fractured in one place allowing the disc pulp to form a small intraspongious herniation.

Table 1. Dynamic compression experiment.

Experiment	Vertebrae examined	Age	Sex	Condition of the disc.			Macroscopic changes in the disc.	End-plate fractures	Compression fractures	Reduction in height of the disc. (lateral view)	Reduction in height of the disc. (frontal view)	Comments
				Normal	Moderately degenerated	Degenerated						
1	2	3	4	5	6	7	8	9	10	11	12	13
A. 15 kg fell 50 cm. Load 25 kg. 1050 kp during 0.006 sec.												
1	3–4	59	M	×	—	—	—	× I	—	17 %	—	
2	2–3	51	F	×	—	—	—	—	—	—	—	
3	4–5	42	M	×	—	—	—	—	—	—	—	
4	2–3	40	F	×	—	—	—	—	—	—	—	
5	2–3	26	F	—	×	—	—	—	—	—	—	
6	2–3	45	—	—	—	×	—	× I	—	—	—	
7	4–5	45	—	—	×	—	—	—	—	—	—	
8	2–3	32	—	×	—	—	—	× I	—	50% d 12% v	—	
9	3–4	22	F	—	—	×	-	—	—	—	—	
10	3–4	40	M	—	×	—	—	× II	—	21%	—	
11	2–3	52	M	×	—	—	—	—	—	—	—	Upper vertebra was reduced in height by 10 %. No fracture visible radiologically or macroscopically.
12	2–3	54	M	—	×	—	—	—	—	—	—	
13	4–5	42	M	—	—	×	—	—	—	—	—	
14	2–3	42	M	—	×	—	—	—	—	—	—	
15	4–5	52	M	—	—	×	—	—	—	—	—	
16	Th_{12}–L_1	54	M	—	—	×	×	—	—	—	—	ruptured disc.
17	4–5	54	M	×	—	—	—	—	—	—	—	
18	4–5	54	M	—	—	×	—	—	—	—	—	
19	4–5	32	—	—	—	×	—	—	—	—	—	
20	2–3	32	—	×	—	—	—	× I	—	22% d	—	
B. 18 kg fell 50 cm. Load 25 kg. 1200 kp during 0.006 sec.												
21	4–5	70	F	—	—	×	—	—	—	—	—	
22	2–3	70	F	—	—	×	—	—	—	—	—	
23	4–5	32	—	—	×	—	—	× I	—	30%	—	
24	Th_{12}–L_1	45	F	×	—	—	—	—	—	—	—	
25	2–3	45	F	—	×	—	—	—	—	—	—	
26	4–5	45	F	—	—	×	—	—	—	—	—	
27	4–5	49	—	—	×	—	—	× II	—	14%	—	

The Roman numerals in the column "end plate fracture" indicate the type of fracture. See text page 34.

In the column "reduction in height of the disc", the figures give the reduction as a percentage of the original height.

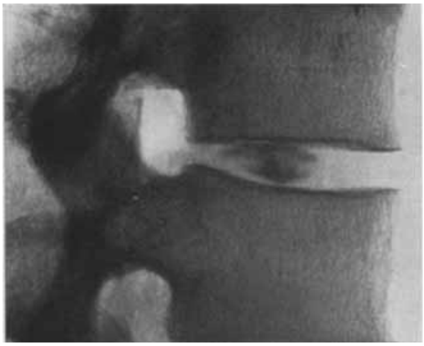
d = dorsally v = ventrally.

Experiment	Vertebrae examined	Age	Sex	Condition of the disc. Normal	Moderately degenerated	Degenerated	Macroscopic changes in the disc.	End-plate fractures	Compression fractures	Reduction in height of the disc. (lateral view)	Reduction in height of the disc. (frontal view)	Comments
1	2	3	4	5	6	7	8	9	10	11	12	13
28	2—3	49	—	—	—	×	—	—	×	—	—	Intraspongious herniation in L_2 and L_3
29	4—5	36	—	×	—	—	—	—	—	—	—	
30	4—5	52	M	—	—	×	—	× I	—	—	—	
31	2—3	52	M	—	×	—	—	—	—	—	—	
32	2—3	40	M	—	×	—	—	—	—	—	—	
33	4—5	40	M	—	×	—	—	—	—	—	—	
34	4—5	36	M	×	—	—	—	—	—	—	—	
35	2—3	36	M	×	—	—	—	—	—	—	—	
36	Th_{12}–L_1	46	F	—	—	×	—	× I	—	43% d 10% v	—	
37	2—3	50	F	×	—	—	—	× III	—	35% d	—	
38	4—5	50	F	—	×	—	—	× I	—	20% d	—	
39	4—5	35	M	×	—	—	—	—	—	—	—	
40	2—3	35	M	×	—	—	—	—	—	—	—	
41	4—5	29	M	×	—	—	—	—	—	—	—	5 kg fell 60 cm. Load 30 kg 400 kp during 0.006 sec.
42	2—3	29	M	×	—	—	—	—	—	—	—	3.5 kg fell 60 cm. Load 35 kg. 300 kp during 0.006 sec.
43	Th_{12}–L_1	29	M	×	—	—	—	—	—	—	—	Same as 42
C. 15 kg fell 50 cm. Load 15 kg. 1250 kp during 0.006 sec.												
44	Th_{12}–L_1	35	M	—	×	—	—	—	—	—	—	
45	Th_{12}–L_1	51	F	—	×	—	—	—	—	—	—	
46	2—3	47	F	—	×	—	—	—	—	—	—	
47	4—5	47	F	—	—	×	—	—	—	—	—	
48	3—4	41	M	×	—	—	—	× III	—	—	20–30%	
49	1—2	41	M	×	—	—	—	× III	—	—	30%	
50	4—5	46	F	—	×	—	—	× II	—	—	0–30%	
51	2—3	46	F	×	—	—	—	× I	—	—	25%	
52	Th_{12}–L_1	46	F	×	—	—	—	—	—	—	—	Intraspongious herniation.
53	3—4	37	M	×	—	—	—	—	—	—	—	
54	1—2	37	M	×	—	—	—	—	—	—	—	
55	3—4	35	M	×	—	—	—	—	—	—	—	
56	1—2	35	M	—	×	—	—	× I	—	—	23%	
57	3—4	46	F	—	—	×	—	—	—	—	—	
58	1—2	46	F	×	—	—	—	× III	—	—	18–36%	
59	3—4	53	F	—	×	—	—	—	—	—	—	
60	1—2	52	F	×	—	—	×	—	—	—	17%	Prolapse trough injection canal

Experiment	Vertebrae examined	Age	Sex	Condition of the disc.			Macroscopic changes in the disc.	End-plate fractures	Compression fractures	Reduction in height of the disc. (lateral view)	Reduction in height of the disc. (frontal view)	Comments
				Normal	Moderately degenerated	Degenerated						
1	2	3	4	5	6	7	8	9	10	11	12	13
D. 15 kg fell 50 cm. Load 10 kg. 1350 kp during 0.006 sec.												
61	2—3	54	M	—	×	—	—	—	×	—	—	
62	Th_{12}–L_1	52	M	—	×	—	—	—	×	—	—	
63	3—4	44	F	—	—	×	—	—	—	—	—	
64	1—2	44	F	×	—	—	—	× III	—	—	18%	
65	3—4	46	M	×	—	—	—	—	—	—	—	
66	1—2	46	M	—	×	—	—	—	×	—	—	
67	Th_{12}–L_1	46	M	—	×	—	—	—	×	—	—	
68	3—4	50	M	—	×	—	—	—	—	—	—	
69	1—2	50	M	—	×	—	—	—	×	—	—	
70	3—4	52	M	×	—	—	—	—	—	—	—	
71	1—2	52	M	×	—	—	—	× III	—	—	0—23%	
72	1—2	52	M	—	—	×	—	—	—	—	—	
73	3—4	52	M	—	×	—	—	—	—	—	—	
74	1—2	52	M	—	×	—	—	—	—	—	—	
75	3—4	52	F	—	—	×	—	—	—	—	—	old fracture at L_3
76	1—2	52	F	—	×	—	—	× I	—	—	—	

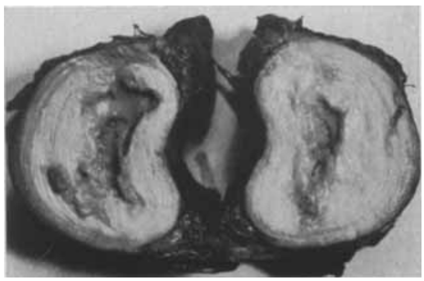
No. 16. Vertebrae Th_{12}—L_1, male, fifty-five years old. Fig. 5. The disc has been considered to be degenerated although only a moderate degeneration was shown by discography in lateral view. When the specimen was sectioned, it could be seen that both evacuations, especially the cranial, extended a long way laterodorsally. The lateral view taken before the blow showed a fissure containing contrast medium which extended dorsally, and in the vertebral canal could be seen a soft-tissue shadow at the level of the disc. This soft-tissue shadow was somewhat larger on the Röntgen plates taken after the blow although the contrast medium had not altered its position. After laminectomy, it was possible to see a typical disc prolapse and sectioning of the disc showed a large fissure which extended to that region. There was no perforation. It seems reasonable to draw the conclusion that the trauma did not cause the disc herniation but that it enlarged an existing prolapse.

No. 60. Vertebrae L_1—L_2. Female, fifty-two years old. Fig. 6. The disc was judged to be normal. A somewhat thicker injection needle, 1 mm in diameter, was used in this instance. The blow pressed the nucleus out through the injection canal. Loss of substance reduced the height of the



A

B



C

Fig. 5. Specimen 16. Male, 54 years. The disc between Th_{12} and L_1 is injected with contrast medium.

A. Before the experiment showing a relatively normal pool of contrast medium with a branch extending cranio-dorsally. A soft tissue shadow is present in the vertebral canal.

B. After the blow. Contrast medium unaltered. Soft-tissue shadow somewhat larger.

C. Disc in cross-section. The left half corresponds to the cranial portion. The large space forms part of the pocket which extends all the way to the posterior longitudinal ligament.

disc by 17 per cent with a similar reduction being shown by the ventral and the dorsal portions. Most writers believe that a normal disc transfers pressure from vertebra to vertebra via the annulus and the nucleus and that the pressure which is absorbed by the nucleus is distributed hydrostatically throughout the space which contains the semigelatinous mass. This experiment shows that the nucleus has a certain expansion force since the height of the disc was reduced by 17 per cent following the evacuation of the nucleus through a very small defect in the annulus. The measurements before and after trauma were made without any load being placed on the specimen. It is, of course, impossible to be sure that the blow did not injure the annulus but similar injury has not been demonstrated macroscopically in any of the other experiments.

Fig. 6. Specimen 60. Female, 52 years, L_1—L_2. The blow has expressed a portion of the nucleus through the injection canal resulting from discography. The height of the disc has been reduced by 17 %.

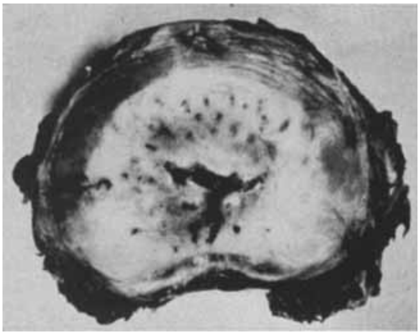
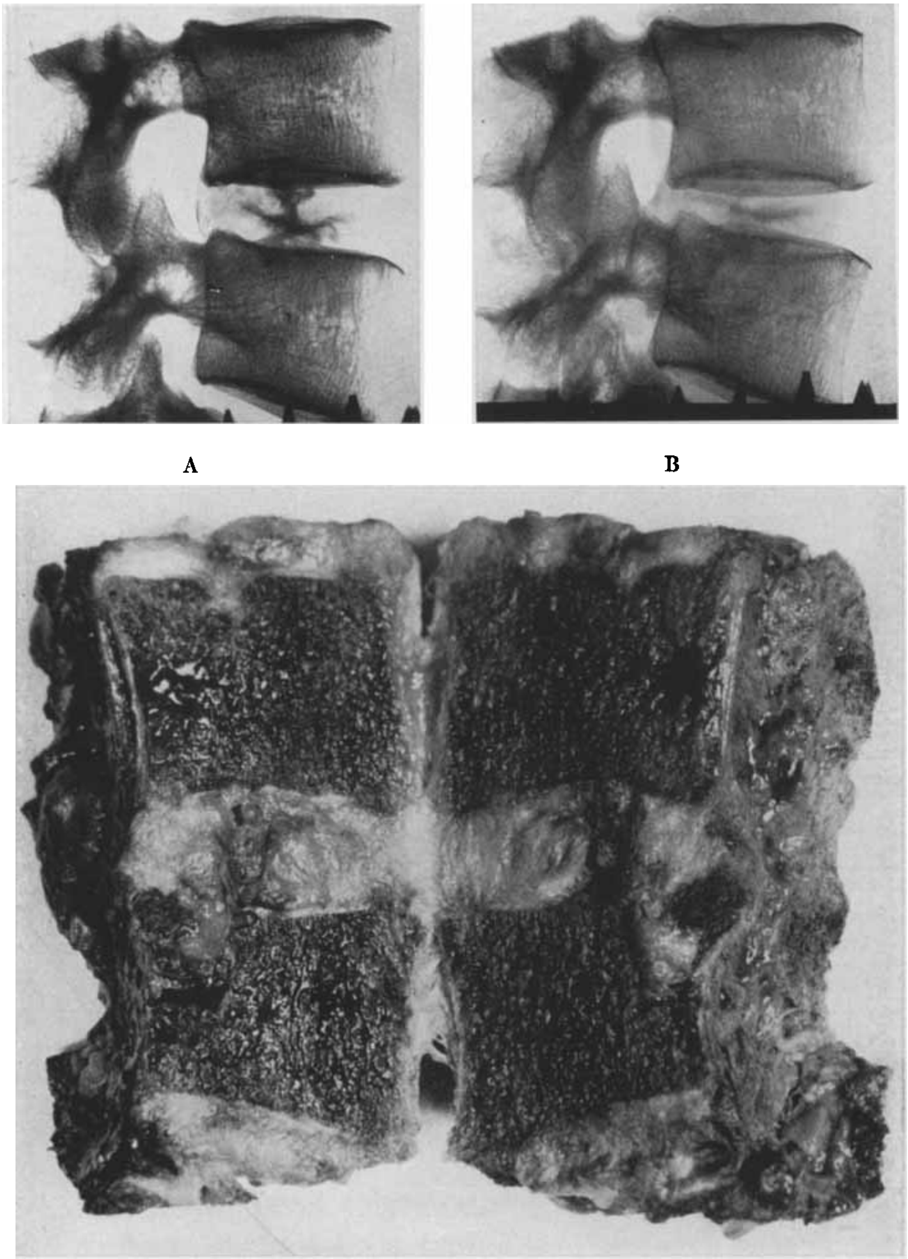


Fig. 7. Disc tissue removed to expose the cartilage-plate. A small fracture caused by the blow is seen centrally.

Fractures of various types occurred in twenty-six of the seventy-six experiments (34 per cent). Compression fractures resulting in wedge-shaped compression have been seen in six instances while in the remaining twenty, fracture of the end-plate without compression of the vertebral body



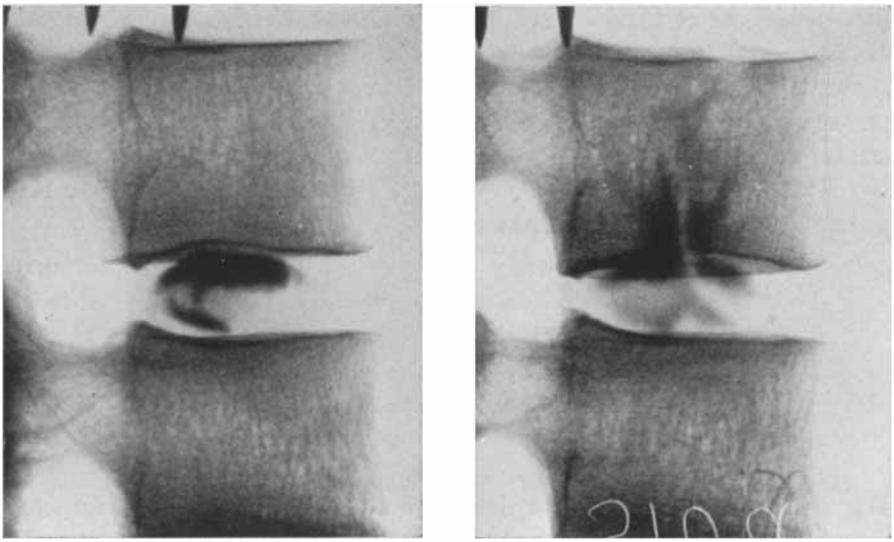
A B

C

Fig. 8. Specimen 10. L_3—L_4. Male, 40 years.

A. Before the experiment. Discography gives a star-shaped appearance as a sign of moderate degeneration.

B. After the blow. The height of the disc has been reduced by the same amount (21 %) in



A B

C

Fig. 9. Specimen 58. L_1—L_2. Female, 46 years.
A. Before the blow. Normal disc.
B. The blow has caused a fissure in L_1 which extends through the entire vertebral body without altering the essential form of the body. (Plates A and B are not taken from exactly the same position).
C. The fissure divides the cartilage-plate into a dorsal and a ventral portion without any displacement between the fragments.

---

both the ventral and the dorsal portion. The contrast medium has lost its density. An area of cloudiness which may be caused by the contrast medium can be seen in the dorsal portion of the lower vertebra.
C. Specimen sawn longitudinally through the centre of the vertebrae. Dorsally in L_4 can be seen a bean-sized displaced fragment which has been pressed dorsally allowing the nucleus to be interposed. The upper dorsal portion of the vertebral body and the dorsal longitudinal ligament produce a distinct bulge into the vertebral canal.

occurred. Some of these fractures were visible on the Röntgen plates only as the result of leakage of the contrast medium through the fracture. This shows that the end-plate, the barrier between the disc and the spongiosa of the vertebral body, must have been perforated (fig. 4). Some of the fractures, on the other hand, were apparent on the Röntgen plates without the aid of the contrast medium (fig. 11). Fractures of the end-plate may be divided into three distinct types.

I. Fractures situated centrally in the end-plate in which a portion of the end-plate is pressed down or in which the end-plate is deflected downwards into the spongiosa on one or both sides of the fracture without compression of the vertebral body. Type I is shown in fig. 7.

II. Fractures of the end-plate which are situated so far peripherally that a corner of the vertebral body is torn loose with or without displacement. Type II is depicted in fig. 8.

III. Fissures extending across the entire end-plate which, when deepened to involve the vertebral body, divide it into two parts. There is usually little or no displacement between the fragments. Typical compression fractures are not included in this group. Type III may be seen in fig. 9.

Fractures of one or the other of the above types occurred in twenty instances (26 per cent) and compression fractures in six instances (8 per cent). This distribution demonstrates that the force used was at the upper limit of that which is suitable for such experiments in which the applied force should be as great as possible without causing compression fractures. The forces were empirically chosen at first and small variations were subsequently made.

In the twenty instances in which fracture of the end-plate occurred, the status of the disc was "normal" in ten, "moderately degenerated" in seven, and "degenerated" in three only.

Distribution of the end-plate fractures among the various discs did not warrant the drawing of any conclusions.

If the occurrence of the various types of fracture is considered in conjunction with the size of the force applied, it can be seen that the central

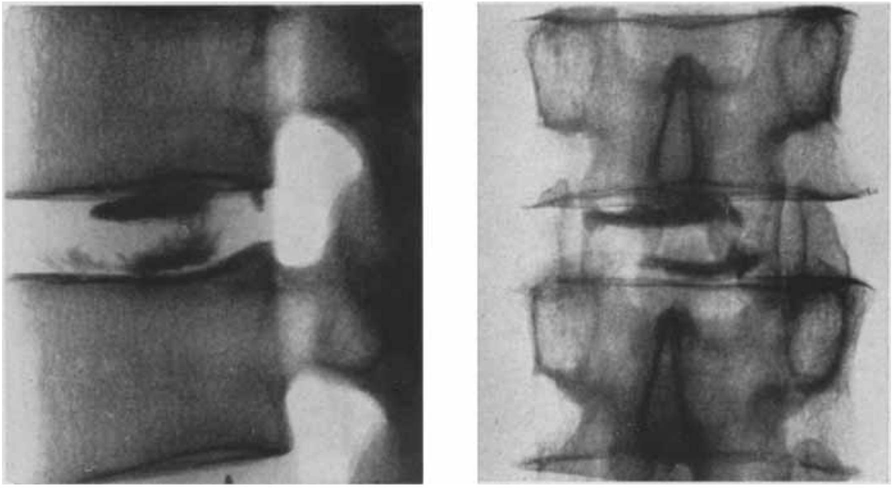
---

Fig. 10. Specimen 76. L_1—L_2. Female, 52 years.

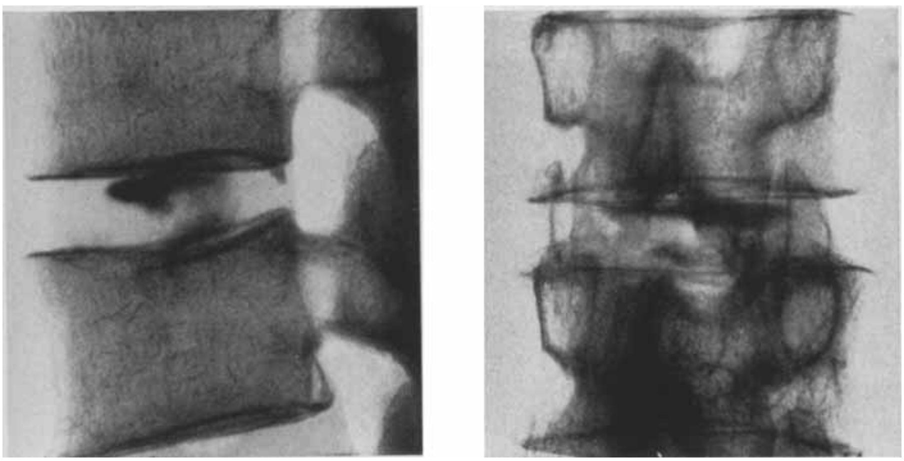
A. Frontal and lateral views of the specimen before the experiment.

B. After the blow. The frontal plates in this case have been made with the position of the specimen unaltered. In the frontal view, the pool of contrast medium has nearly completely disappeared. The lateral view shows a small interruption of continuity towards the edge of the end-plate.

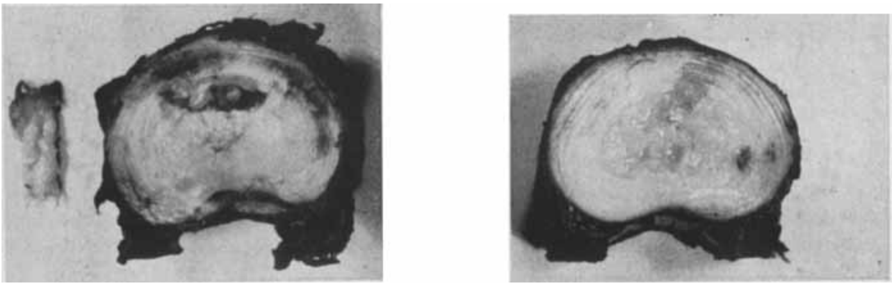
C. Cross-section of the disc. The disc tissue has been removed from L_2 and the piece which is shown at the side represents the size of the portion which was pressed down into the fracture. The other half of the disc has not been disturbed after cross-sectioning.



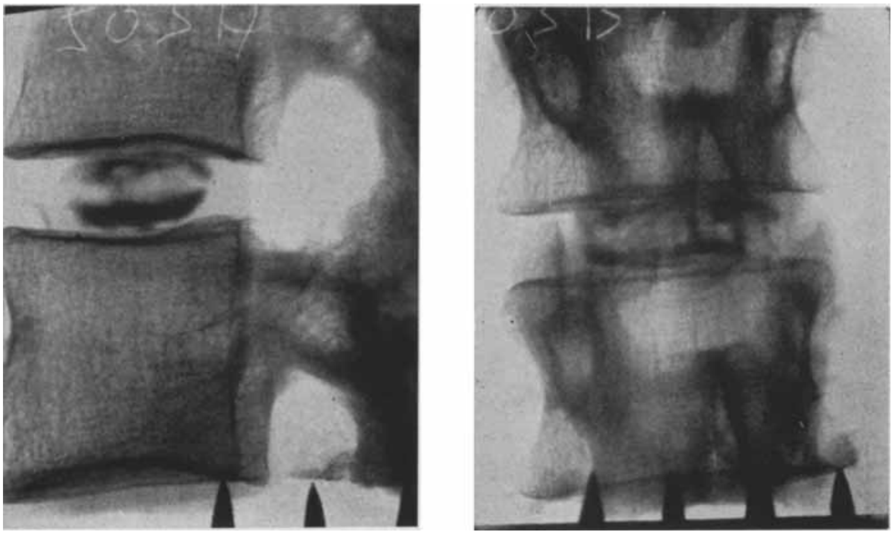
A



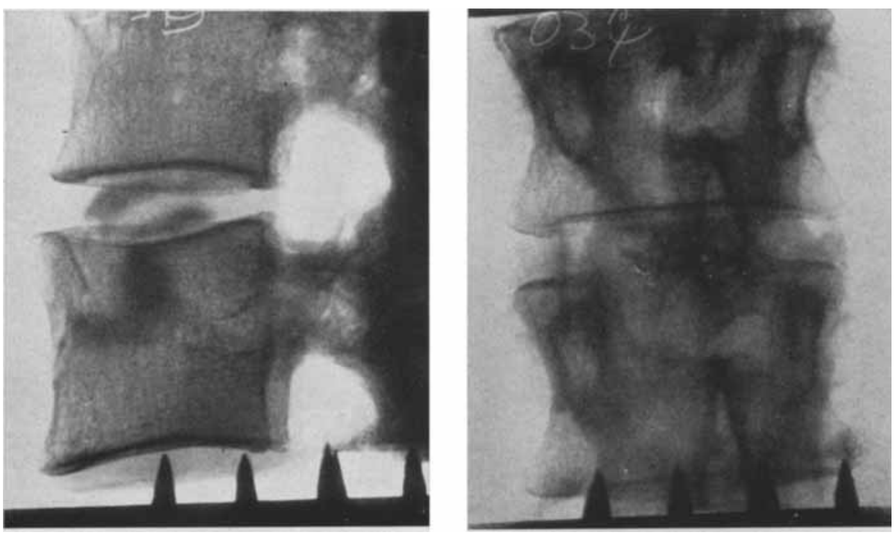
B



C



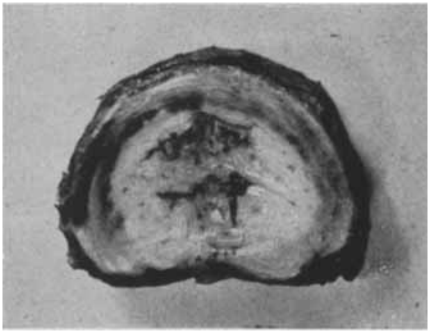
A



B

Fig. 11. Specimen 51. L_2—L_3. Female, 46 years.

A and B show the frontal and lateral views before and after the blow. The frontal views have been taken from exactly the same position. The height of the disc has been reduced by 25 % following the blow. The lateral view in B shows a sharp line in the cranio-anterior portion of L_3. No interruption of continuity can be detected in the central portion of the end-plate.



C

C. The end-plate has been fractured in two places, anteriorly and centrally.

Table 2.

Type of end-plate fracture			I	II	III	Compression fractures
Total			11	3	6	6
Distribution of the types according to the magnitude of the forces applied.						
1050 kp			4	1	0	0
1200 kp			4	1	1	1
1250 kp			2	1	3	0
1350 kp			1	0	2	5
Condition of the disc						
Normal			4	0	6	0
Moderately degenerated			4	3	0	5
Degenerated			3	0	0	1
Vertebrae examined						
Th_{12}—L_1	Total	9	1	—	—	2
L_1—L_2	Total	12	2	—	4	2
L_2—L_3	Total	21	4	—	1	2
L_3—L_4	Total	14	1	1	1	—
L_4—L_5	Total	20	3	2	—	—

end-plate fractures were mainly found in the groups in which the force was least and that complete fissuring of the end-plate (type III) as well as compression fractures were chiefly found in the groups with greater stress (table 2).

In three experiments which have not been included in the groups described above, (expts. 41—43), pairs of vertebrae from a twenty-nine-years-old man with completely normal discs were subjected to stress in the same manner as the other specimens, but the effective force was 400 kp

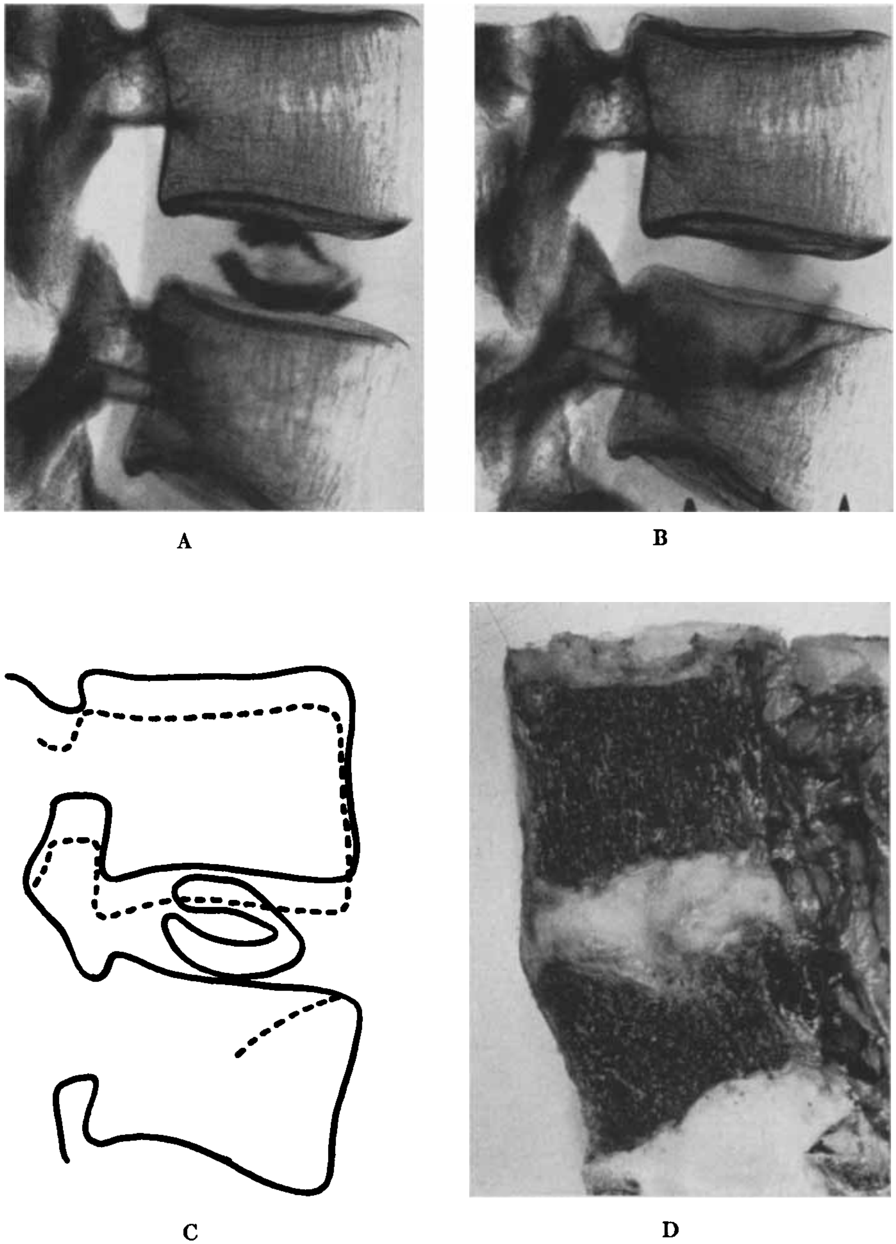


Fig. 12. Specimen 23. L_4—L_5. 32 years.

A. Before the experiment. The disc has been considered to be moderately degenerated.

B. After the blow. The contrast medium has practically completely pressed down into the spongiosa of the vertebral body. A denser part can be seen forming a line extending from the ventral portion of the fractured end-plate to approximately the centre of the vertebral body.

in one experiment and 300 kp in two others. No visible changes were produced.

These fractures are of radiological interest inasmuch as they are difficult to detect since the injury is limited to a portion of the vertebral body which is easily obscured on a Röntgen plate by the other parts of the vertebral body (fig. 10 and 11). In the present experiments, these lesions were easily detected through the use of a contrast medium which, in conjunction with the damage to the vertebral bodies, gave useful clues towards a diagnosis (fig. 12).

Tomography was carried out in some instances with the specimens subsequently being sawn into slices of equal thickness. Röntgen plates were then made in order to be able to compare the tomographic appearance with the actual state of affairs. Tomography satisfactorily revealed the end-plate fractures (fig. 13, 14, and 15).

Summary. Localised end-plate fractures occurred in 26 per cent of experiments in which specimens consisting of two vertebrae and the intervening disc were exposed to forces ranging between 300 kp and 1350 kp lasting for 0.006 sec. Not all of these fractures were visible on routine Röntgen plates of the specimens but they could be demonstrated radiologically with the aid of discography or tomography. No isolated disc injuries due to the blow could be determined.

II. Static stress due to compression[1]

During manual labour, the vertebral column is often subjected to great stress in which the force is slowly increased. The purpose of the investigations reported below has been to determine by experimental means the maximum forces which may be applied without causing irreversible changes and the nature of the changes which occur when the force applied exceeds this maximum.

a) Experiment using discographic and radiological techniques

Specimens were collected in the same manner as described before. Two vertebrae and the intervening disc were used for these experiments. Follow-

[1] This work was carried out at the Gustav V Institute for Scientific Research.

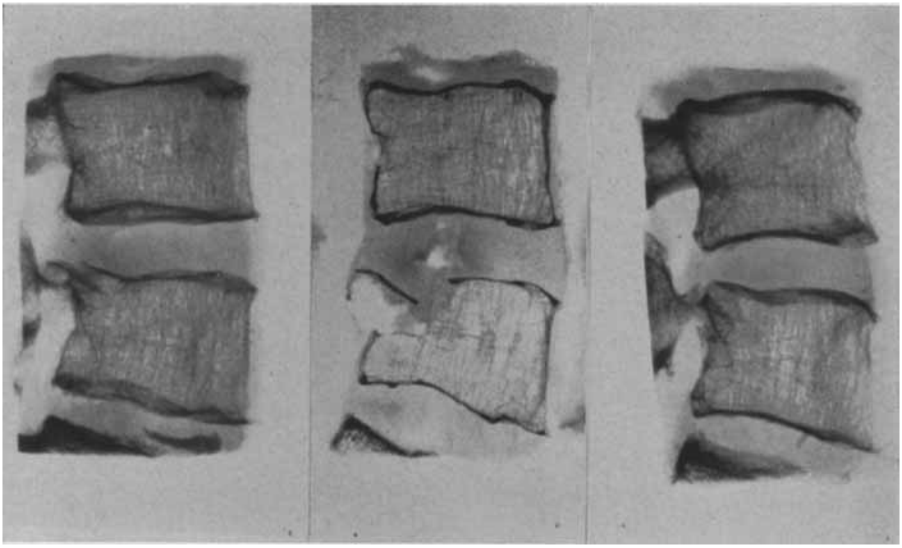
C. The heavy line traces the contours of the vertebral body before the experiment and the interrupted line the contours after the blow. The height of the disc has been reduced by 30 %.

D. Specimen sawn longitudinally through the centre revealing the changes which have occurred.

A

B

C



D

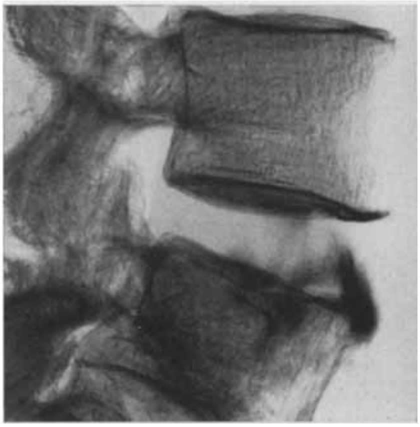
Fig. 13. Specimen 27. L_4—L_5, 49 years.

A and B show the röntgen plates taken before and after the blow.

C. Specimen sawn longitudinally through the centre. A large fragment is displaced and produces a bulge in the dorsal longitudinal ligament.

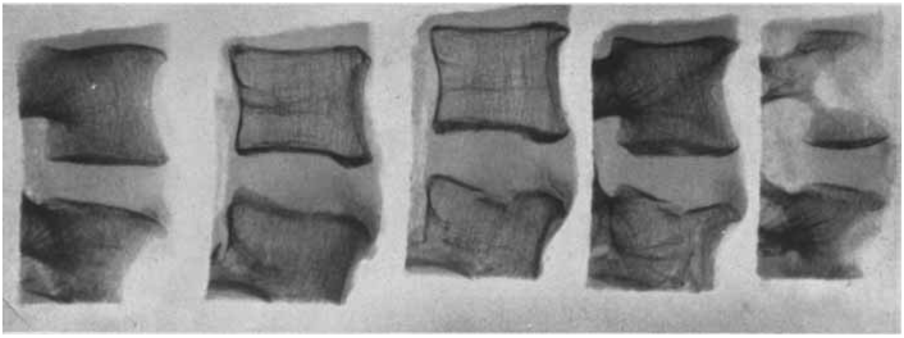
D. Röntgen plates made of slices of the specimen. A fracture with a displaced fragment is seen in the central slice while those representing the peripheral portions show no fracture.

A



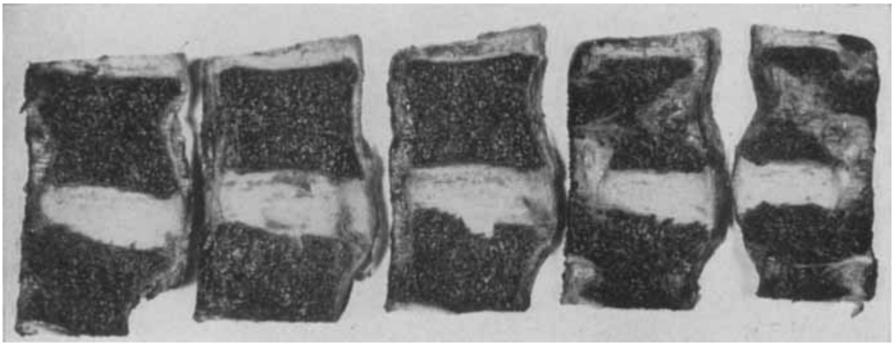
B

C



1 2 3 4 5

D



1 2 3 4 5

E

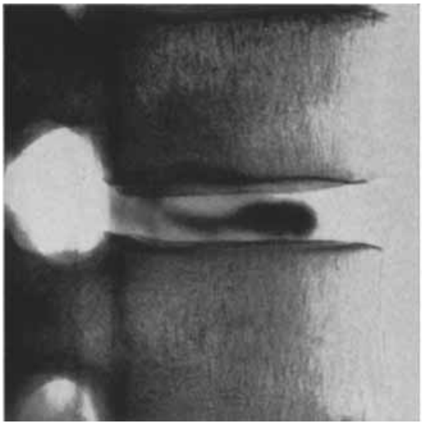
Fig. 14. Specimen 38. L_4—L_5. Female, 50 years.

A and B, before and after the blow. B shows that the central pool of contrast medium has been pressed down into the vertebral body. A portion of the L_5 end-plate is depressed.

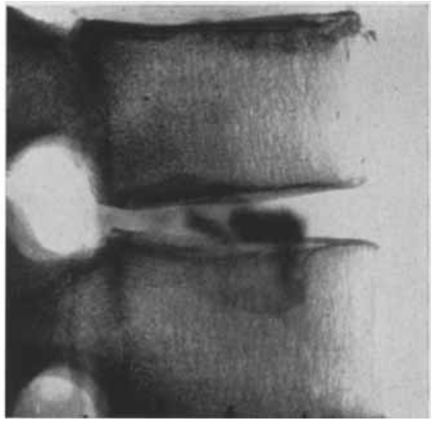
C. Tomography of specimen, centre section, showing an interruption in the cartilage-plate and a depressed fragment immediately below.

D. Röntgen plates of five, approximately equally thick slices of the specimen. Slices 3 and 4 show the end-plate pressed down. The end-plate is entire in the other three slices.

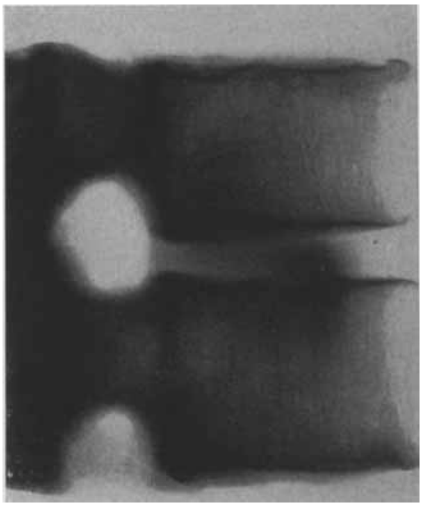
E. The same slices as in D. Slice 5 has been reversed. Only slice 3 shows a fracture. The fracture is not seen in slice 4 because the lateral edge of the fracture lies within the slice and the fractured side is turned away from the camera.



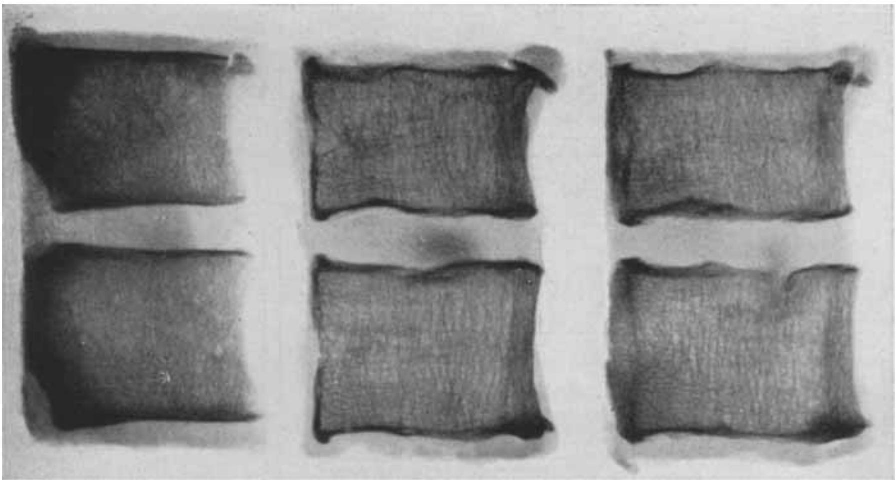
A



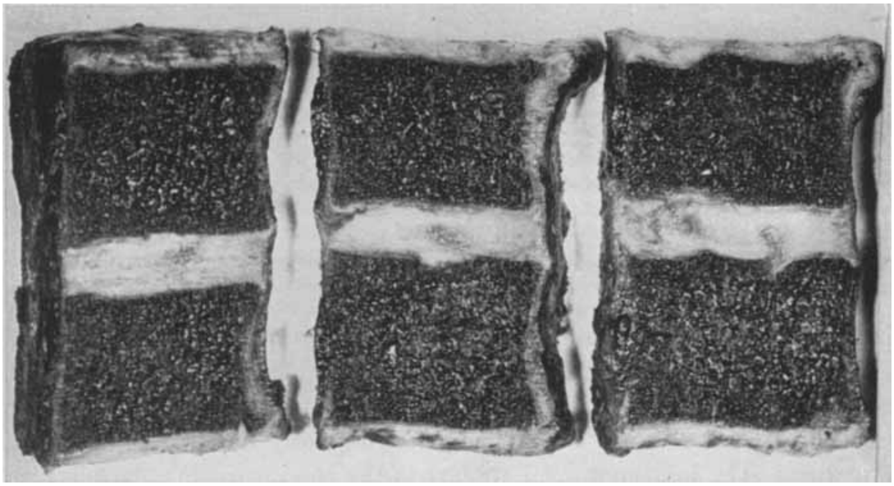
B



C



D



E

Fig. 15. Specimen 36. Th_{12}—L_1. Female, 46 years.

A and B, before and after the blow. B shows the contrast medium pressed down into the anterior third of the spongiosa of the vertebral body but no fracture can be seen.

C. Tomograph showing two interruptions of continuity in the lower end-plate.

D. Röntgen plates of three slices of the specimen. The left slice, no visible fracture. The middle slice, fracture in the centre of the end-plate. The right slice, fracture in the anterior third.

E. Photographs of the slices described in D.

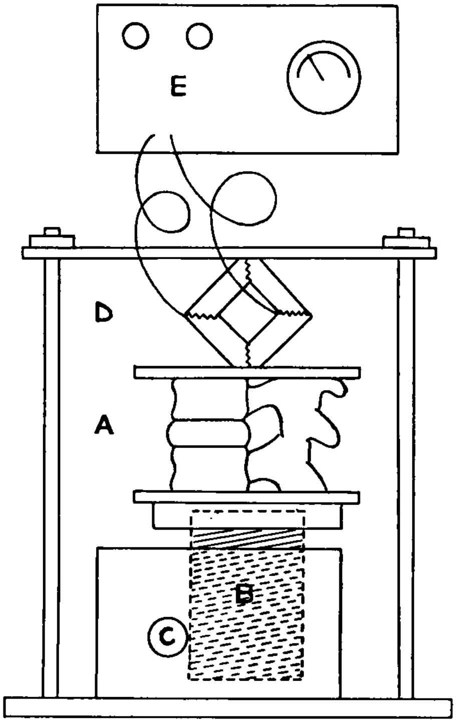


Fig. 16. Compression apparatus in which the specimens were subjected to pressure (maximum 500 kp), recorded by a measuring bridge at the same time as Röntgen plates were made.

A. Specimen. B. Mechanically driven screw. D. Strain gauge. E. Measuring bridge.

ing discography, the specimens were placed in a mechanical compression apparatus in which the pressure, measured by means of a strain gauge connected to a measuring bridge, was applied at right-angles to the disc (fig. 16). Changes within the disc were continuously recorded on Röntgen film strips. The maximum load applied to the specimens was 500 kp. Five experiments were carried out in this manner but in no instance was the breaking-point for the specimens reached. Röntgen plates of the lateral view showed no changes in the distribution of the contrast medium within the disc during any of these five experiments. The only visible alteration which could be detected when the load was increased was compression of the disc dorsally. See table 3.

It proved necessary to use another apparatus in which sufficient pressure could be exerted to reach the breaking-point of the specimens. A material-testing apparatus, with a maximum pressure of 5000 kp was obtained.

Table 3.

No.	Age	Vertebrae	Condition of the discs.			Changes in the contrast medium	Compression of the disc	
			normal	moderately degenerated	degenerated		dorsally	ventrally
1	56	L_{4-5}	—	×	—	0	36 %	6 %
2	55	L_{4-5}	×	—	—	0	18 %	0
3	56	L_{2-3}	—	×	—	0	30 %	0
4	62	L_{4-5}	—	—	×	0	35 %	0
5	51	L_{2-3}	—	×	—	0	0	0

Static compression of two vertebrae and the intervening disc in a mechanical compression apparatus with a maximum effect of 500 kp. Discography carried out and a continous Röntgen record made. Compression of the discs has been measured on enlarged copies of the Röntgen plates.

b) Description of Amsler's material-testing apparatus

The apparatus used in these experiments was manufactured by Alfred J. Amsler & Co., Schaffhausen, Switzerland, number 9704. See fig. 17. Compression is obtained between a stationary and a moving part (piston a) and force is applied to the piston hydrostatically. An electric pump supplies two chambers with oil under pressure. Both these chambers are equipped with adjustable valves (b and c). Opening one of these valves increases the pressure in the expansion chamber causing the mobile part to come closer to the stationary while the other valve serves to reduce the pressure. A system of tubes connects the expansion chamber to a pressure metre which is balanced on a spring (d) so that the pressure between the stationary part and the piston can be read directly from a scale as kp. Four springs of various strengths for maximum loads of 500, 1000, 2500, and 5000 kp are supplied with the apparatus. A recorder (e) is attached to the metre. The cylinder against which the recorder acts rotates as the piston changes position. This action takes place mechanically and for all these experiments, a gear ratio of 1: 2 has been used. When the piston moves upwards without resistance, a straight line, the base line, is traced by the recorder. When resistance is encountered, the recorder deviates from the base line and the height above the base line in millimetres is proportional to the pressure in kp. By these means it was possible to obtain a graphic representation of deformation and force on the respective axes.

c) Material

Discography was not carried out on the specimens placed in the material-testing apparatus. It was not possible to carry out continuous radiography during the course of the experiments since the specimens had to be taken to another place for this purpose. Because of this, it was impossible to obtain strictly comparable Röntgen plates and the disadvantages of discography under these circumstances outweighed the possible advantages. The possibility could not be eliminated that 0.5 ml fluid introduced into the nucleus would change the hydromechanical relationships.

Forty-three specimens consisting of two vertebrae and the intervening disc were investigated in the material-testing apparatus. The ages of the

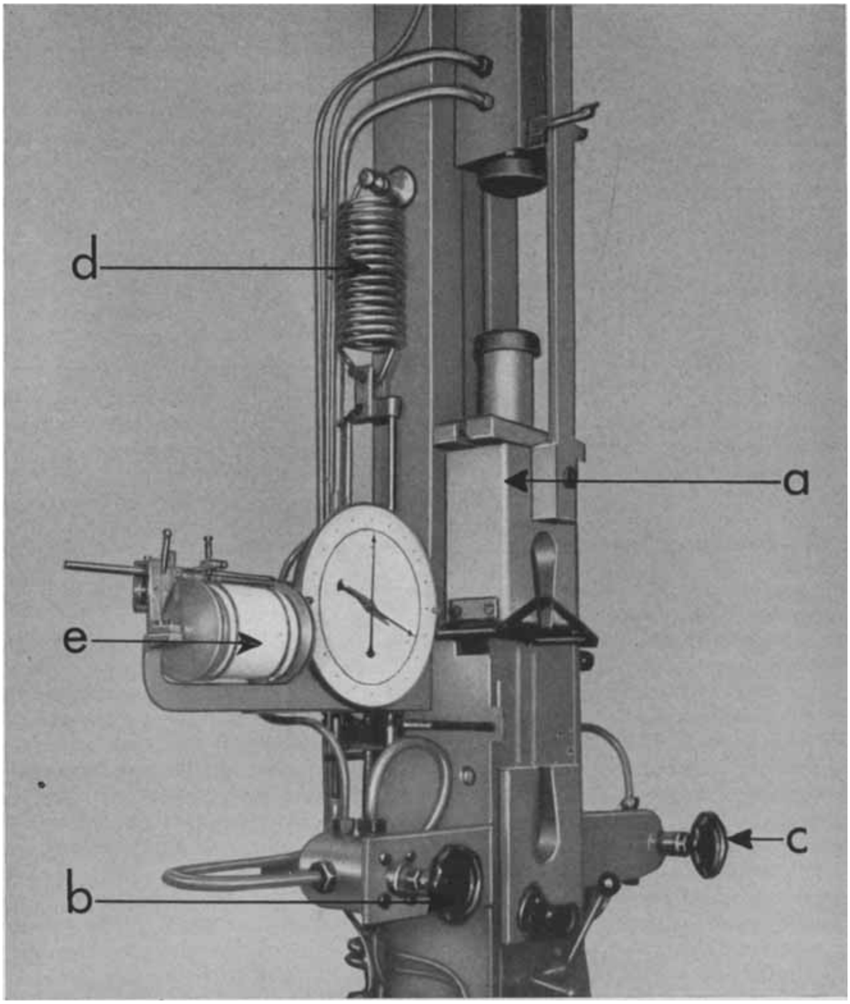


Fig. 17. Material-testing apparatus made by Amsler. a. Movable piston which, when under pressure, moves upwards so that the specimen to be examined is subjected to pressure between the two round plates. b and c, hand-operated valves. d. Spring which balances the pressure metre. e. Recorder attatched to the pressure metre.

subjects and the various vertebrae combinations are shown in table 4. The pressure was increased at a constant rate in every instance and the breaking-point was reached after one to two minutes. Röntgen plates of the specimens were made in most instances before and after these were subjected to pressure. The specimens were subsequently sawn into slices 0.5 cm thick. These slices were examined macroscopically and, when desired, photographed. Stress was interrupted in three instances before

Table 4. Static stress in two vertebrae and the intervening disc placed in a material-testing apparatus.

	Over 60 years	60—51 years	50—40 years	Under 40 years
L_{4-5}	$400^{\circ\circ\circ}$ $380^{\circ\circ\circ}$ -300	$600^{\circ\circ}$ 340 680 $600^{\circ\circ\circ}$	330°	1 $010^{\circ\circ\circ}$ $800^{\circ\circ\circ}$ 500° 600
L_{3-4}	$530^{\circ\circ\circ}$ $430^{\circ\circ\circ}$ 300	$500^{\circ\circ}$		1 $100^{\circ\circ}$ 580°
L_{2-3}	$350^{\circ\circ\circ}$ $380^{\circ\circ\circ}$	575° 550°	250°	870 750° 575°
L_{1-2}	-200 290 410	-300 430° 440°		$900^{\circ\circ}$ ☿ 510°
L_1–Th_{12}	$350^{\circ\circ\circ}$	225°	340° 230	$900^{\circ\circ}$ 760° 1 050 $750^{\circ\circ}$ ☿ 800°

The figures represent the breaking-points for the specimens. Those figures which are underlined indicate the experiments in which only end-plate fractures were seen on macroscopic examination. The figures marked with the prefix — indicate that stress ceased at that pressure although the breaking-point was not reached according to the curve.

° = normal disc.

°° = moderately degenerated disc.

°°° = degenerated disc.

☿ = "Knorpelknötchen" were found in the specimen.

the breaking-point was reached and the end-plates from these specimens were examined microscopically.

d) Results of the experiments on specimens consisting of two vertebrae

Examination of the forty specimens for which the breaking-point was reached revealed thirteen macroscopically evident end-plate fractures with herniation of the disc pulp into the spongiosa. These cases represented 32 per cent of the material. The distribution of the fractures was striking inasmuch as they were most frequent in the younger age groups and among the upper lumbar vertebrae.

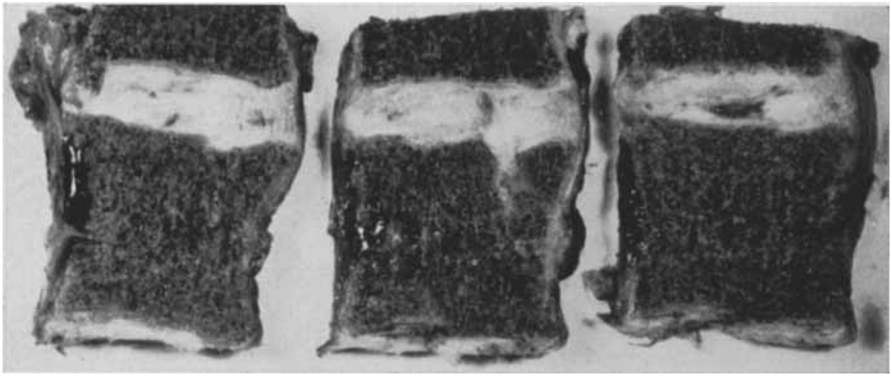


Fig. 18. Disc between L_2—L_3. Male, 26 years. Breaking-point 750 kp. Specimen sawn longitudinally into slices. The middle slice distinctly shows the disc pulp pressed downwards between the fragment and the vertebral body and the fissure extending to the cortex. The small fragment which represents the ventral portion of the vertebral body is retained in position mainly by the ventral longitudinal ligament. An impression of the size of the fragment can be gained from the slice at the right of the figure; no fracture is visible here.

No end-plate fractures were seen in the ten experiments belonging to the group "over sixty years" while three fractures out of ten experiments were encountered in the group "fifty-one to sixty years". Two of these fractures occurred in the L_1 disc and one in the Th_{12} disc. In the group "forty to fifty years", three fractures were obtained in four experiments, one in the L_2 disc and two at Th_{12}. Seven fractures in sixteen experiments were obtained in the "under forty group". Only one fracture each was obtained in the L_4 and L_3 discs. The discs Th_{12}, L_1, and L_2 in the age groups under sixty years showed twelve end-plate fractures out of eighteen experiments, an incidence of 67 per cent.

The condition of the discs has been assessed macroscopically. Since the specimens were sawn longitudinally, it was difficult to judge the condition of the discs involved in the fractures and consequently, the neighbouring discs were examined. The neighbouring discs were sectioned at right-angles to the longitudinal dimension of the spine. If these were normal and if no definite changes were seen on the cut surface of the fractured disc, this was considered to be normal. It was impossible to assess the fractured disc accurately in nine instances. Of the other specimens, fifteen were normal, six were moderately degenerated, and ten degenerated. In those instances in which fracture of the end-plate occurred, nine of the discs were normal and one was moderately degenerated.

Ten of the fractures obtained in this series were of type I with a central depression and three were of type II with a fractured corner. The fragment was displaced in one case and not in the other two. Even so, it was possible to see that the fissure produced extended to the cortical bone (fig. 18).

Large "Schmorlsche Knorpelknötchen" were detected radiologically in two instances before the experiment was carried out. They remained unchanged. The specimens were able to withstand various pressures. For

Tabell 5. Static stress in three vertebrae and the intervening discs placed in a material-testing apparatus.

	Over 60 years	60—51 years	50—40 years	Under 40 years
$L_5L_4L_3$	$660^{\circ\circ\circ}$ $530^{\circ\circ\circ}$	560	$\underline{350}^{\circ}L_4L_3$ 550° $430^{\circ\circ}$ $\underline{400}^{\circ}L_3$ + 400°	400° $\underline{790}^{\circ}L_4$
$L_3L_2L_1$				$550^{\circ\circ\circ}$
$L_2L_1Th_{12}$	$660^{\circ\circ\circ}$ $530^{\circ\circ\circ}$	450	$\underline{330}^{\circ}L_2$ 450° $\underline{300}^{\circ\circ\circ}L_1Th_{12}$ 480 340°	450° $\underline{650}^{\circ}Th_{12}$
$L_1Th_{12}Th_{11}$	$\underline{240}^{\circ\circ\circ}Th_{12}$ $\underline{940}^{\circ\circ\circ}Th_{12}$			$\underline{460}^{\circ}L_1$

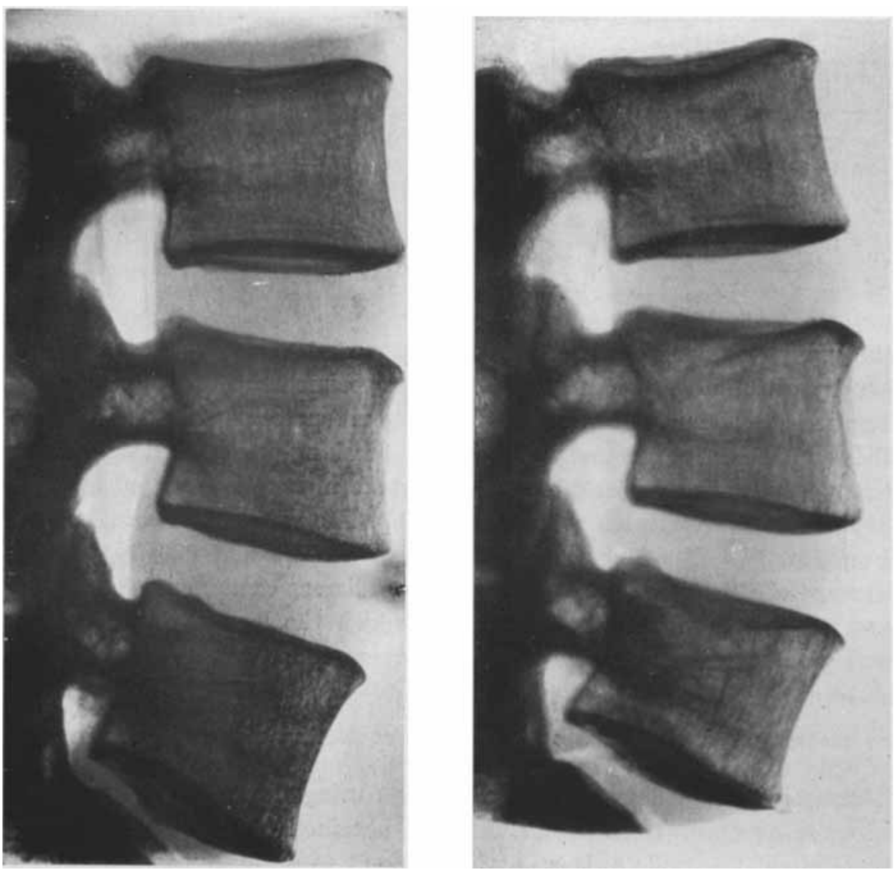
The figures indicate the breaking-points for the specimens.
The underlined figures were obtained for specimens in which end-plate fracture occurred. The vertebrae fractured are indicated after the figures.
$^{\circ}$ = normal disc.
$^{\circ\circ}$ = moderately degenerated disc.
$^{\circ\circ\circ}$ = degenerated disc.
\+ = specimen showing spondylolysis.

the group "over sixty years", the breaking-point varied between 290 and 530 kp with an average of 425 kp for ten specimens from five individuals. The remaining thirty specimens obtained from fourteen different individuals showed distinctly greater variations in breaking-point. For the "under forty" group, the values were on the whole higher and ranged between 510 and 1100 kp with an average of 780 kp. The values for the individuals from forty to fifty-nine years varied between 225 and 680 kp with an average of 435 kp. The resistance of the specimens examined is thus much greater in the "under forty" group in which the lowest value obtained was greater than the averages for the other groups.

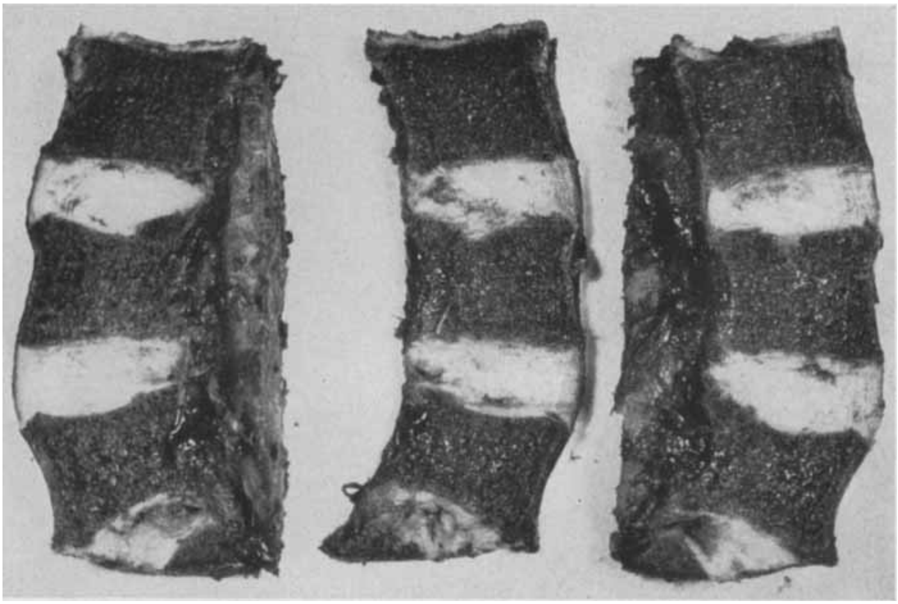
e) Results of experiments on specimens consisting of three vertebrae

Twenty-four experiments were carried out using three vertebrae and the intervening discs. These specimens were obtained from thirteen different individuals. See table 5. It was more difficult to estimate the condition of these discs. Thirteen of twenty-two were considered to be normal, one moderately degenerated, and eight degenerated. All of the discs obtained from individuals over sixty years of age were markedly degenerated. Röntgen plates were made of all the specimens before and after the experiments but as it was necessary to remove the specimens from the material-testing apparatus for this purpose, the plates obtained are not exactly comparable.

Spondylolysis, unchanged after the experiment, was found in one instance. Fracture of the end-plate occurred in ten of these experiments (42 per cent), and in two of the experiments, two end-plates were fractured (fig. 19). Only one of the fractures produced was of type II. This was seen in the spine from an old individual with pronounced disc degeneration and severe spondylosis with complete osseous bridges on the ventral surface. A fissure appeared dorsally in the vertebral body to divide off a fragment. The fragment was not displaced and the disc pulp had not



A B



C

Fig. 19. L_3—L_5. Female, 41 years. Breaking-point 350 kp.

A. Röntgen plate of the specimen before the experiment.

B. Röntgen plate after the experiment. In comparison with A it is possible to see that the cranial end-plate of L_4 has a central depression and a sharp contour has appeared. The L_5 end-plate is also fractured but shows another appearance with an interruption of continuity as the chief finding.

C. Photograph of the sawn specimen. The depressed portion of the L_4 end-plate is clearly seen in the centre slice. The slice to the right shows a depression of the L_5 end-plate giving an appearance similar to that of a fish vertebra. The spongiosa under the end-plate is fractured.

penetrated into the fissure since the disc was quite degenerated (fig. 20). As in the previous series, most of the fractures were seen in the upper lumbar region among younger individuals.

f) Discussion of the Röntgen plates

Discography was performed in all the experiments with dynamic stress and plates were made before and after with the position of the specimens unchanged. In the experiments using static stress, discography was not carried out and the Röntgen plates made before and after the experiments are not strictly comparable since the specimens had to be moved from the laboratory to the radiology department. Among the specimens which were subjected to static stress and of which Röntgen plates were made by these means, end-plate fractures of type I occurred in nine instances

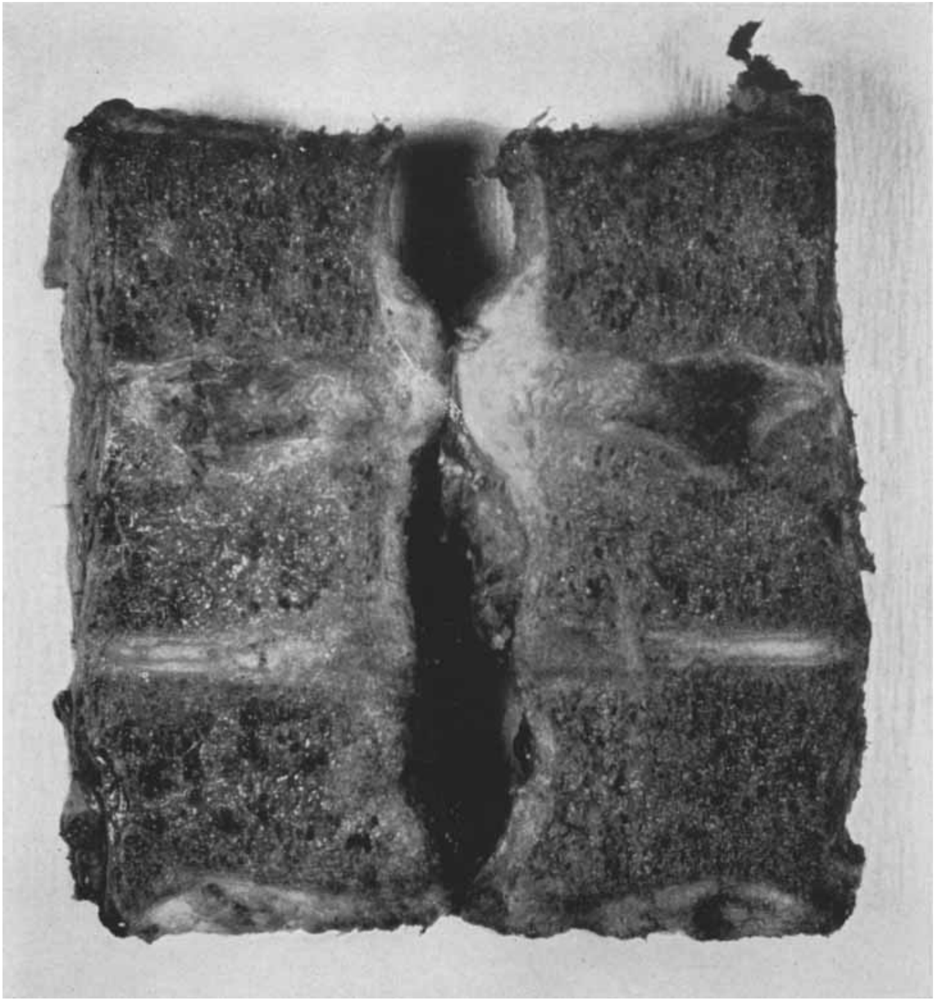


Fig. 20. Photograph of a sawn specimen consisting of Th_{12}, L_1, and L_2 from a sixty-eight-years-old man. Disc L_1—L_2 is very narrow and is bridged over by osseous processes. Disc Th_{12}—L_1 is higher but quite degenerated. The vertebral bodies are united on the ventral side by pronounced overgrowth of connective tissue. In the upper dorsal portion of L_1 is seen a fracture line which divides off a fragment. The degenerated nucleus has not been pressed into the fracture.

and of type II in one specimen. Careful examination of the Röntgen plates for this lesion disclosed the fracture in four instances. It was impossible to determine accurately whether or not fracture had occurred in the other six. In those cases in which discography was not carried out, the fractures were difficult to detect although the plates were made of muscle-free specimens. By placing the specimens in a suitable phantom it would be

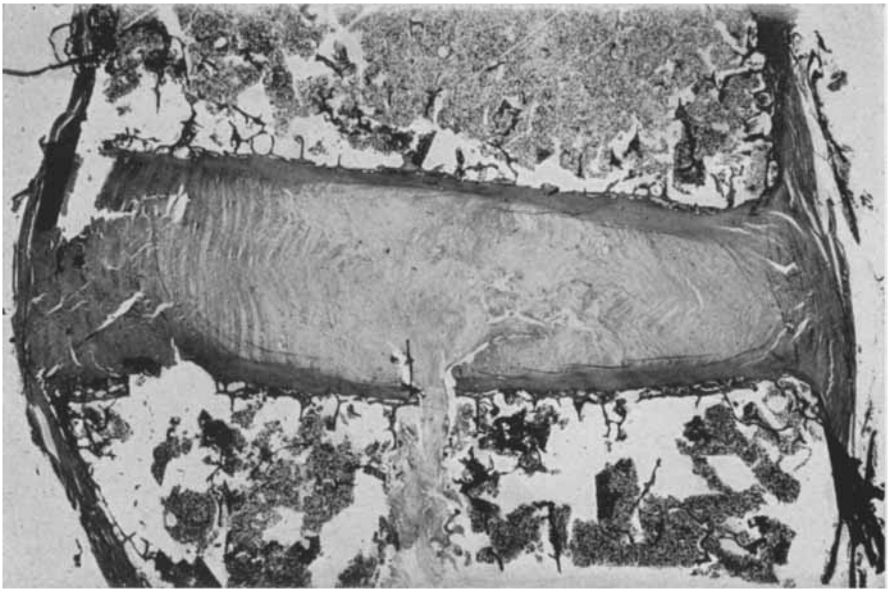


Fig. 21. A centrally-situated, postmortem fracture of the end-plate.

possible to obtain plates which more nearly correspond to natural conditions.

g) Microscopic examination

Microscopic examinations were carried out in order to ascertain that the end-plate fractures which were produced actually occurred post mortem and to check whether or not fissures appeared in the end-plates which were not visible macroscopically.

It seems reasonable to suppose that the lesions observed actually occurred post mortem since it was possible to see how the contrast medium was pressed down during the experiments. The possibility remains, however, that the contrast medium was merely pressed down into previously existing intra vital lesions.

Thirty end-plates were examined of which eight were obtained from specimens subjected to single blows and the remaining twenty-two had been used in the experiments on static stress. Eight of the end-plates displayed fractures and in no instance was there any indication that the end-plate or the underlying spongiosa had been damaged in vivo. The end-plates and the trabeculae of the spongiosa showed sharp broken edges with no traces of haemorrhage or reaction around the lesions (fig. 21 and 22). End-plate fractures were not detected in the other cases in spite of the fact that pressure was applied until the breaking-point was reached.

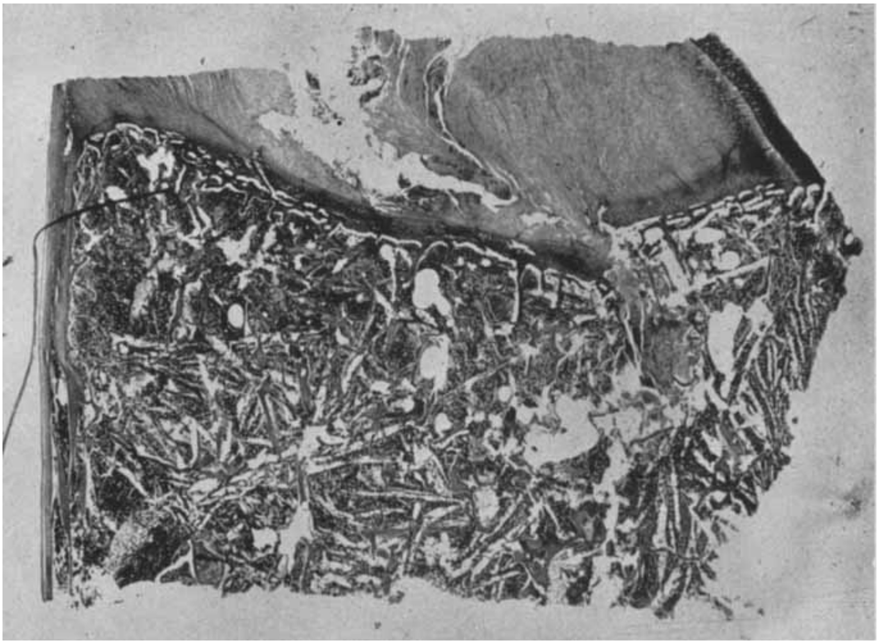


Fig. 22. End-plate fracture, type II. The disc has been pressed into the spongiosa. The entire trabecular structure in this section is fractured.

In his investigations of intraspongious disc herniation, Putschar found that 25 per cent were microscopic. He believed that all such herniations which are smaller than 1 mm are not detectable macroscopically. The absence of any end-plate fractures in the present series which could be detected only upon microscopic examination may depend upon the magnitude of the pressures used having been so great that the disc pulp was pressed down into the fissures in such quantities that it was readily detected macroscopically.

Summary. End-plate fractures of the same types as were obtained by single blows were observed following the application of slowly-increasing pressure to specimens. Fractures were chiefly seen in specimens prepared from the upper lumbar vertebrae obtained from young individuals. Resistance was greatest among the younger age groups. It was often difficult to detect the fractures by means of routine Röntgen plates although only specimens were used. No fractures occurred which could be detected only by microscopic examination.

III. Investigation of the resistance of the vertebral body and the end-plate and calculation of the surface area of the end-plate

In order to analyse the results of the experiments described above, it was necessary to determine the resistance of both the vertebral body and the end-plate.

a) Resistance of the vertebral body

In order to investigate the resistance offerred by the vertebral body to pressure, the arches and discs were removed from fresh specimens leaving only the vertebral bodies with their end-plates. Only vertebrae in which the surfaces of the end-plates were parallel were used. Because of this, it was difficult to obtain suitable specimens, especially of the lower lumbar vertebrae. Those cases in which the end-plates were fractured were not included since this indicated an undesirable straining of the specimen. Eighty-one vertebral bodies were examined of which thirty-one were from seven individuals. All the others were obtained from different individuals since single vertebrae were available from the other experiments. Sixty-two of the eighty-one vertebrae were obtained from subjects under sixty years of age and of these, only fourteen were obtained from individuals less than forty years of age. The range was wide but it was possible to distinguish a distinct difference in resistance between the age groups under and over sixty years of age. Only five vertebrae or 8 per cent of those examined from the younger age groups showed a resistance under 400 kp. Of the nineteen vertebrae belonging to the group over sixty years of age, only one had a resistance greater than 400 kp (diagram I). The following average values for the resistance of the vertebral bodies were obtained.

	Under 60 years kp	Over 60 years kp
L_1	520	270
L_2	600	260
L_3	635	250
L_4	650	270
L_5	590	(240)

The average values suggest that the lower lumbar vertebrae were somewhat stronger than the upper. Diagram 2 reveals a similar tendency in the curves showing the breaking-points for the various vertebral bodies making up single back specimens.

Since the tendency towards weakness shown by the vertebral bodies situated towards L_1 was not pronounced and the range of the whole

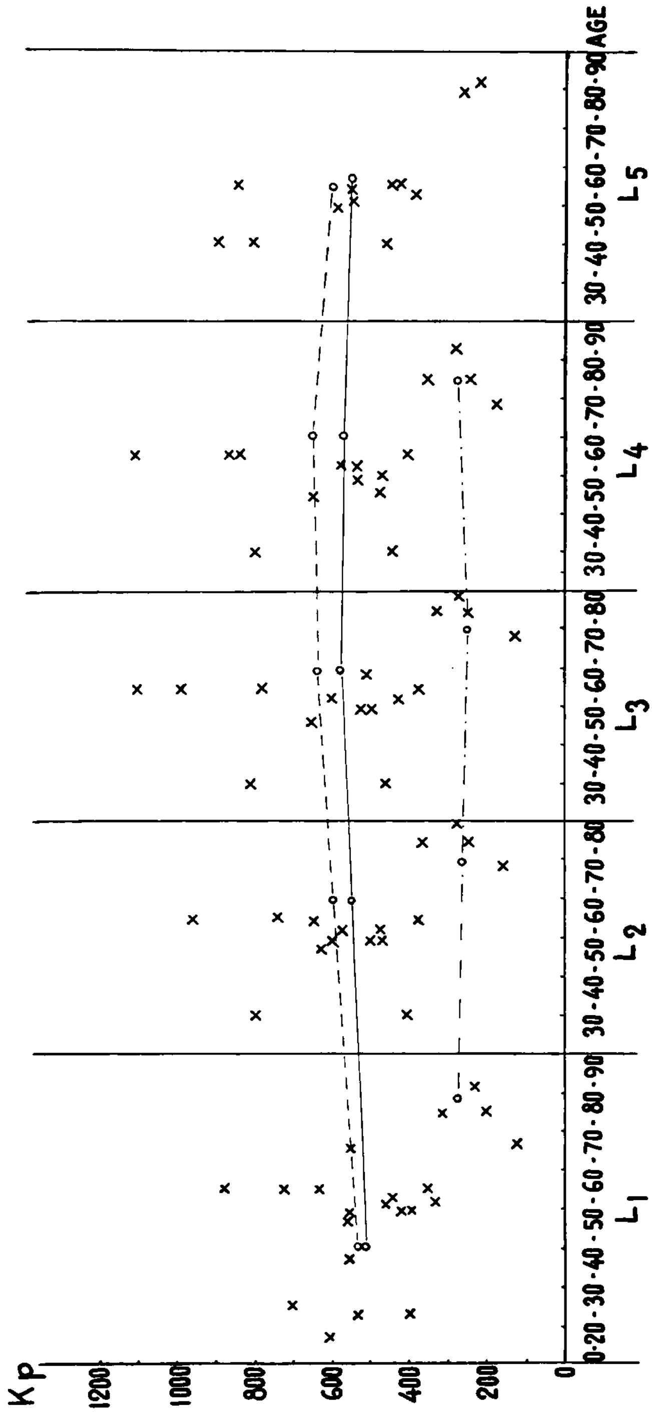


Diagram 1. Resistance of the vertebral body.

— — — — joins the average values obtained for the different lumbar vertebrae in the group under sixty years.

— · — · — joins the medians obtained in the group over sixty years.

———— joins the medians obtained for the different lumbar vertebrae under sixty years.

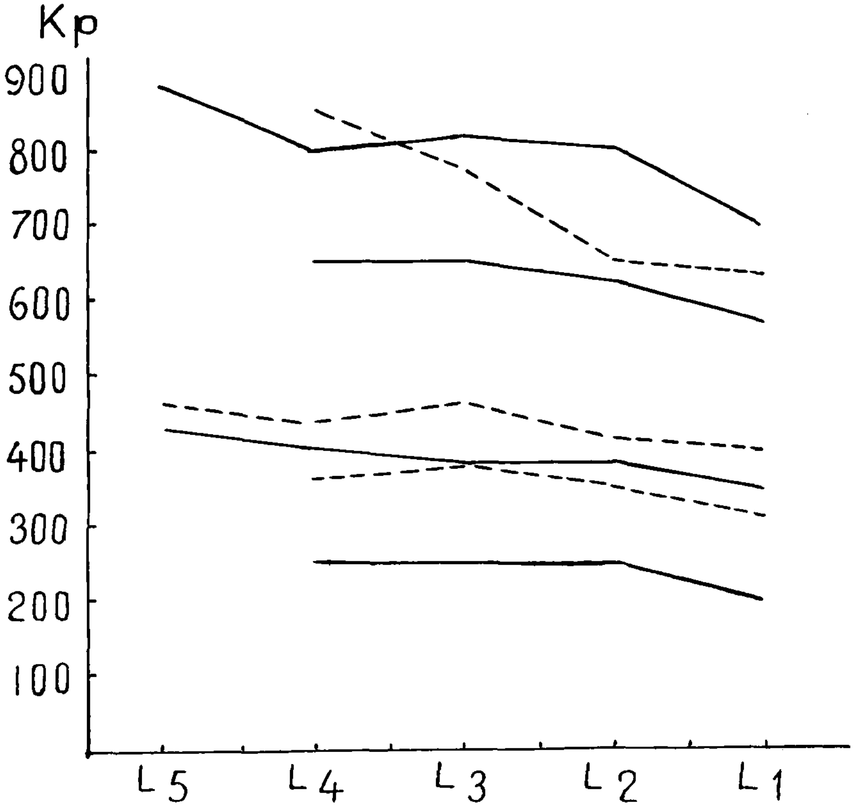


Diagram 2. Each curve indicates the resistance of the different lumbar vertebrae from one specimen.

material was wide, it is possible to calculate the average for the values obtained for all the vertebral bodies under and over sixty years of age. These values are 600 kp and 260 kp respectively. As was mentioned before on page 20, measurement of the resistance gives a curve in which deformation is indicated in relation to the pressure applied. A typical example obtained from a test on vertebral bodies is shown in fig. 23. The portion b gives the extent of compression of the vertebral body by force a. In those cases in which measurements of the height of the vertebral bodies were made (measurement made on the ventral surface), compression has been expressed as a percentage of the original height (table 6). It can be seen that the vertebral bodies were compressed 16 per cent on the average before the breaking-point was reached. The averages for the groups over and under sixty years of age were similar. In spite of great individual variations, the average values for elasticity were similar in all age groups.

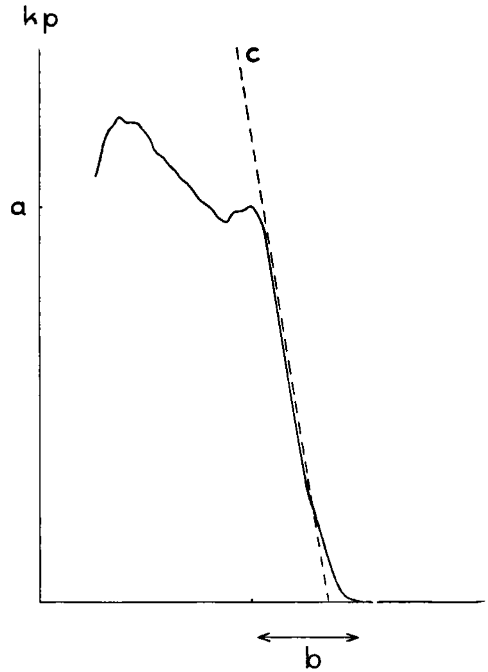


Fig. 23. A typical pressure curve for a vertebral body.
a. Resistance, 460 kp.
b. Maximum compressibility, 16 %.
c. Spring constant, 240 kp/mm.

The spring constant in these experiments has been expressed as kp/mm. This value can be obtained from line c. It was possible to measure the spring constant in only forty-six experiments (thirty-one under and fifteen over sixty years of age). In the remaining instances, the proportional part of the curve was too short to allow accurate determinations of the angle between the curve and the base line to be made. The average value for the spring constant in the group under sixty years of age was 220 and for that over sixty, 100. Since the elasticity in both groups was identical, a similar relationship should exist between the spring constant and the breaking-force. The average value for the breaking-force in the two groups is $600/260 = 2.3$ while the spring constant is 2.2. Although the numbers examined were not great, it can be stated that the values obtained agree so closely with the other mechanical relationships that they can be confidently taken as representing the actual state of affairs.

Table 6. The resistance of vertebral bodies.

	Up to 50 years			51—60 years			61 years and over		
	σ_B	s.c.	max. comp.	σ_B	s.c.	max. comp.	σ_B	s.c.	max. comp.
L_1	530	200		330			310	100	19 %
	550			880	310	16 %	200	70	
	600	150		720	240	17 %	230	90	14 %
	560	170	24 %	640		15 %	550	150	
	410		8 %	450			125		
	550			460					
	400			350	210	17 %			
	700	200	19 %						
	400		20 %						
L_2	630	180	20 %	960	380	16 %	360	140	15 %
	500		13 %	740	250	11 %	250	80	18 %
	600			650		14 %	280	80	16 %
	480			480			155		
	800	300	14 %	580					
	410	170	14 %	380	150	16 %			
L_3	520	140	15 %	990	250	19 %	330	140	17 %
	650	250	17 %	1 000		18 %	250	70	18 %
	510			780		12 %	275	130	14 %
	500			430			135		
	810	280	18 %	600					
	460	260	25 %	370	110	15 %			
L_4	540	140	18 %	870	300	13 %	360	130	19 %
	650	200	18 %	1 110	310	19 %	250	90	16 %
	590			850		16 %	290	100	13 %
	470			540			180		
	800	230	21 %	570					
	450	250	16 %	400	230	16 %			
L_5	590			420			255	70	16 %
	800			840	240	15 %	220	60	21 %
	890	210	20 %	550	140	17 %			
	460	240	16 %	370					
				550					
				430	110	16 %			

σ_B = breaking-point of the vertebral body in kp.

s.c. = spring constant in kp/mm.

max comp. = compression of the vertebral body under maximum pressure expressed as a percentage of the original height of the vertebral body measured on the ventral surface.

b) Resistance of the end-plate

Resistance of the end-plate itself is of great interest in the consideration of fracture of this structure. In addition to knowing the absolute tolerance of this structure for pressure, it is desirable to determine whether or not there are differences between the resistance of the central and the peripheral portions of the end-plate. Many believe that the notochord causes a central weakness while others consider that central weakness is present because of the canals which, during embryonal life, conduct blood vessels from the vertebra to the disc. In order to clarify this point, eighty-one end-plates from Th_{12} to L_5 were investigated at three sites—centrally, laterally, and ventrally. Pressure measurements were made on the material-testing apparatus and the pressure was transmitted to the end-plate by a round, level peg with a surface area of 1 cm^2. The disc tissue was removed and the cartilage-plate was left intact as much as possible. In some instances, it was not possible to examine all the sites as a level surface for the application of the peg could not be obtained. As the range of values in this series as in the previous ones was wide, it has been considered most suitable to express the deviations as a percentage of the value which was obtained for the central portion. The average for the deviations from that value is 4.9 per cent and its standard error is ± 1.8 per cent. This does not support the assumption that there is a difference in the resistance offered by the various portions of the end-plate. The resistance of the central portions has been investigated in two hundred and twenty-three instances including the eighty-one measurements mentioned above divided into the following age groups.

Over sixty years	78	end-plates
51—60	57	,,
41—50	43	,,
31—40	30	,,
20—30	15	,,

The resistance was the same for all the lumbar vertebrae from the same individual but the variations between individuals were great (diagram 3). There was no difference between men and women.

The following average values were obtained for the various age groups.

Age group years	Upper Quartile kp	Median kp	Lower Quartile kp
20—30	130	107	90
31—40	128	98	85
41—50	85	76	69
51—60	104	77	67
over 60	55	43	34

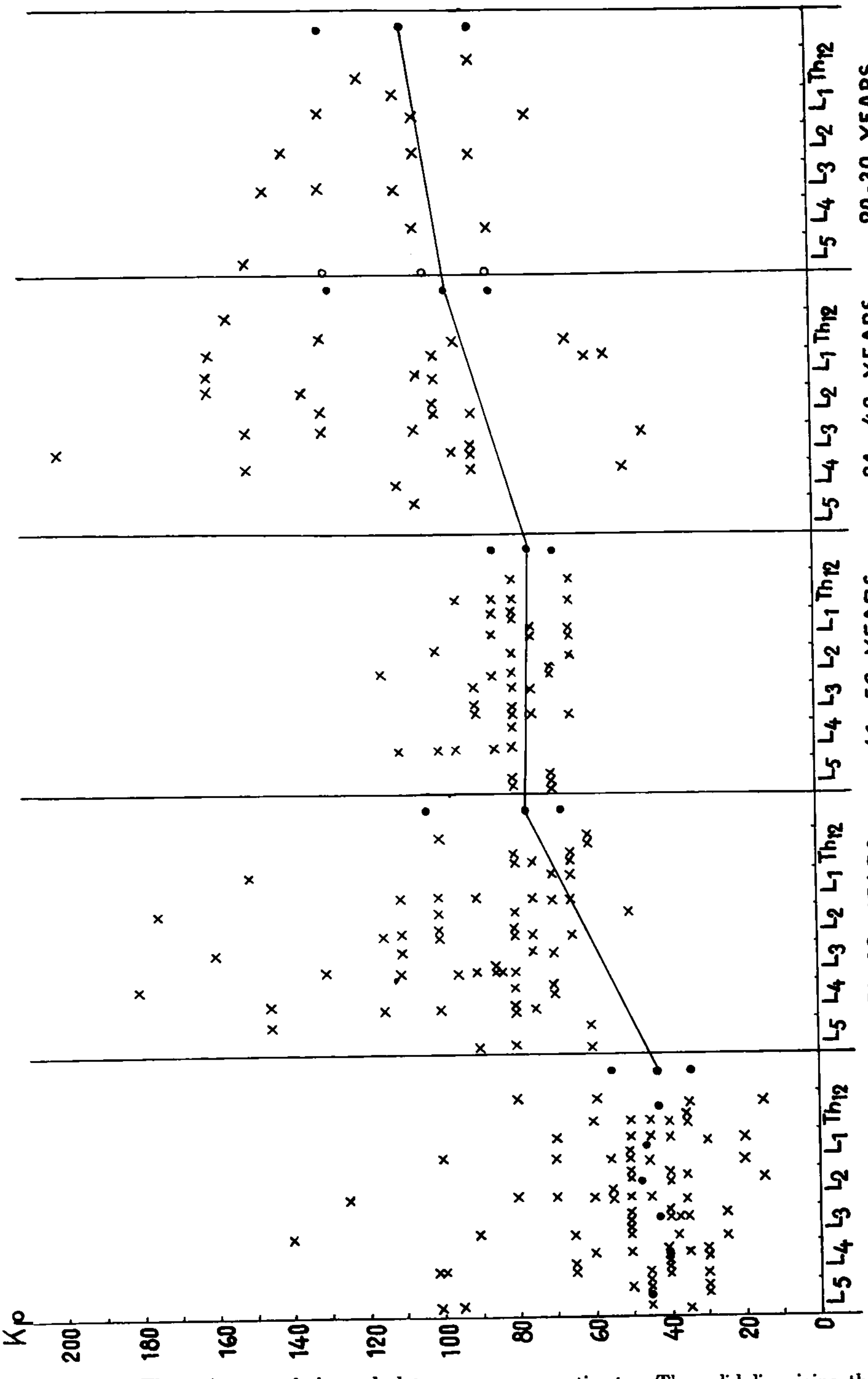


Diagram 3. The resistance of the end-plate per square centimetre. The solid line joins the medians for the different age groups. The median for each vertebra in the group over sixty years is indicated. The other •-signs indicate the upper and lower quartiles. The median and quartiles in the group 20—40 years are given by o-signs.

The value for the median for the forty-one to fifty group was thus reduced by over 25 per cent compared with the two younger age groups. The range within the two younger groups was wide but the mean and the median have practically the same value (109 and 103 respectively) and the range is almost similarly distributed about the median. The median for the group over sixty years of age is 43 kp and the quartiles are 55 and 34 kp. The value for the median in this group is 44 per cent lower than in the next younger group. Although the distribution upwards within the oldest age group is great—the largest value obtained was 140 kp—most of the values were grouped about the lower values so that the upper is 55 kp. Only three measurements among all the younger age groups are less than that value.

It can be seen from these results that the resistance of the end-plates was the same centrally, laterally, and ventrally. On the other hand, the resistance of the end-plates decreased with increasing age so that sixty years of age formed a distinct limit over which the resistance was markedly weakened.

c) Area of the end-plate

The forces applied in the previous experiments have been expressed as absolute values and not in relationship to the area of the specimens examined as is customary. It is also of significance to know the area for both the disc and that portion of the nucleus which abuts onto the end-plate in order to understand how a force is transmitted from one vertebra to another by the disc.

The average size of the lumbar discs was obtained by photographing one hundred and eighty-eight discs beside a scale so that the area could easily be calculated (diagram 4). It was seen that L_4 and L_5 were approximately the same size, 18 and 17.8 cm^2 respectively, L_3 was 16.3 cm^2, L_2 15.8 cm^2, and L_1 14.3 cm^2. The distal surface of each vertebra was used.

It proved difficult to measure the surface of the nucleus since there is no sharply demarcated border between the annulus and the nucleus in mature individuals. Measurement of the normal nucleus was made by following the border between the lamellae of the annulus and the bulging part of the nucleus. Forty-four of the one hundred and eighty-eight discs photographed showed little or no degeneration. The nucleus was measured in these discs and was found to occupy 26 per cent of the surface of the entire disc on the average.

Summary. The average value for the resistance of the lumbar vertebral bodies described in this section was 600 kp for the group under sixty years of age and 260 kp for the group over sixty.

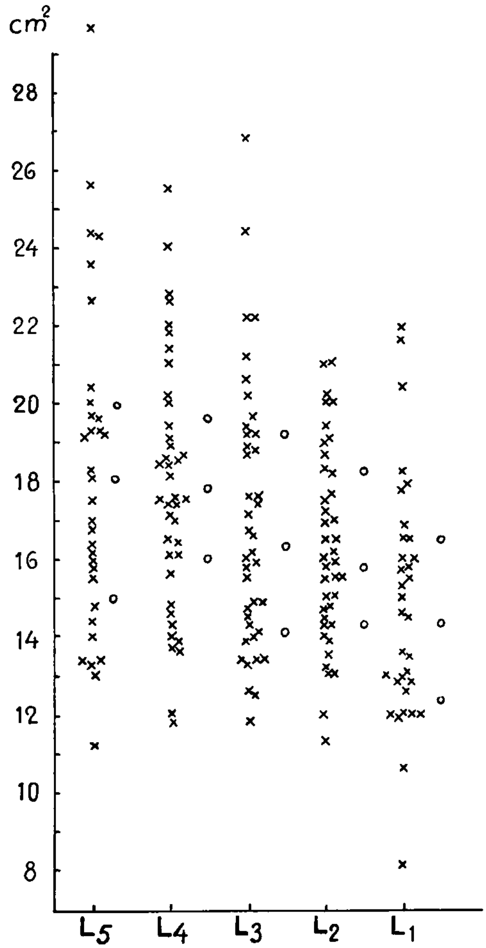


Diagram 4. The area of the end-plates of the various lumbar discs expressed in square centimetres. The medians and the upper and lower quartiles are indicated by o-signs.

No statistically significant difference between the resistance of the central, lateral, and vertral portions of the end-plate could be demonstrated. The median value for the resistance per square centimetre of the age group twenty to thirty years was 109 kp and for the over-sixty group, 43 kp.

IV. Pathogenesis of end-plate fractures

The distinction has been made earlier between the fractures which are situated in the central portions of the end-plate and those which lie peripherally. It is most likely that these lesions develop differently.

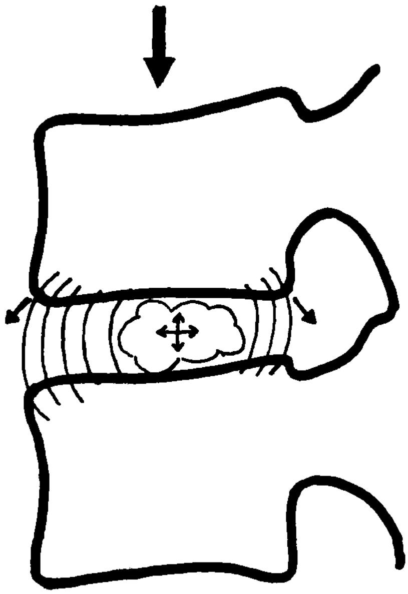


Fig. 24. In a normal disc, pressure is transferred from the upper vertebra to the lower partly by the annulus and partly by the nucleus. The internal disc pressure is distributed hydrostatically to the annulus and end-plate. In a degenerated disc, the moisture content has decreased and consequently a greater proportion of the pressure is taken up by the annulus.

Fractures which are situated centrally in the end-plate probably result from an increase of pressure within the disc. That such pressure increase actually occurs is shown by fig. 6 in which the nucleus was pressed out through an injection canal. Using degenerated discs from osteodystrophic dogs, Olsson has demonstrated that if the pressure between two vertebrae is increased, the mineralised nucleur pulp can be forced out through a fine rupture.

A normal disc transfers pressure partly by the annulus and partly by the nucleus. The nucleus is enclosed within a space with the annulus and the bordering end-plates forming the walls (fig. 24). It has been demonstrated in the present experiments that the annulus does not rupture following the application of force but rather that it is the end-plate which forms the weak point of this wall. In the eleven experiments in which end-plate fractures of types I and II were obtained using a static force, the surface area of the disc and the nucleus as well as the resistance per square centimetre of the upper end-plate of the specimens were measured. It was shown earlier that the resistance of the central portions of the end-plate was approximately the same for all the lumbar vertebrae from one individual. It was thus possible to determine the approximate resistance

Table 7.

Expt.	Area* of the disc, cm^2	Area* of the nucleus in %	Area* of the nucleus in cm^2	Resistance of the end-plate in kp/cm^2	Theoretical value for fraucture, kp	Registred value for fraucture, kp	Type of fracture	Deviation in % from the registred value
211	11	34	3.8	55	205	230	I	— 11
212	13	25	3.3	50	165	340	II	
213	15.8	26	4.1	65	267	250	I	7
216	17.5	23	4.1	130	533	870	II	
217	16 8	28	4.7	160	752	800	I	— 6
220	22.3	25	5 5	130	715	750	I	— 5
221	16.5	34	5.7	100	570	610	I	— 7
223	17.4	35	6.1	90	550	575	I	— 4
226	15.5	35	5.4	100	540	575	I	— 6
229	15.8	29	4.6	100	460	470	I	— 5
230	14.8	25	3.7	75	275	220	I	25

* Area of the surface abutting upon the end-plate.

of that portion of the end-plate which borders onto the nucleus. This theoretical value agrees well with the values obtained by experiment (table 7). In all but two of the cases of type I fracture, the deviation has been less than 10 per cent.

Type II fractures, on the other hand, arise by quite other means. When the moisture content of the nucleus is low, the entire pressure is transferred by the annulus via Sharpey's fibres so that strain arises towards the periphery of the vertebral body. If the strain becomes too great, the portion of osseous tissue which serves as anchorage for the fibres is torn loose.

A central fracture of the end-plate is most likely to arise when the disc is normal and the resistance of the vertebral body greater than the maximum pressure within the disc. Both the resistance of the vertebral body and the resistance of the end-plate per square centimetre surface area have been investigated in sixty-three instances. If it is assumed that 26 per cent of the entire surface area of the end-plate is occupied by the nucleus, it can be estimated that the resistance of that portion of the end-plate was greater than the resistance of the entire vertebral body in only two instances and that in an additional three instances, the resistance of the end-plate approached that of the vertebral body so closely that the difference was less than 10 per cent. If, on the other hand, the surface area of the nucleus is assumed to be 30 per cent of the entire end-plate, the resistance of that portion of the end-plate exceeds that of the vertebral body in seven instances. An additional five instances show a breaking-point closely agreeing with that obtained for the vertebral body with the difference being less than 10 per cent. It was impossible to arrive at exact values since the border between the nucleus and the annulus is diffuse. Two values have consequently been taken as examples. It can thus be stated that the vertebral body in most cases was stronger than the end-plate. If the moisture content of the nucleus decreases as it does with increasing age and degeneration, the mechanical relationships within the disc are altered. Increasing the pressure applied to a vertebral body will not correspondingly increase the internal disc pressure. Consequently, the end-plate will not be subjected to such great pressure centrally that it fractures.

V. Discussion

a) Critical examination of the experimental work

Since it is very difficult to reconstruct a biomechanical phenomenon, an experimental investigation of this type always involves a number of complicating factors which are not encountered in reality. During the dynamic tests, a force was applied to a small portion of the spine fastened to an inanimate support. It proved technically impossible to use larger specimens because of limitations of the photographic field. The inanimate support could easily have been eliminated but in that case, it would have been impossible to follow the course of events radiologically from unaltered positions.

In the experiments with static loads, larger specimens, even complete lumbar spines, could have been exposed to the effects of stress. Such long specimens, however, would always be subjected to a combination of compression, buckling, and twisting. These disturbances would not have any relationship with actual conditions since the normal muscular support was missing. In addition, the measurements and curves obtained would not have given any information which could have been related to the vertebral bodies and discs.

Temperature and moisture content greatly influence the mechanical properties of the specimens as has been shown by Rauber and Evans. They mechanically investigated sections of long bones under various temperature and moisture conditions. The experiments described in the present studies were carried out at room temperature (20—22° C) and dehydration was prevented during the course of the experiments by covering the specimens with moist towels. Between the time of removal in the autopsy room and the carrying-out of the experiments, the specimens were placed in plastic bags.

Göcke wrote that an injury occurred in cells through irritation caused by exceeding a certain threshold value for pressure. Bone cells also have such a threshold value for pressure and when this is exceeded, they lose their vitality. The difficulty in determining this limit lies in the latent period following the application of external force during which no immediate damage can be seen. Göcke believes that a disturbance of the cristal-colloid relationship occurs within the cell during the latent period and it is physical consequences of this disturbance which can be recognised.

Lange believes that the mechanical properties depend to a great extent upon the spaces in the spongy bone being filled by a protein solution which exerts hydraulic force on the spongiosa trabeculae when pressure is applied. After death, the fluid in the spongy tissue has a different osmotic pressure which varies from individual to individual.

It is impossible to measure the significance of these two factors and there are no means by which to eliminate these sources of error.

b) Comparison with previous biomechanical investigations

The resistance of the vertebral body has been investigated by Messerer, Göcke, Rauber, and Ruff. Their published values are given in table 8. Since Messerer measured the resistance of the vertebral body by the same means used in the present investigation, his values and those given here are entirely comparable. These two series show good agreement in the values obtained for resistance. Göcke's experiments were chiefly concerned with the mechanical changes within the vertebral body due to exhaustion. Two of the values given by him were obtained without previous exhaustion. In addition, Göcke states that the breaking-point for the lumbar region as a whole is 57—70 kg/cm^2 without giving an average value for the surface area of the vertebral body. He writes only that "entire vertebrae from the lumbar region of different age groups have been investigated". Rauber was chiefly concerned with the effects of temperature, moisture content, and age on the biomechanical properties and gives only one value for a lumbar vertebra without any more details. Vertebrae from individuals who died in an accident or after a short illness were examined by Ruff. His specimens consisted not only of the vertebrae to be examined but also both the neighbouring discs and portions of the adjacent vertebrae. Thus it is not possible to compare his investigations with those described here.

Discs have been generally considered to serve as shock-absorbers and joints. A surprising aspect of the shock-absorbing effect was revealed by the lack of any distinct difference between the values obtained for the pressure-deformation curves for single vertebrae and those for two vertebrae with the intervening disc. It was noteworthy, on the other hand, that the vertebral body alone had a great elasticity. During compression to

Table 8.

Author	Sex	Age	Th_{12}	L_1	L_2	L_3	L_4	L_5	Area	Compression
Messerer, O	M	56	375	400	425	350	400	425	—	
	F	25	—	620	—	—	—	—	11.1	
	F	25	—	—	—	—	—	740	11.6	
	M	30	—	1 000	—	—	—	—	12.7	
	M	50	—	—	—	—	—	975	12.5	
	F	34	—	—	—	—	800	—	12.9	
	F	51	—	540	—	—	—	—	8	
	F	51	—	—	—	—	—	560	9.3	
	M	56	—	400	—	—	—	—	12.5	
	M	56	—	—	—	—	400	—	12.3	
	M	56	—	—	—	—	—	425	12.6	
	F	80	—	—	—	—	250	—	11.2	
	F	81	—	240	—	—	—	—	9	
Göcke, C	M	35	1 050	—	—	—	—	—	—	—
			720	—	—	—	—	—	—	15 % (4.5/30 mm)
			57—70 kg/cm²						—	12.8—21.3 %
Rauber, A			0.84 kg/mm² = 1,260 kg						15.0	
Ruff, S		19	—	720	—	900	—	—		
		21	900	—	990	—	—	1 020		
		21	690	840	—	—	—	—		
		33	800	—	800	—	1 100	—		
		38	800	—	830	—	900	—		
		43	—	900	—	940	—	1 000		
		44	—	800	—	—	950	—		
		46	—	800	—	1 100	—	1 200		

the breaking-point, the average deformation was sixteen per cent, a compression of four to five millimetres for the lumbar region. As can be seen from fig. 23, there is a rounding-off of the first portion of the curve which indicates that a very small force gives a relatively large compression. The curve soon bends and enters the proportional part. Thus, the spring constant cannot be used for the estimation of small forces. The spring constant for the specimens under sixty years of age was 220 which means that 220 kp were required to compress the vertebral body by 1 mm. From the curve it can be seen that a pressure of 100 kp compresses the vertebral body by 1 to 1.5 mm. In his investigations of the effects of static pressure on discs, Hirsch found that a load of 100 kp compressed the disc by

1.3 mm. This would seem to indicate that the elasticity of the disc and the vertebral body is similar. Virgin has obtained values from compression experiments which lie somewhat lower, not quite 1 mm with 100 kp.

The elasticity curves also indicate that the vertebral body is not a unit but rather a construction. This means that if a trabecular system should fracture, a new body with new mechanical properties has appeared from a mechanical point of view.

If the annulus is entire, its elastic limits cannot be exceeded without the appearance of a vertebral fracture (Bürkle de la Camp, Friberg, Mayr, Ellis and others). Hansen and Olsson have carried out experiments on dogs and found that after a single trauma, vertebral fracture occurs twice as often as disc rupture.

It was impossible to detect new fissures in the disc arising after the trauma applied during the present series of dynamic investigations. Dorsal disc herniation did not occur in any instance during the static experiments although the forces applied always reached the breaking-point. These results agree with the opinion advanced by, among others, Friberg, Ghormley, Waldenström, and Wiberg, that trauma seldom causes disc herniation. Others believe that disc herniation often or practically always arises from a trauma (Barr, Cloward, Granthan & Spurling, Lewin, and Love & Camp). Several of these writers define trauma and use the word in its widest sense and also state that single, severe trauma can seldom be considered as the cause. From the point of veiw of insurance—and the definition of trauma which was given in the introduction—most writers share the opinion that disc herniation in general is not caused by trauma and this clinical observation is supported by the present experimental investigations.

c) End-plate fractures from a clinical point of view

Central fractures of the end-plate have been experimentally produced in a significant number of instances during the present investigations. Taking fig. 4 c or fig. 7 as examples, it seems likely that if these injuries had occurred in a living person, a connective-tissue wall would have been formed around the depressed disc pulp and that this would be later ossified. In other words, a picture resembling a Knorpelknötchen would be produced. If this assumption is correct, it would be equally correct to assume that a number of intraspongious disc herniations are traumatic in origin. It was shown in the historical survey that a traumatic origin for these formations was proposed but since no convincing evidence for this was presented, interest in the theory declined. The intraspongious disc herniations of Schmorl were subsequently considered to lack clinical importance and largely ignored. Only a few cases of recent fracture of the end-plate have been published and these were described only in passing.

Cloward & Buzaid have published a case of end-plate fracture in which the diagnosis was made by discography. The subject, a fifty-two-years-old man, complained of lumbago following a heavy lift. This patient also showed a moderate osteoporosis. The end-plate fracture, not detectable on the routine Röntgen plates, was assumed by the writers to be the result of the injury. Congenital weakness of the cartilage plate was discussed as a possible predisposing factor. The writers made the general comment on end-plate fractures that the diagnosis must be based on the discographic findings. Because of the thickness of the vertebral body and the absence of sclerotic borders around the nodule, they can neither be demonstrated nor identified on routine Röntgen plates.

With the aid of Röntgen plates and photographs of specimens, Lob has shown how the entire disc is damaged in a number of vertebral fractures. On the basis of his experimental work on the production of vertebral fractures. Lob has come to the opinion that these arise through an expansive action of the nucleus.

Brailsford has published a Röntgen plate from his series of ten thousand patients with back pain which shows a distinct fracture of the end-plate with the legend "osteoporosis of the spine associated with expansion of the disc. Female, sixty-four years old."

It can be concluded that isolated cases of end-plate fracture occur but that they are seldom diagnosed because of the difficulty of demonstrating them radiologically. As was pointed out above, the establishment of the diagnosis is made easier by the use of discography. Although this is a reliable means of establishing the diagnosis, its risks cannot be ignored. Tomography is a more desirable diagnostic method from the point of view of the patient. The image obtained on a routine Röntgen plate represents the sum of the two outer compact layers and the intervening spongiosa. This means that a lesion within the vertebral body is not necessarily visible as long as the compact tissues are intact. It is difficult to detect a lesion 20 mm in diameter on a routine plate, but a lesion of 15 mm is readily seen on tomographic plates (Ardran, Bokström, Knutsson, Moore, and Watson).

Weinbren has carried out detailed tomographic studies of the vertebral column with special attention devoted to fractures and noticed that end-plate fractures often occurred in association with compression fractures. He believes that fifty per cent of fractures in the vertebral column are multiple. "Herniation into the body" was distinguished as a special type of fracture by him in 1954. It is his opinion that all patients suspected of having fracture of the vertebral column should be tomographed.

Fig. 25. A compression fracture of the upper anterior portion of L_5 without any reduction in the anterior height of the vertebral body.

Fig. 26. Tomograph of the same case shown in Fig. 25. The entire anterior portion of the upper L_5 end-plate is fractured and depressed by a distance representing one-third of the original height of the vertebral body.

The orthopedic clinic at Karolinska Institute (NBI) accepts cases on a consultation basis. The material is selected and it is, accordingly, impossible to carry out clinical investigations on cases of acute (recent) end-plate fractures. Only four cases have been selected, therefore, to serve as clinical examples of the experimental results.

I. H.P. NBI, mechanic, fifty-two years old. First visit in April 1955 for dull pain in the back. In March 1954, the patient had lifted a part of an automobile and experienced such a severe pain in the lumbar region that he nearly fainted. Pain was intense for two weeks and then successively subsided. At the time of visiting NBI, one year after the accident, he had a moderate degree of pain in the lower lumbar and sacral regions. The pain increased after exertion or after standing or walking more than usual. No sciatica. The patient had continued to work. Only a slightly decreased degree of mobility could be detected by clinical examination. A Röntgen plate showed a consolidated compression fracture in the upper anterior portion of the L_5 vertebral body with depression of the anterior part of the cephalic end-plate. There was no reduction in

Fig. 27. A survey plate on which it is possible to see that the upper anterior corner of Th_{11} is fractured. Th_{12} shows unaltered contours. A shadow forming a line from the upper anterior corner of the vertebral body arouses suspicion of fracture in this vertebra as well.

Fig. 28. Tomograph plate of the same portion shown in fig. 27. A large central defect in Th_{12} can be seen.

height of the vertebral body anteriorly (fig. 25). Tomography shows a fracture in the upper anterior portion of L_5 where the depression is more pronounced centrally than anteriorly. Reduction of the anterior height of the vertebra was a few millimetres at the greatest (fig. 26).

This case illustrates that a heavy lift probably caused a fracture of the end-plate which was visible on a routine Röntgen plate while its great extent was revealed by the tomographic plates.

II. E.A. Fifty-nine-years-old married woman. On 29.1.56 the patient fell onto an icy pavement. The legs slipped out from under the body and she landed upon the tip of the sacrum. Severe pains in the back were immediately noticed. Advised by the treating physician to remain in bed for three weeks. Distinct pain on movement was still felt after nine months.

A routine Röntgen plate revealed a fracture of Th_{10} in its upper anterior portion. Fracture of the Th_{11} end-plate was suspected (fig. 27). Tomography verified the suspicion (fig. 28).

III. B.V. (NBI 2245/55). Thirty-years-old agricultural labourer. On 1.2.55, the patient fell approximately seven metres down a flight of stairs. Admitted to hospital showing back pain, painful and tympanic abdomen, and difficult urination. After twenty days the patient was relatively free from pain and was released. Two months after the accident, the back pains had become so pronounced that the patient was admitted to NBI for examination. Survey Röntgen plates made immediately after the

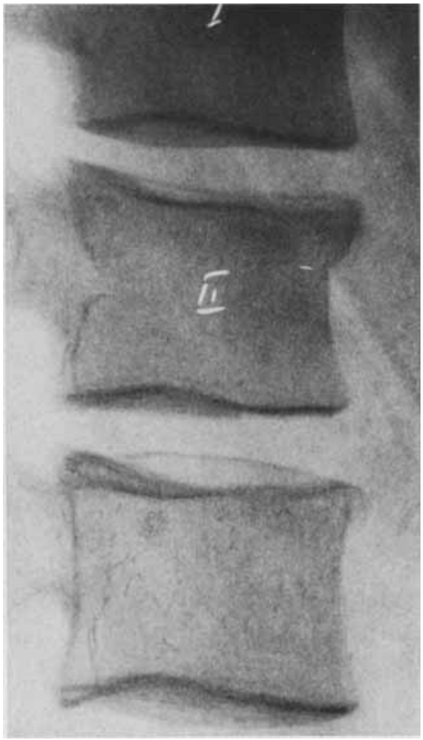


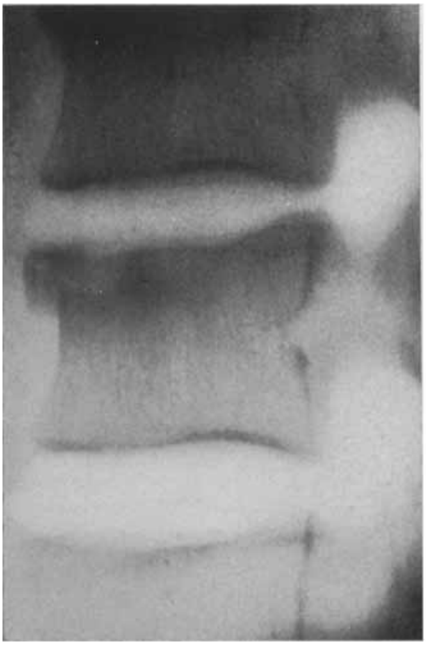
Fig. 29. Survey plate of L_2 and L_3. A fracture can be detected in the upper anterior portion of L_2.

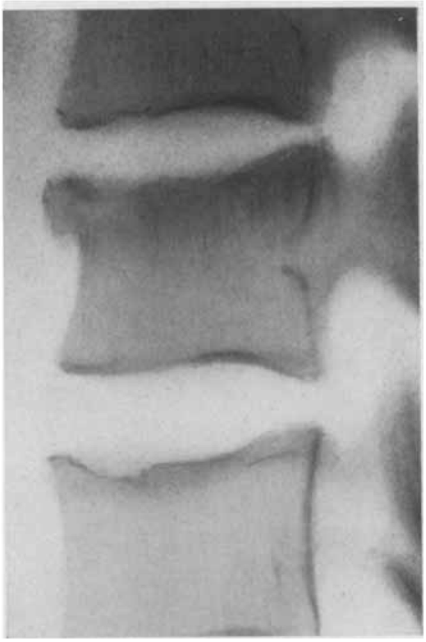
accident showed a fracture of the upper anterior edge of the first and second lumbar vertebrae (fig. 29). Tomography revealed an interruption of the normal contour of the upper end-plate of the third lumbar vertebra over an area 1 cm in diameter (fig. 30, A—C).

In this case, the patient experienced an accident which caused two compression fractures which were visible on the survey Röntgen plate. It is, therefore, quite probable that the interruption of continuity which is seen on the end-plate of the adjacent vertebra is a fracture which occurred at the time of accident.

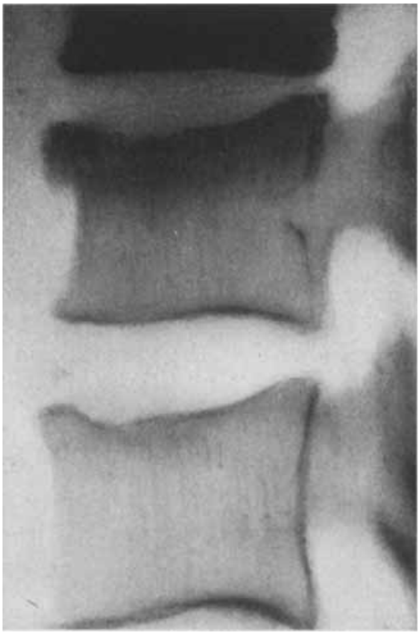
IV.[1] Seventeen-years-old girl, run over and killed by a tram. The entire lumbar and lower thoracic region of the spine was removed at autopsy. Röntgen plates of the spine specimen revealed fractures of the upper anterior corners of L_1 and L_2. No other lesions could be detected on

[1] The Röntgen plates and photograps of this have been kindly placed at my disposal by Professor Knut Lindblom (Karolinska Hospital) and Dr. Sten Erik Olsson (Royal Veterinary College), Stockholm, to be published as a practical illustration of the experimental results.





A B



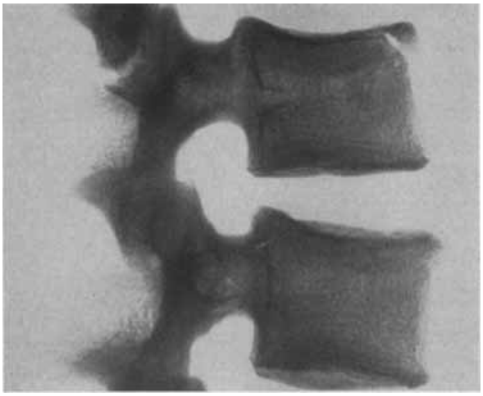
C

Fig. 30. Tomograph of the same case shown in Fig. 29.

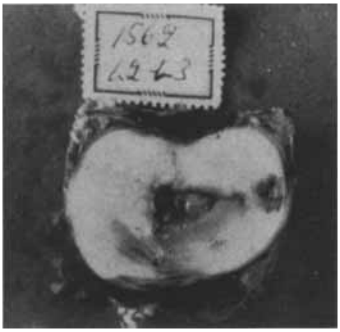
A. 15 cm. deep. Fracture of L_2 visible.

B. 15,5 cm. deep. An interruption of the upper end-plate of L_3 appears.

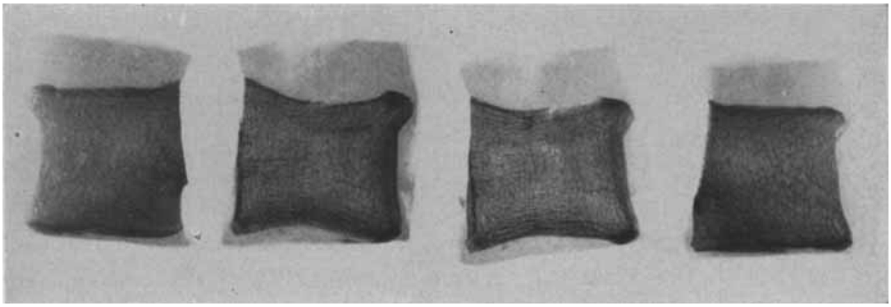
C. 16,5 cm. deep. A definite interruption of the contour of the upper L_3 end-plate is not detectable.



A



B



C

Fig. 31. Female, 17 years old. Killed in a traffic accident.

A. Roentgen plate of the excised specimen consisting of L_2 and L_3. A recent fracture in the upper anterior portion of L_2 is seen; no other skeletal lesions are detectable.

B. Cross-section of the L_2—L_3 disc showing a fresh, central haemorrhage.

C. L_3 sawn into 4 slices. The upper end-plate of the two slices in the middle shows an interruption of continuity which macroscopically appeared to be a quite recent injury.

plates showing L_2 and L_3 (fig. 31 A). Upon sectioning the discs it was found that the disc L_2—L_3 contained a fresh haemorrhage (fig. 31 B). Since the haemorrhage was chiefly central in the disc, it followed that a fracture of the caudal L_2 or the cephalic L_3 end-plate must have occurred. Sectioning of the vertebrae showed a central fracture of the cephalic L_3 end-plate (fig. 31 C).

d) Static stresses

It has been clinically demonstrated that heavy lifting not associated with any form of accident can give rise to vertebral fractures. A mathematical calculation of the weight which can be lifted without risking fracture is impossible since a number of biological factors cannot be taken into account. It is interesting, however, to estimate the magnitude of the forces which act upon the lumbar region through applying accepted mechanical laws. Such calculations have been made earlier by Bradford & Spurling, de Sèze, Waris, and Matthiash who came to the conclusion that there is a great load placed on the lumbar region even in the case of what would appear to be small strains. When lifting a weight with the back bent forwards at an angle of 90°, the pressure on the lower lumbar discs is ten to twenty times greater than the weight lifted. If a man, 180 cm tall, lifts 10 kg with the back bent forwards at 90° and the arms extended straight downwards, the leverage is 10×50 in which 50 is the distance in cm. along the back from the shoulder joint to L_5. With L_5 as fulcrum, this force is chiefly compensated for by the spinal erector muscle. Measurements were made on ten specimens used in the present investigations and the average distance between the centre of the L_5 disc and the approximate centre for m. erector spinae projected onto the spinous process was about 5 cm. In order to balance the weight of 10 kg, a force of 100 kp is required. In addition to this, the upper parts of the body must be supported. In the following calculations the head is considered to belong to the upper body. It is necessary to know where the centre of gravity for the upper body in an erect position is located and this has been roughly established. According to Matthiash, the centre of gravity lies in the vertebral column approximately 5 cm below a line drawn between the shoulder joints. According to the same writer, the weight of the upper body is sixty per cent of the total body weight and Ruff has arrived at the same value. If the man cited as an example is assumed to weigh 75 kg, the upper body weighs 45 kg. The total load placed upon L_5 would in this instance be 505 kp. If he lifted 30 kg instead, the load on L_5 calculated on the same basis would be 705 kp. If similar approximate calculations are carried out on the same subject standing

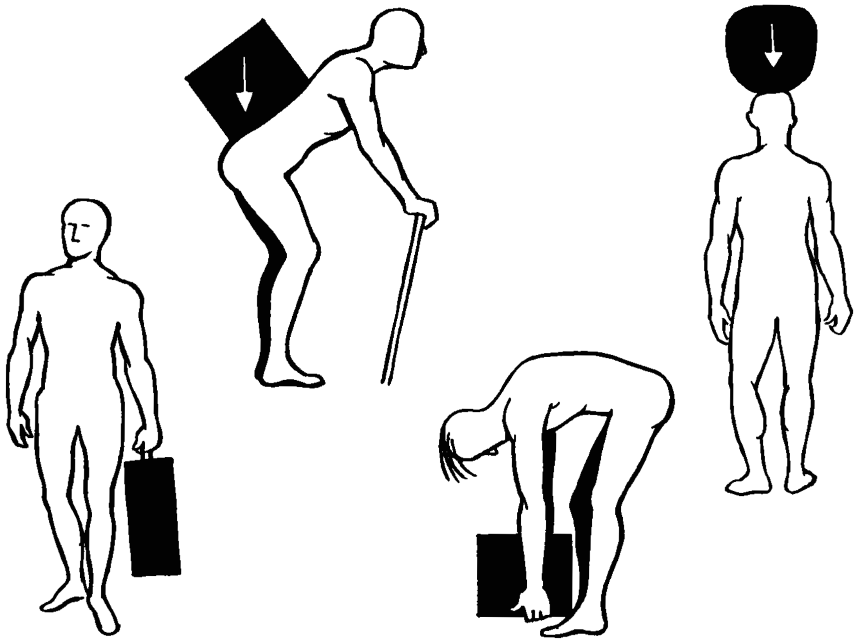


Fig. 32.

and holding a weight of 10 kg in one hand, one portion of the lever is represented by the distance between the shoulder joint and the spinous process or 20 cm. The portion of the lever represented by the muscles is longer since the load is placed on only one side. This would be approximately 10 cm when estimated from anatomic drawings. When the weight of the body is considered together with the load, the combined load will be 75 kp. If this subject were to hold 30 kg in one hand, the pressure would be 135 kp. When the body is deviated laterally so that the shoulder joint of the side bearing the weight is placed vertically over L_5, the lever is shortened and with this, the load. It is naturally better and requires less muscular exertion to carry loads on the head so that the weight comes directly above the centre of gravity. The most satisfactory way of all to carry a burden is to place it on the back so that no weight comes on L_5 (fig. 32).

There is, accordingly, reason to believe that the magnitude of the forces which act upon the lower lumbar spine when lifting an object of ordinary weight is such that fracture of the end-plate can occur.

It seems likely that a number of these end-plate fractures, when healed, have the same radiological appearance as Schmorl's intraspongious disc herniations. It cannot be assumed, however, that all intraspongious disc herniations are traumatic.

End-plate fractures may also occur as secondary phenomena in other diseases. In addition to cases of osteoporosis, they have seen in hyperparathyroidism and overdosage with cortisone (Curtiss, Clark & Herndon, Ballin, Bauer, and Funster) and in diseases which give rise to local weakness of the vertebral body such as infections and various types of tumour.

Fracture of the end-plate results in important functional changes within the disc. The nucleus is believed to serve as centre of movement in a young, normal disc (Calvé & Galland) and a vertebra moves in relationship to an adjoining one using the nucleus as a centre. If the nucleus is eliminated from the system, the entire load is placed upon the annulus and the disc serves merely as an elastic tube during movement.

e) Dynamic stresses (Catapult ejection)

de Haven mechanically and mathematically analysed eight accidents in which individuals fell from heights ranging between fifteen and fifty metres. All survived with insignificant injuries. Vertebral fracture occurred in one case in which the estimated speed at landing was 94 km/hour. The acceleration in several of these cases reached 200 g. It is surprising that the human body can be subjected to such fantastic forces without the occurrence of major injuries. In these eight cases, all the factors of significance must have combined favourably.

In dealing with accidents, the forces at work are not very important. The physician has only to determine the nature of the injuries which have occurred and to treat them. In a number of instances, however, individuals are intentionally exposed to forces of a magnitude which can be compared to those of an accident. An example of this is the flyer who escapes from a crashing aircraft by ejection in a catapult seat.

Previously, a flyer could jump from an aircraft without any danger, but with the speeds now reached, such a thing is impossible. The problem was solved by ejecting the flyers from the aircraft so that they rapidly came clear. Even this rescue method has encountered difficulties since it is necessary that the flyer rapidly reaches a point sufficiently far from the aircraft to avoid being entangled in the tail structures.

Various aviation medical institutions have worked intensively on this problem. Through the use of a catapult rail along which a person can be propelled while sitting in an aircraft seat, it has been possible to obtain measurements during the first rapid and dangerous acceleration. Not only the acceleration of the seat can be measured but also that of various portions of the body. Changes in body position, alterations in circulation and cerebral function, and other details can be studied by this means.

Fig. 33. Flyer in the shield-type of seat. This seat accelerates along a fixed track and is used for training and research purposes.

The results of these investigations cannot, however, be completely applied in practice. It has proved necessary to compromise with the constructor and to a certain extent, with the flyer as well. For example, the seat must be placed so that the flyer can comfortably reach all the instruments and see all the indicators. Since the knees must be placed somewhat under the instrument panel, the seat is ejected backwards at a slight angle. The seat must be so shaped that the flyer can comfortably sit in it for several hours but at the same time it is dangerous if the seat is too soft. The flyer would in this case be subjected to a very dangerous arrest of acceleration when the seat was ejected.

In the faster aircraft nowadays, ejection takes place as follows. The flyer stretches up his arms and using two handles, draws down a shield in front of his face. This shield is fastened to the seat and prevents the head of the flyer from dipping forwards during the rapid acceleration and also serves as a necessary protection against the great air pressure during ejection. At the same time as the shield is drawn down, the roof hatch is opened and the first charge which ejects the seat is detonated. Immediately after this, a second charge explodes. A great initial acceleration is avoided by these means. Ejection takes place with the flyer sitting in the seat with the head relatively stabilised between the back of the seat and the shield, the arms outstretched, and the hands gripping two sturdy handles (fig. 33).

In aviation medicine, a distinction is made between prolonged and short acceleration. By definition, a prolonged acceleration is associated with changes in circulation and respiration and requires about one second. The short acceleration does not cause any changes up to that point where mechanical ruptures occur in the tissues which are especially exposed to extreme strain. The problems associated with short, vertical acceleration are mainly orthopedic problems concerning the back according to Watts et al. Acceleration first affects the pelvis and from there, the shock is transferred to the back. Pelvic fractures, however, seldom occur and are seen only in 3.2 per cent of all fractures according to Evans & Lissner. Injuries of the vertebral column are much more common. Many of those who have rescued themselves by catapult ejection have received back injuries and several distinctly remember a sensation of pain immediately after ejection.

Watts et al. have described three vertebral fractures which occurred during acceleration to 16—19 g with a short top of 25 g. The limit for human tolerance is stated to be 20 g by Arnes, Sweeney & Savely, Geertz, Glasser on the basis of empirical observations. The German air force established 20—22 g as a maximum during the Second World War but it was considered that a top of 28 g could be tolerated for less than 1/100 sec. Experimental investigations showed that vertebrae could withstand 23—25 g.

The modern types of Swedish catapult seats have a maximum acceleration of approximately 21 g. This high value is reached after approximately 0.07 sec. during which time the seat accelerates from 0 to the maximum at a rate which does exceed 300 g/sec. The acceleration is then held constant at 15 to 20 g. The entire acceleration takes place over a distance of 90 cm and the ultimate speed is approximately 17 m/sec. or 60 km/hour.

In order to estimate the stresses in the lumbar spine, it is necessary to know the acceleration of the flyer which is not the same as that of the seat (diagram 5). The flyer reaches his maximum acceleration somewhat later than the seat because of the springiness of the seat cushion. The flyer also reaches a greater maximum acceleration for the same reason. Using American and English figures as a guide, the maximum for the flyer will be approximately 25 g in a seat reaching a maximum of 20 g.

It is also necessary to know the weight of the object accelerated, i.e. the flyer, in order to calculate the forces acting during a given acceleration. The force which acts upon the lumbar spine of the flyer depends upon

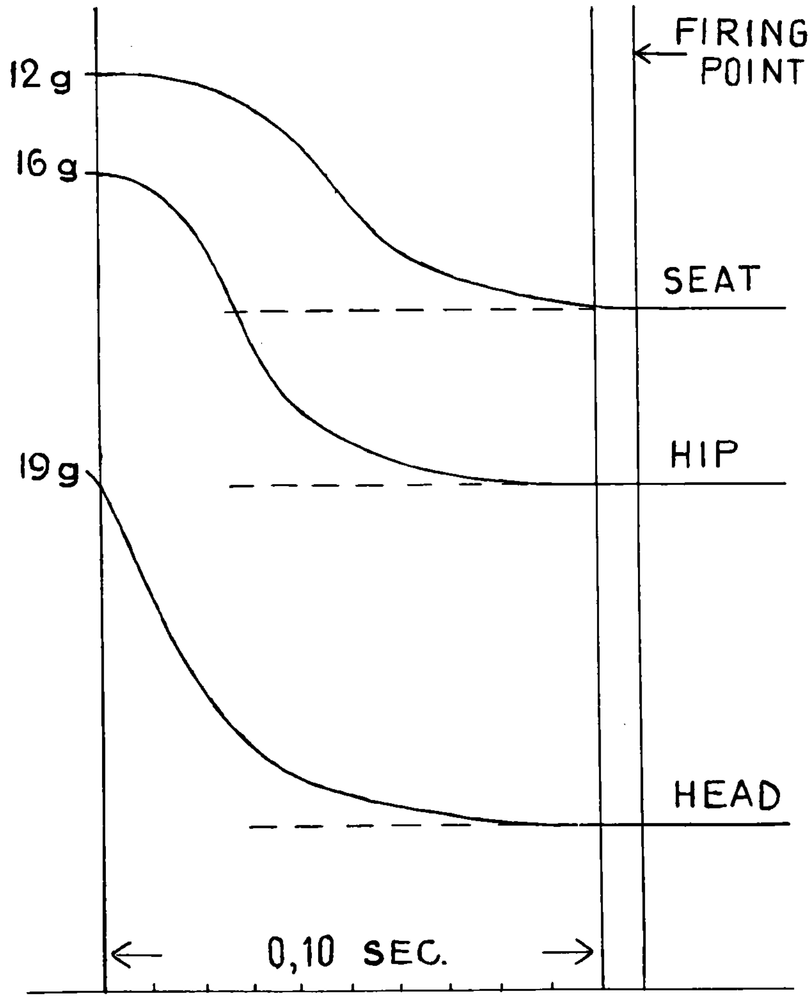


Diagram 5. Schematic reproduction of oscillographic curves showing the acceleration in a catapult ejection seat with face shield. The hip region has a steeper curve and reaches a higher value than the seat.

the weight borne by this region. Such a calculation is quite approximate. Assume that the flyer with flying suit weighs 75 kg. As was described above, the upper body comprises sixty per cent of the total body weight or 45 kg. The weight of the upper body will be somewhat reduced because the flyer grips the two handles in the shield and some of the abdominal organs are depressed into the pelvis. This reduction can be taken as 10 kg. The strain on the lumbar spine is then equal to g $\times$ 35.

Twenty-five g as the maximum acceleration of the flyer means that

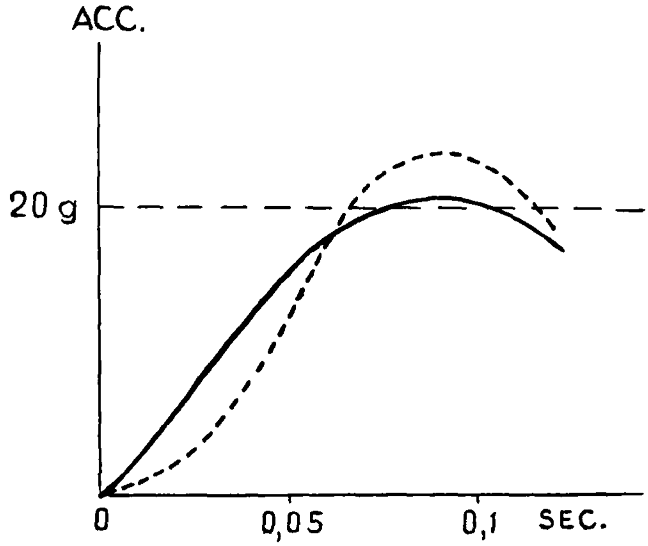


Diagram 6. Approximate relationship between the acceleration of the flyer (broken line) and seat (solid line) during ejection.

the top of the acceleration curve reaches that value and the force exerted by 25 g is effective only during a very short time (diagram 6).

If the effective force acting during a certain time, eg 0.05 sec, is calculated, an average acceleration of 22 g is obtained from the curve given in diagram 6 and thus an average load of 770 kp during that period.

It is known that most materials and constructions are able to withstand greater strain during a short period than they can for a longer period. It is not surprising, therefore, that in the experimental series using dynamic force, fractures of the end-plate occurred in thirty-seven per cent at 1200 kp while fractures occurred in forty-three per cent at 620 kp during the application of static force. (Only the specimens obtained from individuals under sixty years of age are included here.) It is rather difficult to develop the full relationship between the time force was applied and the force required to reach the breaking-point on the basis of these two experimental series. An additional factor is that flyers belong to younger age groups than the specimens which were examined.

Experiments on metals and glass have given certain such associations and a mathematical formula which approximates the results obtained in the present investigations (Broberg).

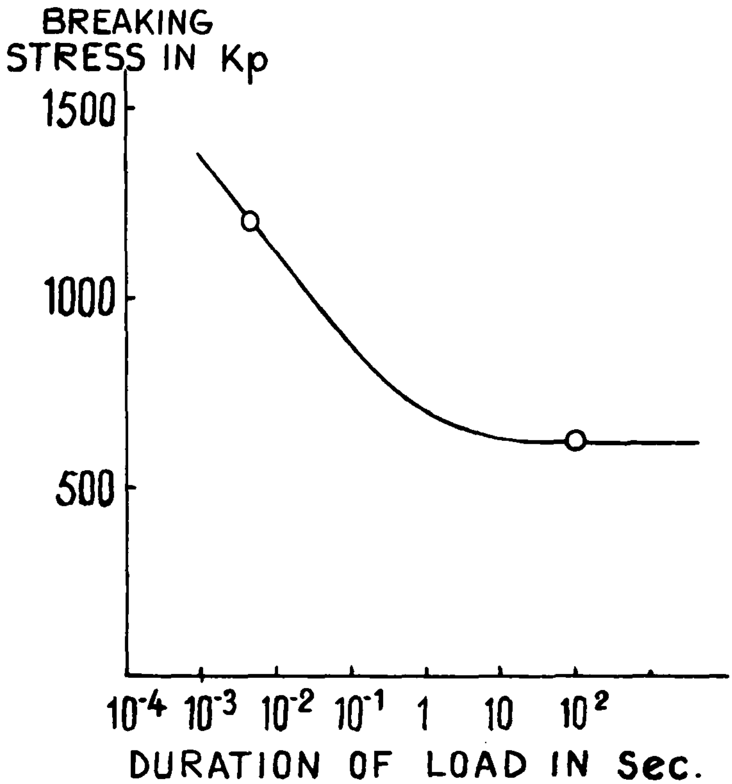


Diagram 7. Approximate resistance of the vertebral body shown in relationship to the duration of the force applied.

$$\sigma_B = \sigma_\infty + \sigma_0 \log (1 + \frac{t_0}{t_B})$$

in which σ_B = breaking-stress under load-time t_B

σ_∞ = » » » t_∞

σ_0 and t_0 are constants for the materials in question.

For the present experiments, it can be assumed that

$$P_B = P_\infty + P_0 \log (1 + \frac{t_0}{t_B})$$

The constants P_0 and t_0 can be estimated from the experiments mentioned for metals and glass. It can be assumed that the mechanical properties of the vertebral body lie somewhere between those of glass and metals. It is possible to use the two experimental results to obtain.

t_B = 6 msec.; P_B = 1200 kp and t_B = 100 sec. P_B = 620 kp.

This estimation gives the approximate results

$$P_0 \approx 260 \text{ kp}$$

$$t_0 \approx 1 \text{ sec.}$$

From this, the relationship between the time during which force is applied and the force required to reach the breaking-point assumes the character shown in diagram 7.

The approximate force which acts upon the lumbar spine during 0.05 sec. was given above as 770 kp. This value is just under the calculated value for maximum pressure. This does not take into account sufficient margin of safety to cover the great biological differences between different individuals. If the flyer neglects to lighten his weight by lifting his arms, he greatly increases the shock and if, in addition, he is wearing heavy clothes, the effective forces rapidly approach the allowable limits.

Summary

Experimental investigations, mainly of a biomechanical nature, have been carried out to establish the nature of the reaction of lumbar vertebrae and their discs to forces applied for different lengths of time.

The *first section* deals with specimens consisting of two vertebrae and the intervening disc which were subjected to a strong force during a short period of time. Stress was etablished within the specimens at right-angles to their cross-sectional dimension. The spaces within the discs have been radiologically visualised by the injection of a contrast medium (discography). Four experimental series were made in which the maximum forces were calculated to be 1050, 1200, 1250, and 1350 kp during approximately 0.006 sec. A total of seventy-six experiments were carried out and the course of events followed radiologically, in some instances by Röntgen plates made at a rate of forty-eight per second and in others, by still plates in conjunction with an image-amplifier.

In no instance did the contrast medium change its position except when simultaneous damage to the vertebral body occurred.

An existing disc herniation was enlarged in one instance.

Compression fractures of the vertebral body occurred in six instances (8 %).

Fracture of the end-plate occurred in twenty instances (26 %). These fractures could be divided into three different types—fractures situated centrally in the end-plate, fractures situated so far peripherally that a portion of the vertebral body was dislodged, and fractures producing transverse fissures extending through the entire end-plate.

These fractures could not always be detected on routine Röntgen plates. Contrast medium was helpful in every instance. Some specimens were tomographed and the end-plate fractures could also be detected by this radiological method.

The *second section* is concerned with the application of static force. Two series of experiments were carried out using specimens consisting of two lumbar vertebrae and the intervening disc and specimens of three lumbar vertebrae with the intervening discs. In some instances the twelfth thoracic vertebra was included in the specimens.

Forty specimens were used in the experimental series on two vertebrae. These were compressed until the breaking-point was reached. The values obtained for the breaking-point varied with age. For the group "over

sixty", the average was 425 kp with a range of 290 to 530 kp. The average for the group "under forty" was 780 kp with a range of 510 to 1100 kp. Macroscopically visible end-plate fractures occurred in thirteen instances or 32 %. When the specimens were classified according to age and the vertebral body which was fractured, it was found that twelve end-plate fractures occurred among the eighteen experiments (67 %) carried out on specimens which included the vertebral bodies from Th_{12} to L_3 from individuals under sixty years of age.

Twenty-four specimens were used in the experimental series using three vertebrae. End-plate fractures occurred in ten instances or 42 %. In two of these ten experiments, two end-plate fractures were obtained in the same specimen. The end-plates bordered onto different discs.

Discography was not carried out in the experiments using static force and the Röntgen plates were not made from exactly the same positions before and after the application of force. Of the ten end-plate fractures which occurred, it was possible to establish the diagnosis radiologically in only four instances.

In the *third section* it was found that the breaking-point for the lumbar vertebrae shows great individual as well as age variations. Eighty-one vertebrae were examined and the average for the group under sixty was 600 kp and over sixty, 260 kp.

The resistance of the central, lateral, and ventral portions of normal end-plates showed no statistical differences in measurements made on eighty-one vertebrae. The resistance of the end-plate centrally was examined on two hundred and twenty-three vertebrae. Individual variations were great. A distinct decrease in resistance was associated with increasing age.

Average values for the age groups

20—30 years	107 kp
31—40 »	98 »
41—50 »	76 »
51—60 »	77 »
over 60 »	43 »

The surface area of the end-plates of one hundred and eighty-eight lumbar vertebrae was calculated and gave the following average values:

L_1	14.3 cm^2
L_2	15.8 »
L_3	16.3 »
L_4	17.8 »
L_5	18.0 »

A normal nucleus in a mature individual occupies twenty-six per cent of the entire surface on the average.

In the *fourth section,* the hypothesis that the central end-plate fractures occur as the result of an increase of pressure within the disc is developed mathematically.

The *fifth section* deals with such practical problems as ejection in a catapult seat from an aircraft. The maximum allowable values for the acceleration of the seat had been calculated earlier on the basis of empirical observations. A curve expressing force in relationship to duration of acceleration has been drawn using the values obtained in the experiments on dynamic and static force. A detailed knowledge of similar curves for glass and metals served as a basis for the construction of this curve.

Résumé

Des recherches expérimentales de caractère principalement biomécanique ont été entreprises afin d'élucider les effets de pressions de plus ou moins longue durée sur les vertèbres et les disques lombaires.

Dans la *première partie,* on étudie les résultats d'une pression violente, mais de courte durée, sur deux vertèbres et disques intermédiaires, produisant dans la préparation un déplacement angulaire par rapport à une coupe transversale du disque. Les porosités internes du disque sont rendues visibles aux rayons X par l'injection d'une solution de contraste (discographie). Quatre séries d'essais ont été faites avec pression maximum estimées à 1050, 1200, 1250 et 1350 kp pendant environ 6/1000e de seconde. En tout, il a été fait 76 essais dont le développement a été radiographié. Dans une partie des cas, la radiographie a été faite sur film cinématographique, avec une vitesse de 48 images par seconde pour certaines des prises de vue. Dans les autres cas, des instantanés ont été pris qui ont ensuite été agrandis pour examen par projection.

Dans aucun des cas, le contraste n'a apporté de modifications sans que le corps de la vertèbre ne se trouve endommagé.

Dans l'un des cas, une rupture de disque déjà existante a été agrandue.

Des fractures dues à la compression du corps de la vertèbre se sont produites dans 6 cas (8 %).

Des fractures de la plaque terminale ont eu lieu dans 20 cas (26 %). Ces fractures ont pu être classifiées en trois groupes déterminés:

a) fractures localisées dans la partie centrale de la plaque terminale;

b) fractures situées dans la périphérie de la plaque terminale et assez proche de la région périphérique pour qu'une pièce s'en détache;

c) fentes à travers toute la plaque.

Ces fractures n'apparaissent pas toujours dans une radiographie d'ensemble, mais dans tous les cas, le contraste donne des indications utiles. Diverses préparations ont été tomographiées et des fractures de la plaque ont pu être constatées par ce procédé radiographique.

Dans la *seconde partie,* il est rendu compte d'essais de pression statique. Deux séries d'essais ont été accomplies. Dans l'une, les préparations consistaient en deux vertèbres lombaires et un disque intermédiaire. Dans l'autre, il s'agissait de trois vertèbres lombaires et disques intermédiaires (dans quelques uns des cas avec le douzième de vertèbre thoracique).

La série d'essais avec préparation comprenant deux vertèbres, 40 préparations ont été étudiées qui ont été comprimées jusqu'au point de rupture. Le coefficient de rupture varie suivant l'âge du sujet. Dans le groupe »au dessous de 60 ans», le coefficient moyen est de 425 kp (variantes: 250—530 kp). Dans le groupe »au dessous de 40 ans», le coefficient moyen était de 780 kp (variantes: 510—1100 kp). Dans toute la série 13 ruptures de plaques terminales visibles à l'œil nu se sont produites (32 %). Si l'on classifie les préparations de cette série d'essais d'après l'âge des sujets ou en tenant compte du corps de la vertèbre fracturée, on constate que 12 fractures de la plaque terminale ont eu lieu dans les 18 essais (67 %) portant sur le groupe au dessous de 60 ans comprenant des vertèbres entre Th_{12} et L_3.

Les séries d'essais portant sur trois vertèbres ont porté sur 24 préparations. Des fractures de plaques terminales se sont produites dans 10 essais (42 %). Dans 2 de ces 10 essais, deux plaques ont été fracturées dans la même préparation. Les plaques terminales touchaient différents disques.

Dans les essais de pression statique, aucune discographie n'a été faite et la préparation n'a pas été radiographiée exactement dans la même position avant et après l'essai de pression. Sur dix préparations dans lesquelles des fractures se sont produites, il n'a été possible de constater la fracture sur image radiographique que dans quatre cas.

Troisième partie. Le point de rupture des vertèbres lombaires n'a pas seulement varié suivant les âges: des différences considérables ont été constatées suivant les individus. 81 vertèbres ont été examinés. Le coefficient moyen de rupture était de 600 kp dans le groupe au dessous de 60 ans et de 260 kp au dessus de cet âge.

Au point de vue statistique, dans des mesures portant sur 81 vertèbres, la plaque normale ne présentait aucune différence de résistance centrale, latérale ou ventrale. La résistance centrale de la plaque a été étudiée sur 233 vertèbres. Les variantes individuelles sont considérables. Il est possible de constater clairement une baisse de la résistance avec l'âge.

Coefficient moyen des groupes

20—30 ans	107 kp
31—40 »	98 »
41—50 »	76 »
51—60 »	77 »
au dessus de 60 »	43 »

La surface des plaques terminales a été calculée pour 188 vertèbres lombaires. Les valeurs moyennes suivantes ont été obtenues:

L_1	14,3 cm^2
L_2	15,8 »
L_3	16,3 »
L_4	17,8 »
L_5	18,0 »

Le nucleus normal chez l'adulte constitue en moyenne 26 % de la surface totale.

Dans la *quatrième partie* il est montré mathématiquement comment il apparait possible que les fractures centrales des plaques se produisent par suite d'une augmentation de la pression interdiscale.

Dans la *cinquième partie,* entre autres sujets, on examine les effets de l'éjection d'un avion par un siège à catapulte. Il a été possible déjà, à l'aide d'observations empiriques, de donner les valeurs maximum permises pour l'accélération du siège. Une courbe enregistrant la pression par rapport à la durée a été établie d'après les valeurs obtenues par des essais de pression dynamique et statique. Cette tâche a été rendue possible grâce à une connaissance détaillée des courbes correspondantes pour le verre et les métaux.

Zusammenfassung

Experimentelle Untersuchungen — hauptsächlich biomechanischer Natur — sind durchgeführt worden, um die Reaktion der Lumbalwirbel und der Lumbalscheiben gegenüber Druck verschiedener Zeitspannen zu untersuchen.

Das *1. Kapitel* beschreibt, wie 2 Wirbel und die zwischenliegende Scheibe kurze Zeit einer starken Belastung ausgesetzt wurden, so dass im Präparat winkelrecht gegen den Scheibendurchschnitt eine Spannung entstand. Die Hohlräume im Inneren der Scheibe wurden mit Hilfe von Kontrastinjektion (Diskographie) sichtbar gemacht. Vier verschiedene Versuchsserien sind durchgeführt worden, wobei die maximalen Kräfte auf 1050, 1200, 1250 und 1350 kp während 6/1000 Sek. berechnet wurden. Insgesamt wurden 76 Versuche ausgeführt, wobei eine Röntgenregistrierung des Versuchsverlaufes vorgenommen wurde — in einigen Fällen mittels Röntgenfilmens (48 Bilder/Sek.), in einigen Fällen mit Hilfe von Stillbildern, wobei der Versuchsverlauf durch einen Bildverstärker verfolgt wurde.

In keinem der Fälle hat das Kontrastmittel seine Lage verändert, ohne dass gleichzeitig ein Wirbelschaden eingetreten ist.

In einem der Fälle wurde ein bereits vorhandener Wirbelzwischenscheibenbruch durch den Versuch vergrössert.

Eine Kompressionsfraktur des Wirbelkörpers ist in 6 Fällen (8 %) aufgetreten.

Eine Fraktur der Schlussplatte ist in 20 Fällen (26 %) eingetroffen. Diese Frakturen kann man in 3 verschiedene Typen einteilen:

a) zentral in der Schlussplatte liegende Fraktur,
b) Fraktur, die so peripheral im Wirbelkörper liegt, dass eine Ecke desselben sich gelöst hat, und
c) eine Spaltung quer durch die ganze Schlussplatte.

Diese Frakturen sind nicht immer auf gewöhnlichen Übersichtsröntgenaufnahmen sichtbar, aber das Kontrastmittel war in sämtlichen Fällen ein guter Wegweiser. Einige Präparate wurden tomografiert, und auch mit dieser Röntgenmethode konnten die Schlussplattenfrakturen erkannt werden.

Im *2. Kapitel* wird ein Versuch mit statischer Belastung beschrieben. Zwei Versuchsserien sind durchgeführt worden. In der ersten Serie bestand das Präparat aus 2 Lumbalwirbeln und der zwischenliegenden Scheibe, während das Präparat in der zweiten Serie aus 3 Lumbalwirbeln und den zwischenliegenden Scheiben bestand. (In einigen Fällen wurde der 12. Thoracalwirbel in das Präparat einbegriffen.)

Die Versuchsserie mit Präparaten, die aus 2 Wirbeln bestanden, umfasste 40 Versuche. Die Präparate wurden zusammengepresst, bis die Bruchgrenze erreicht war. Die Zahlen für den „Bruchpunkt“ variieren mit dem Alter. In der Gruppe „über 60 Jahre“ ist der Durchschnittswert 425 kp (Variation zwischen 290—530 kp.) In der Gruppe „unter 40 Jahren“ lag der Durchschnittswert bei 780 kp .(Variationen zwischen 510—1100 kp.) In der ganzen Serie entstanden 13 makroskopisch sichtbare Schlussplattenfrakturen (32 %). Wenn man das Präparat in dieser Versuchsserie mit Rücksicht auf Alter und darauf, welcher Wirbelkörper gebrochen ist, gruppiert, findet man, dass 12 Schlussplattenfrakturen in den 18 Versuchen (67 %) aufgetreten sind, die mit Präparaten der Altersgruppe „unter 60 Jahren“ und Wirbelkörpern zwischen Th_{12} und L_3 ausgeführt wurden.

Die Versuchsserie mit Präparaten, bestehend aus 3 Wirbeln, umfasste 24 Präparate. Schlussplattenfrakturen entstanden in 10 Versuchen (42 %). In 2 dieser 10 Versuche brachen 2 Schlussplatten in ein und demselben Präparat. Die Schlussplatten grenzten an verschiedene Scheiben.

In den statischen Belastungsversuchen wurde keine Diskographie ausgeführt, und die Präparate wurden nicht in genau der gleichen Projektion vor und nach der Druckbelastung röntgen-photografiert. Unter 10 Präparaten, in denen eine Schlussplattenfraktur entstanden war, war es nur bei 4 möglich, auf der Röntgenaufnahme die Fraktur festzustellen.

3. Kapitel. Der „Bruchpunkt“ im Wirbelkörper variiert nicht nur mit dem Alter, sondern weist auch grosse individuelle Unterschiede auf. 81 Wirbel wurden untersucht. Der Durchschnittswert für den Lumbalwirbel-„Bruchpunkt“ innerhalb der Gruppe „unter 60 Jahren“ war 600 kp und „über 60 Jahre“ 260 kp.

Die normale Schlussplatte zeigte keinen statistischen Unterschied betreffs Haltbarkeit — weder zentral, lateral oder ventral — bei Messungen, ausgeführt an 81 Wirbeln. Die Haltbarkeit der Schlussplatte zentral wurde an 223 Wirbeln untersucht. Die individuellen Unterschiedlichkeiten waren gross. Ein deutliches Nachlassen der Haltbarkeit mit steigendem Alter lag vor.

Altersgruppen — Mittelwert

20—30	Jahre	107 kp
31—40	»	98 »
41—50	»	76 »
51—60	»	77 »
über 60	»	43 »

Die Fläche der Schlussplatte wurde bei 188 Lumbalwirbeln bestimmt, wobei sich folgende Mittelwerte ergaben:

L_1	14,3 cm^2
L_2	15,8 »
L_3	16,3 »
L_4	17,8 »
L_5	18,0 »

Ein normaler Nucleus umfasst bei einem Erwachsenen durchschnittlich 26 % der Gesamtfläche.

Im *4. Kapitel* wird mathematisch gezeigt, dass die zentralen Schlussplattenfrakturen möglicherweise durch eine intradiscale Druckerhöhung entstehen.

Das *5. Kapitel* enthält eine Diskussion im Zusammenhang mit dem „Abschiessen" von Katapultstühlen. Auf Grund von empirischen Beobachtungen hat man bereits Maximalwerte für die Acceleration des Stuhles festgesetzt. Eine Kurve, die die Druck-Kraft im Verhältnis zur Druck-Dauer registriert, ist auf Grund der Werte, die bei dynamischen und statischen Druckversuchen erhalten wurden, zusammengestellt worden. Dies war möglich, da man die entsprechenden Kurven für Glas und Metalle kannte.

References

Alvik, I. Tuberculosis of the spine. Acta chir. Scandinav., suppl. 141, 1948.

Ardran, G. Bone destruction not demonstrable by radiography. Brit. J. Radiol. 24: 107: 1951.

Arnell, S. Myelography with water-soluble contrast. Acta radiol., suppl. 75, 1948.

Arnes, W. H., Sweeney, H. M., Savely, H. E. Human tolerance to acceleration in pilot ejection. Aviation medicine 18: 548: 1947.

Ballin, M. Parathyroidism in reference to orthopedic surgery. J. Bone & Joint Surg. 31: 120: 1933.

Bardeen, Ch. R. The development of the thoracic vertebrae in man. Am. J. Anat. 4: 163: 1905.

— Studies of the development of the human skeleton. Am. J. Anat. 4: 265: 1905.

Barr, J. Sciatica caused by intervertebral disc lesions. J. Bone & Joint Surg. 19: 323: 1937.

Bauer, W. Hyperparathyroidism: a distinct disease entity. J. Bone & Joint Surg. 31: 135: 1933.

Beadle, O. A. The intervertebral discs. Observations on their normal and morbid anatomy in relation to certain spinal deformities. Med. Research Council Special Report Series no. 161, London 1931.

Bokström, I. Principles of vertebral tomography. Acta radiol., suppl. 103, 1953.

Bradford, F. K., Spurling, R. G. The intervertebral disc with special reference to rupture of the annulus fibrosus with herniation of the nucleus pulposus. Springfield. Illinois. Ch. Thomas 1947.

Brailsford, J. Lesions of the intervertebral discs. Brit. J. Radiol. 28: 415: 1955.

Brandes, K. Über die Bedeutung der Schmorlschen Knorpelknötchen und ihnen röntgenologischen Nachweis. Deutsche Ztschr. f. Chir. 231: 361: 1931.

Broberg, K. B. Shock waves in elastic plastic media. Stockholm 1956. (Tekniska Högskolan.)

Broman, I. Människans utveckling före födelsen. Glerup, Lund 1927.

Broman, J. Wirbelsäule und Brustkorb. Grundriss der Entwicklungsgeschichte des Menschen. München-Wiesbaden 1921.

Buisson, Marie. Un caso di ernic discali intraspongiose multiple. Boll. Soc. Piemont. Chir. 4: 245: 1934. Ref. in Zentralbl. f. d. ges. Chir. u. Grenzgeb. 66: 671: 1934.

Bürkle de la Camp, H. Zur Frage der unfallbedingten Entstehung des Bandscheibenschadens. Arch. f. klin. Chir. 267: 479: 1951.

Böhmig, R. Die Blutgefässversorgung der Wirbelbandscheiben das Verhalten des intervertebralen Chordasegments und die Bedeutung beider für die Bandscheibendegeneration zugleich ein Beitrag zur enchondralen Ossification der Wirbelkörper. Arch. f. klin. Chir. 158: 374: 1930.

Böhmig, R., Prévot, R. Vergleichende Untersuchungen zur Pathologie und Röntgenologie der Wirbelsäule. Fortschr. a. d. Geb. d. Röntgenstrahlen 43: 541: 1931.

Calvé, J., Galland, M. Le nucleus pulposus intervertébral, son anatomie, sa physiologie, sa pathologie. Presse méd. 38: 520: 1930.
— Étude clinique de 24 cas de hernies nucléaires vertebrales et de 3 épiphysites. Rev. d'orthop. 17: 723: 1930.
— Physiologie pathologique du mal de Pott. Rev. d'orthop. 17: 5: 1930.
Cloward, R. Anterior herniation of a ruptured lumbar intervertebral disk. A.M.A. Arch. Surg. 64: 457: 1952.
Cloward, R., Buzaid, L. Discography: technique, indications, and evaluation of the normal and abnormal intervertebral disc. Am. J. Roentgenol. 68: 552: 1952.
Code, Ch., Williams, M. D., Baldes, E. J., Ghormley, R. K. Are the intervertebral disks displaced during positive acceleration? J. Aviation Med. 18: 1947.
Compere, E., Keyes, D. Roentgenological studies of the intervertebral disc. Am. J. Roentgenol. 29: 774: 1933.
Coventry, M., Ghormley, R., Kernohan, J. The intervertebral disc: its microscopic anatomy and pathology. Part I. J. Bone & Joint Surg. 43: 105: 1945. Part II. J. Bone & Joint Surg. 43: 233: 1945. Part III. J. Bone & Joint Surg. 43: 460: 1945.
Curtiss, P. H., Clark, W. S., Herndon, Ch. H. Vertebral fractures resulting from prolonged cortisone and corticotropin therapy. J. A.M.A. 156: 467: 1954.
Davis, A. G. Fractures of the spine. J. Bone & Joint Surg. 11: 133: 1929.
— Fractures of spine. Am. J. Surg. 15: 325: 1932.
Dunlop, J., Parker, C. H. Correction of compressed fractures of vertebrae. J. A.M.A. 94: 89: 1930.
— Treatment of compressed and impacted fractures of bodies of vertebrae. Radiology. 17: 228: 1931.
— Correction of compressed and impacted fractures of vertebrae. J. Bone & Joint Surg. 15: 153: 1933.
Eckert, Ch., Decker, A. Pathological studies of intervertebral discs. J Bone & Joint Surg. 29: 447: 1947.
Ellis, J. Compression fractures of vertebral bodies. J. Bone & Joint Surg. 42: 139: 1944.
Elward, J. Motion in the vertebral column. Am. J. Roentegenol. 42: 91: 1939.
Evans, G. Stress and strain in the long bones of the lower extremity. Am. Acad. Orthop. Surg. Instructional Course lectures. 9: 264: 1952.
— Methods of studying the biomechanical significance of bone form. Am. J. Phys. Anthropol. 11: 413: 1953.
— Studies in human biomechanism. An. N.Y. Academy of Sciences. 63: 586: 1955.
Evans, G., Lebow, M. The strength of human compact bone as revealed by engineering technics. Am. J. Surg. 83: 326: 1952.
Evans, G., Lissner, H. R. Studies on pelvic deformations and fractures. Anat. Rec. 121: 141: 1955.
Fick, R. A. Handbuch der Anatomie und Mechanik der Gelenke unter Berücksichtigung der beweglichen Muskeln. Jena 1911.
Friberg, S. Low back and sciatic pain caused by intervertebral disc herniation. Acta chir. Scandinav. suppl. 64, 1941.
— On late results of operative treatment for intervertebral disc prolapses in the lumbar region. Acta chir. Scandinav. 93: 161: 1946.
— Anatomical studies on lumbar disc degeneration. Acta orthop. Scandinav. 17: 224: 1948.
— Lumbar disc degeneration in problem of lumbago sciatica. Bull Hosp. Joint Dis. 15: 1: 1954.

Friberg, S., Hirsch, C. Anatomical and clinical studies on lumbar disc degeneration. Acta orthop. Scandinav. 19: 222: 1949.

Friberg, S., Hult, L. Comparative study of Abrodil myelography and operative findings in low back pain and sciatica. Acta orthop. Scandinav. 20: 303: 1953.

Funster, R. Certain arthritic disturbances associated with parathyroidism. J. Bone & Joint Surg. 31: 112: 1933.

Galland, M. Les hernies nucleaires vertébrales intraspongieuses. Bull. et mém. Soc. Méd. d. hôp. de Paris. 9, 24 mai 1930.

Geertz, A. Grenzen und Sonderprobleme bei der Anwendung von Sitzkatapulten. Doctorate thesis 1944. Techn. Hochschule Stuttgart. Ref. by Glasser, O.

Ghormley, M. An etiologic study of backache and sciatic pain. 5: Congrès de la Société Internationale de Chirurgie Orthopédique et de Traumatologie p 179, 1951.

Glasser, O. Medical Physics. (Effects of acceleration vol. 2, p. 51.) The Year Book Publ. inc. 1950.

Grantham, E. G., Spurling, G. Ruptured lumbar intervertebral discs. M. Clin. North America. 37: 479: 1953.

Göcke, C. Beitrage zur Druckfestigkeit des spongiösen Knochens. Beitr. z. klin. Chir. 143: 539: 1928.

— Das Verhalten spongiösen Knochens im Druck- und Schlagversuch. Verh. d. 20. Kongr. Dtsch. Ortop. Ges.

— Traumatische Wirbelumformung im Versuch. Hefte Unfallheilkunde. 8: 136: 1931.

Hansen, H. J. A pathologic-anatomical study on disc degeneration in dog. Acta orthop. Scandinav. suppl. 11, 1952.

Hansen, H. J., Olsson, S. E. The effect of a single violent trauma on the spine of the dog. Acta orthop. Scandinav. 24: 1: 1954.

de Haven, H. Mechanical analysis of survival in falls from heights of 50 to 150 feet. War Med. 2: 586: 1942.

Hellner, H. Wirbelfrakturen und Spondylitis deformans. Arch. f. Orthop. u. Unfall-Chir. 29: 417: 1930.

Henle, A. Beitrage zur Lehre im den traumatischen Erkrankungen der Wirbelsäule. Arch. f. klin. Chir. 5: 1: 1896.

Hirsch, C. An attempt to diagnose the level of a disc lession clinically by disc puncture. Acta orthop. Scandinav. 18: 132: 1949.

— Studies on the mechanism of low back pain. Acta orthop. Scandinav. 20: 261: 1951.

— The reaction of intervertebral discs to compression forces. J. Bone & Joint Surg. 37: 1188: 1955.

Hirsch, C., Schajowicz, F. Structural changes in the lumbar annulus fibrosus. Acta orthop. Scandinav. 22: 184: 1952.

Hirsch, C., Nachemson, A. A new observation on the mechanical behavior of lumbar discs. Acta orthop. Scandinav. 23: 254: 1954.

Hult, L. The Munkfors investigation. Acta orthop. Scandinav. suppl. 16, 1954.

— Cervical, dorsal and lumbar spinal syndromes. Acta orthop. Scandinav. suppl. 17, 1954.

Imbert, L., Vial, F. La spondylite traumatique. La Presse Méd. 19: 561: 1911.

Inman, V. T., Saunders, J. Anatomico-physiological aspects of injuries to the intervertebral disc. 29: 461: 1947.

Joplin, R. J. The intervertebral disc. Embryology, anatomy, physiology and pathology. Surg. Gynec. & Obst. 61: 591: 1935.

Jung, A., Brunschwig, A. L'innervation des articulations des corps vertebraux. Presse Méd. 40: 316: 1932.
Junghanns, H. Die anatomischen Grundlagen für die Erkennung der Chondrosis und Osteochondrosis Intervertebralis im Röntgenbild. Acta radiol., suppl. 116 p. 276, 1954.
Keegan, J. Alterations of the lumbar curve related to posture and seating. J. Bone & Joint Surg. 35: 589: 1953.
Kellogg, L. C. Impossibility of moving vertebrae. J. A.M.A. 81: 233: 1923.
Keyes, D. C., Compere, E. L. The normal and pathological physiology of the nucleus pulposus of the intervertebral disc. J. Bone & Joint Surg. 14: 897: 1932.
Knutsson, F. Experiences with epidural contrast investigation of the lumbo-sacral canal in disc prolapse. Acta radiol. 22: 694: 1941.
— Epidurale Kontrastuntersuchung bei Bandscheibenprotussion im Lendenteil. Acta chir. Scandinav. 37: 214: 1942.
— The vacuum phenomen in the intervertebral disc. Acta radiol. 23: 173: 1942.
— The instability associated with disc degeneration in the lumbar spine. Acta radiol. 25: 593: 1944.
— Om röntgendiagnostik av diskdegeneration i ryggraden. Nord. Med. 7: 1367: 1944.
— A qualitative comparison between the standard type of examination and tomography for certain intraosseous structural changes. Brit. J. Radiol. 26: 113: 1953.
Kümmel, H. Über die traumatischen Erkrankungen der Wirbelsäule. Deutsche med. Wchnschr. 11: 180: 1895.
— Der heutige Standpunkt der posttraumatischen Wirbelkrankungen (Kümmelsche Krankheit). Arch. f. Orthop. u. Unfall-Chir. 26: 471: 1928.
Landoff, G. A. Vertebral fractures in insured and uninsured patients. Acta orthop. Scandinav. suppl. 13, 1953.
Lange, Ch. Untersuchungen über Elasticitätsverhältnisse in den menschlichen Rückenwirbeln mit Bemerkungen über die Pathogenese der Deformitäten. Ztschr. Orthop. Chir. 10: 47: 1902.
— Über Elasticitätswerte in Rückenwirbeln und über osteomalacia traumatica. Verhandl. d. deutsch. orthop. Gesellsch. 1920.
Lewin, Ph. The back and its disk syndromes. Lea and Febiger Philadelphia 1955.
Lindblom, K. Eine anatomische Studie über lumbale Zwischenwirbelscheibenprotrusionen und Zwischenwirbelscheibenbrüche in die Foramina Intervertebralia hinein. Acta radiol. 22: 711: 1941.
— Protrusions of disks and nerve compression in the lumbar region. Acta radiol. 25: 195: 1944.
— Diagnostic puncture of intervertebral disks in sciatica. Acta orthop. Scandinav. 17: 231: 1948.
— Technique and results in myelography and disc puncture. Acta radiol. 34: 321: 1950.
— Technique and results of diagnostic disc puncture and injection in the lumbar region. Acta orthop. Scandinav. 20: 315: 1951.
— On microtomography. Acta radiol. 42: 465: 1954.
Lindblom, K., Rexed, B. Spinal nerve injury in dorso-lateral protrusions of lumbar disks. J. Neurosurg. 5: 413: 1948.
Lindblom, K., Hultqvist, G. Absorption of protruded disc tissue. J. Bone & Joint Surg. 32A: 557: 1950.

Lindbom, Å. The roentgenographic appearance of injuries to the intervertebral discs. Acta radiol. 45: 129: 1956.

Lob, A. Die Wirbelsäulenverletzungen und ihre Ausheilung. Leipzig 1941.

— Das Röntgenbild und seine pathologisch-anatomischen Unterlagen bei der Ausheilung von Wirbelsäulenverlezungen. Fortschr. a. d. Geb. d. Röntgenstrahlen. 60: 199: 1939.

Love, G. Camp, J. Root pain resulting from intraspinal protrusion of intervertebral discs. J. Bone & Joint Surg. 19: 776: 1937.

von Luschka, H. Die Halbgelenke des menschlichen Körpers. Berlin. G. Reimer 1858.

Matthiash, H. Arbeitshaltung und Bandscheibenbelastung. Arch. Orthop. Chir. 18: 11: 1956.

Mayr, S. Nucleushernie und Unfall. Wien. med. Wchnschr. 100: 271: 1950.

Messerer, O. Über Elasticität und Festigkeit der menschlichen Knochen. Stuttgart 1880.

Mixter, W. J., Barr, J. Rupture of the intervertebral disc with involvment of spinal canal. New England J. Med. 211: 210: 1934.

Mixter, W. J., Ayer, J. B. Herniation or rupture of the intervertebral disc into the spinal canal. New England J. Med. 213: 385: 1935.

Moore, S. Body section roentgenography with the laminography. Am. J. Roentgenol. 39: 514: 1938.

Nicoll, M. E. A. Closed fractures of the spine. Soc. Internat. Chir. Orthop. et Traumat. 1948.

Nordin, J. Olycksfallsskada och sjukdom. Almqvist och Wiksell. Uppsala 1935.

— Olycksfall i arbete. Almqvist och Wicksell. Uppsala 1936.

— Yrkesskadeförsäkringslagen och invaliditetsgradsättning. Almqvist och Wiksell. Uppsala 1955.

Olin, H. A. Intervertebral disc; involvment in vertebral fractures and in spinal pathology; report of 56 cases. Am. J. Roentgenolog. 42: 235: 1939.

Olsson, S. E. Personal cummunication.

Perey, O. Contrast medium examination of intervertebral discs of lower lumbar spine. Acta orthop. Scandinav. 20: 327: 1951.

Petter, Ch. Methods of messuring the pressure of the intervertebral disc. J. Bone & Joint Surg. 31: 365: 1933.

Putschar, W. Zur Kentniss der Knorpelinseln in den Wirbelkörpern. Beitr. Path. Anat. 79: 150: 1927.

— Über Knorpelinseln in den Wirbelkörpern. Verh. Dtsch. Path. Ges. 22: 262: 1927.

Püschel, J. Der Wassergehalt normaler und degenerierter Zwischenwirbelscheiben. Beitr. z. path. Anat. u. z. allg. Path. 84: 123: 1930.

Rauber, A. A. Elasticität und Festigkeit der Knochen. W. Engelmann. Leipzig 1876.

Robert, Eine eigenthümliche, angeborene Lordose, wharscheinlich bedingt durch eine Verschiebung des Körpers des letzten Lendenwirbels auf die vordere Fläcke des ersten Kreuzbeinwirbels (Spondylolisthesis Kilian) nebst Bemerkungen über die Mechanik dieser Bechenformation. Monatschr. f. Geburtsk. und Frauenkrankh. 5: 81: 1855.

Rogers, M. The end results of compressed fracture of the spine. Boston M. & S. J. 193: 494: 1925.

Roofe, P. G. Innervation of the annulus fibrosus and the posterior longitudinal ligament. Arch. Neurol. & Psychiat. 44: 100: 1940.

Rose, G., von Mentzingen, A. Knorpelknoten im Wirbelkörper und Trauma. Chirurg. 2: 418: 1930.

Ruff, S. German Aviation Medicine. World War II. Washington 25 DC.
Schantz, A. Krankenvorstellungen. München. med. Wchnschr. 48: 553: 1910.
— Wirbelsäule und Trauma. Arch. f. klin. Chir. 148: 187: 1927.
Schmieden, V. Trauma und Wirbelsäule. Unfallheilkunde 8: 4: 1931.
Schmorl, G. Über die an den Wirbelbandscheiben vorkommenden Ausdenungs- und Zerreisungsvorgänge und die dadurch an ihnen und der Wirbelspongiosa hervorgerufenen Veränderungen. Verhandl. d. deutsch. path. Gesellsch. 22: 250: 1927.
— Über Knorpelknötchen und den Wirbelbandscheiben. Fortschr. a. d. Geb. d. Röntgenstrahlen. 28: 265: 1928.
— Zur pathologischen Anatomie der Wirbelsäule. Klin. Wchnschr. 8: 1234: 1929.
— Beitrage zur pathologischen Anatomie der Wirbelbandscheiben und ihre Beziehungen zu den Wirbelkörpern. Arch. f. Orthop. u. Unfall-Chir. 29: 389: 1931.
Schmorl, G., Junghanns, H. Die gesunde und die kranke Wirbelsäule in Röntgenbild und Klinik. 3. Auflage Georg Thieme. Stuttgart 1953.
Schackman, R., Harrison, C. V. Occult bone metastases. Brit. J. Surg. 35: 385: 1948.
de Sèze, S. Les accidents de la détérioration structurale du disque. Semaine d. hôp. Paris. 31: 2267: 1955.
Singer, R. Personal communication.
Steindler, A. Kinesiology of the human body. Ch. Thomas Springfield. Illinois 1955.
Sylvén, B. On the biology of nucleus pulposus. Acta orthop. Scandinav. 20: 275: 1951.
Übermuth, H. Die Bedeutung der Altersveränderungen der menschlichen Bandscheiben für die Pathologie der Wirbelsäule. Arch. f. klin. Chir. 156: 567: 1929.
Unander-Scharin, L. On low back pain with special reference to the value of operative treatment with fusion. Acta orthop. Scandinav. suppl. 5, 1950.
Waldenström, H. Diskbråck-ischias och olycksfall. Svenska läk.tid. 42: 1560: 1945.
Wallace, J. O. Crush fractures of the spine. J. Bone & Joint Surg. 5: 28: 1923.
Waris, W. Lumbar disc herniation. Acta chir. Scandinav. suppl. 140, 1948.
Watson, W. Simultaneus multisection radiography. Radiography. 17: 221: 1951.
Watson-Jones, R. Fractures and joint injuries. 4: Edition. E. & S. Livingstone. London 1955.
Watts, D. T., Mendelson, E. S., Hunter, H. N., Kornfield, A. T., Popper, J. R. Tolerance to vertical acceleration required for seat ejection. J. Aviation Med. 18: 554: 1947.
Weinbren, M. A manual of tomography. H. K. Lewis. London 1946.
— The value of tomography in the examination of fractured vertebra. Acta radiol. suppl. 116 p. 184, 1954.
Wiberg, G. Sambandet mellan trauma och diskprolaps. Svenska läk.tid. 38: 1219: 1941.
— Back pain in relation to the nerve supply of the intervertebral disc. Acta orthop. Scandinav. 19: 211: 1949.
Williams, L. W. The later development of the notochord in mammals. Am. J. Anat. 8: 251: 1908.
Virgin, W. J. Experimental investigations into the physical properties of the intervertebral disc. J. Bone & Joint Surg. 33 B: 607: 1951.
Wissing, O. Über Knorpelknötchen in der Columna. Acta path. et microbiol. Scandinav. suppl. 3 p. 499, 1930.