

# I Introduction

When Eduard Albert introduced arthrodesis (*arthron* a joint, *desis* binding together) in 1882, he unquestionably provided orthopaedics with a valuable method of treatment.

The same principle of eliminating function by achieving a bony union between vertebral segments was presented in 1886 by Wilkins.

Since that time, the fixation of vertebral segments (spondylodesis, ankylosing operation of the spine, grafting of the spine, fusion) has been a much used surgical treatment. The operation was applied early to tuberculous spondylitis and vertebral fractures. Subsequently the indications were extended to comprise various types of deformities and states of pain, which it was held, were induced by mechanical disturbances in the mobile junctions between vertebrae.

The manner of performing the operation has been gradually modified, the aim being to arrive at the technique which would be most likely to ensure a bony union. The resultant mechanical stability has been questioned from time to time, but, as a rule, healed fusion has been regarded as synonymous with a good clinical result. Considerable attention has been paid to the healing of the spinal graft, whereas little has been done to investigate the fusion's mechanical efficiency.

Part of the difficulty in developing a surgical technique for spinal fusion is that the movements between two vertebrae involve three elements, the disc and the two intervertebral joints. The surgeon is thus faced with the choice of either attempting to fuse the posterior elements to a greater or lesser extent (posterior fusion) or, by excision of the disc, attempt to establish a direct connection between the vertebrae (interbody fusion). There are advantages and disadvantages with both methods. In relation to the disc, dorsal fusion is an extraarticular spondylodesis and its mechanical potential for relieving the disc has been called in question. Consequently, the fusion has come to include more and more of the vertebral arches, i.e. the spinous, articular and transverse processes. The attraction of interbody fusion, on the other hand, is that it both permits extirpation of disc tissue, which has been regarded as the site of pathological changes, and provides large areas of spongy substance for the fusion.

Discussion concerning the choice of method has concentrated upon the complications presented by imperfect healing and also upon failure to relieve pain.

In the present study, experiments have been conducted on autopsy specimens from the lumbar spine. The idea was to study how vertebrae move in relation to one another when loaded vertically and also to assess the stabilizing effect of various types of dorsal fusion.

The purpose of the experiments was to develop a method for simulating posterior lumbar fusion in accordance with a number of the principle techniques and to investigate the effect of vertical loading. Equipment was designed for measuring and registering deformations in vertebrae and discs, with comparisons under identical loading conditions between intact specimens and the same specimens subjected to simulated fusion or some other alteration. By applying eccentric loads, the vertebral segment could be made to adopt positions of equilibrium corresponding to extension, flexion and lateral bending.

During the loading experiments, recordings were made of the intradiscal pressure as well as of the deformations which arose in and between the various parts of the vertebrae. The mathematical units expressing the force applied and the deformations measured have been selected with a view to facilitating comparisons between specimens from different individuals.

## II Revue of literature

### Development of fusion operations

#### *Surgical technique*

In the first operations to stabilize the spine, wires were looped around laminae and spinous processes (Wilkins, 1886; Hadra, 1891; Chipault, (1900). On the grounds that the wire loops could not cope with the mechanical strains in the spine, Lange 1910—1911 preferred to fit steel rods paraspinally, a method which he tried out for several years in animal experiments as well as clinically on man.

Then, in 1911, several methods were reported for bridging posterior parts of the vertebral arch with bone. In Albee's operation, a tibial graft is inserted into a split in the spinous processes. Henle advocated placing a tibial graft on either side of the spinous processes (paraspinally), considering it an advantage that the laminae are thereby included in the bony union. Similar methods were described by Whitman (1911) and de Quervain (1912). A somewhat different principle involved division of the spinous processes and downward fracture of bony flaps to interdigitate between the laminae below (Hibbs, 1911).

Numerous modifications and combinations of these methods were published during the next few years, one of which involved fusion between laminae by chiselling out the base of the spinous process and inserting a tibial graft (Halstead, 1915). Hibbs (1918) extended his method to include arthrodesis of the intervertebral joints by curettage of the joint cartilage. Fixation of the primary graft was improved by resecting the spinous processes and downward fracture of bony flaps to interdigitate between the adjacent healthy spinous processes (Waygiel, 1922). Having resected the base of the spinous process, the tibial graft could be embedded in the laminae (Calvé & Galland, 1920). A further development was to shape the tibial graft like a fish tail or clothes-pin to fit in between the spinous processes (Gibson, 1931). Similarly, a massive H-shaped graft was taken from the ilium and reinforced with iliac strips to include the intervertebral joints (Bosworth, 1942, 1945, 1952), a technique which has been applied by several authors (Blount, 1942; Breck & Basom, 1943).

The importance of widening the intervertebral space dorsally has been emphasised (e.g. Bosworth, 1942; Breck & Basom, 1943; McBride, 1949), the last of these authors using a "mortised transfacet bone block" in order to achieve a primary stability that will permit early mobilisation of the patient. Other means which have been tried to this end are screws through the articular facets (King, 1948), a paraspinous metal plate and matching graft (Straub, 1949; Wilson & Straub, 1952) and double metal plates fixed by bolts and nuts through the spinal processes (Williams, 1950).

Combined lumbosacral and sacro-iliac fusion has been recommended by several writers (Smith-Petersen, 1924; Chandler, 1929; Campbell, 1930). In a modification of Hibbs' technique, transplants were placed between the transverse processes (Mathieu & Demirleau, 1936; Watkins, 1953; Adkins, 1955; Truchly & Thompson, 1962; Wiltse, 1964).

A method for interbody fusion was published in 1936 by Mercer, who had tried it out in two cases: using a dorsal approach, the dorsal part of the disc and the adjacent vertebral surfaces are resected and two iliac transplants are wedged into the space thereby created. (This method has subsequently been adopted by Owens & Williams, 1945; Jaslow, 1946; James & Nisbeth, 1953; Cloward, 1953; DuToit, Domisse & Müller, 1956; Domisse, 1959.)

As early as 1923 tuberculous spondylitis was treated with radical resection from a transabdominal approach and tibial grafts in the defect (cf. Ito, Tsuchia & Asami, 1934). This method has recently been advocated by Felländer (1955, 1965) and Stock (1962).

Another proposal for interbody arthrodesis with a ventral approach called for a tibial graft in a borehole through the 5th lumbar to the 1st sacral vertebra (Capener, 1932). This was put into practice by Burns (1933), Jenkins (1936), Speed (1938) and Friberg (1939). A similar fixation has been obtained with two fibular grafts and a screw introduced prismatically in different planes (Henschen, 1942) and with three-flanged nails (Ramser, 1943). Another method involves radical excision of the disc from a ventral, transperitoneal approach and its replacement with a U-shaped heterologous transplant, which is kept in place with vertical grafts (Lane & Moore, 1948). This method has been further developed (Harmon, 1959, 1962; Sacks, 1962, 1965; Raney and Adams, 1962).

Very good results have been reported for a combination of interbody and posterior fusion in one session (Harmon, 1963).

In this development of surgical techniques there is a trend towards increasingly massive fusions, incorporating more and more of the two vertebrae. Although the reasons behind the modifications are not always stated explicitly, the primary aim has presumably been to achieve greater

mechanical stability and thereby ensure healing and improve the clinical result. In principle, four surgical techniques have emerged:

1. Bony union between spinal processes (Albee, Henle and others).
2. Fusion including arches and intervertebral joints (Hibbs, Bosworth and others).
3. Fusion comprising the entire vertebral arch, i.e. including the transverse processes (Mathieau & Demirleau; Boucher & Vancouver; Watkins; Wiltse and others).
4. Interbody fusion from dorsal (Mercer; Cloward) or ventral approach (Lane & More; Harmon and others).

### Special indications for fusion

#### *Tuberculous spondylitis.*

In the early years of this century, fusion was chiefly used for tuberculous spondylitis and to some extent for vertebral fractures, i.e. conditions with defects in the supporting bony structure and a danger of progressive spinal deformities. In such cases the graft had to be able to carry practically the entire load placed upon the spine, particularly after forced reduction as proposed by Calot (1905). Successive correction over a long period (Waldenström, 1924) followed by surgical grafting in a quiet phase was reported to give good results. Yet, as Biesalski (1923) points out, in spite of the favourable reports from America, many surgeons in Germany rejected surgical grafting for tuberculous spondylitis. Biesalski believed that opinions differed so widely because the operation was performed without fixed indications. He considers that one cannot both unload and fix the spine but only achieve a certain compromise. The only way of demonstrating the effect of a grafting operation, according to Bachlechner (1921), is by post mortem studies. Taking a specimen from a 5-year old boy who had died of millitary tuberculosis 8 weeks after the operation, he showed that the graft formed a firm union. With the transverse process of T 11 placed against the articular process of T 12, all flexion was prevented and the graft was subject to traction only, not to flexion forces. Investigating ten specimens, partly healed and partly resorbed, after fusion according to Albee or Henle, Biesalski (1923) found that in no case had the graft grown longer or broader and was in many instances wafer-thin. Roeren (1924) questioned the use of a graft, since it prevents contact and spontaneous union between the vertebral bodies. He allowed that the graft may be well suited to carry bending forces in the

sagittal plane, but doubted whether this was equally true for rotation about the longitudinal axis. He preferred Hibbs' method, arguing that fusion according to Albee made a lever too long in relation to the static force: "The nearer the fusion approximates the vertebral body the sooner it is able to fulfill its task." The same objections have been made by Whitman (1911), Bachlechner (1921) and Hoffman (1925). According to Henle (1926), the technique developed by Halstead (1915) has the disadvantage that the graft has its smallest cross-section in the frontal plane and is thus inferior to a paraspinal graft in preventing flexion and extension. Lange's original site for the metal rods was criticised by v. Baeyer (1922), however, as being too close to the segment's axis; consequently, he shaped celluloid rods to fit against the apex of the spinous process.

Most authors at this time recommend that fusion for spondylitis should include at least one healthy vertebra on each side of the affected segment. Along with Roeren, however, Calvé & Galland (1920, 1936) stress the importance of direct contact between the vertebral bodies; they favour a short fusion — involving diseased vertebrae only and without any correction. The gibbus thereby can be compensated in adjacent healthy segments. They place the graft as far ventrally as possible and ankylose or chisel off the intervertebral joints, which serve as a fulcrum for the deformity. On the basis of 23 operated cases of spondylitis and an autopsy specimen, Joisten (1929) concluded that the fusion, unable to withstand the deforming forces, had been transformed to correspond to the healed kyphosis, so that his patients could have been spared the operation. Of the 76 orthopaedic surgeons in Europe who answered a questionnaire, Schmieden (1930) found that 8 supported the method (Henle, Albee), 38 in isolated cases, 17 were not interested and 13 were definitely opposed.

It is said that dorsal fusion does not accelerate bony union between the vertebral bodies by means of ventral growth and depends entirely upon the type of infection focus (Puig Guri, 1947). Union is achieved soonest with a focus close to the edges of the bodies; it never takes less than a year to form, however, and is seldom complete in under 3-4 years.

In an X-ray examination of 507 cases of operated spondylitis, Alvik (1949) detected mobility (max.  $9^{\circ}$ ) even though fusion had been achieved without complications involving the graft. He ascribed this mobility to the elasticity of the graft, spinous process and arches, arguing that for complete stability the fusion must include as much of the posterior segment as possible.

A study has been made of all the cases of spondylitis which have been

operated upon at the New York Orthopaedic Hospital, — 1,009 cases up to 1947 (Hallock & Jones, 1954). 210 patients operated upon from 1911—1915 were previously studied by Hibbs (1918). 286 patients operated upon from 1915—1920 were reported by Hibbs & Risser (1928). Swift (1940) reported on 817 cases operated upon from 1918—1930. "The presence of solid fusion may not prevent increasing spinal deformity. The amount of the deformity was directly proportional to the degree of destruction of the vertebral bodies. In none of the patients did the fusion hold apart the diseased vertebrae for a prolonged period of time."

Having used dorsal fusion for tuberculous spondylitis up to 1955, Stock (1962) found the results far from satisfactory. Consequently, 418 cases were treated in 1955—60 by radical extirpation and interbody fusion, using a ventral approach. It did not take long for the fusion to become stable, and the patient could be allowed up even earlier, since the load on the spine stimulated hypertrophy of the graft and accelerated healing. Only 17 per cent of the results were good with dorsal fusion, (cf. Cleveland 55 per cent and Swett less than 40 per cent), whereas interbody fusion produced a solid union in 90—95 per cent.

### *Fractures.*

The considerations governing surgery for fractures of the spine have been much the same as those for spondylitis. There is a tendency to functional treatment of stable fractures with early mobilisation, while surgery is considered for unstable fractures (liable to dislocate). It has been argued that unstable fractures should in principle be protected until spontaneous anterior fusion develops (Nicoll, 1949); out of ten miners with unstable, dislocated fractures treated conservatively seven made a complete recovery, whereas none of those undergoing arthrodesis returned to a coal-face job; "posterior fusion is mechanically less sound because the graft is under tension instead of compression". Watson-Jones (1955) agrees with Nicoll that the ideal end result is solid fusion but notes that, as this takes several years to achieve and the patient is an invalid during this period, rehabilitation becomes a serious problem. He therefore prefers early dorsal fusion according to Hibbs, including the intervertebral joints and with additional crista bone chips. Spinal metal plates have been reported to be "safe and effective" (Holdsworth & Hardy, 1953) and to arrest the development of a gibbus (Pennybacker, 1953; Dick, 1953). Subsequently, however, it has been shown that metal plates do not prevent gibbus, as witnessed by the finding of loosened plates, screws and bolts, while several cases with post-operative progressive nerve symptoms suggest that the method cannot be regarded as "safe" (Guttman, 1959).

### *Spondylolisthesis.*

During the Twenties and the Thirties special attention was paid to anomalies and deformities in the lumbosacral angle (Johanson, 1920; Willis, 1924, 1941; Schamburrow, 1926; Wiles, 1935; Kimberley, 1937) and in particular spondylolisthesis. Rayerson (1932) reports that he operated on the first case of spondylolisthesis in 1911. Albee (1927) reports that without exception, the results were most gratifying in the eight cases in which he employed his operation for spondylolisthesis. The latter's report, however, is described as summary and unconvincing by Mouchet & Roederer (1927), who ask how this dorsal graft can ensure fusion "in cases of spondylolisthesis where the dislocation affects the vertebral body" and suggest placing the graft between the articular processes of the adjacent inferior and superior vertebrae. Salmon & Contiadés (1933) believe that once dislocation has started, it is almost bound to continue owing to the body weight and the oblique position of the sacrum; the operation should aim at changing the line of force from the superimposed body weight and preventing luxation of L 5. They consider that the transplant meets these requirements indirectly by carrying part of the body weight behind the laminae from L 3 — S 1. Albee's method is criticised for inferior adaptation to pronounced lordosis and a poor attachment to the sacrum. They find it logical to try to fix the spine as close to the centre of gravity as possible (according to Campbell and Lance & Arousseau) but consider that the technique is too difficult; instead, they recommend bilateral paraspinous grafting according to Henle.

Arguing that a dorsal transplant has an insufficient mechanical efficiency in spondylolisthesis, Capener (1932) proposed direct fixation of the displaced vertebral body. This started the development of interbody fusion (Burns, 1933; Mercer, 1936; Jenkins, 1936; Friberg, 1939; Gjessing, 1951; d'Aubigné, 1952; Laurent, 1958). Friberg (1939) questioned "the justification for placing the transplant far ventrally", since this gives it a shorter lever. He points out that an arthrodesis in the intervertebral joints cannot prevent slipping in spondylolisthesis because it does not affect the slipped anterior fragment. However, he also demonstrates that slipping does not occur in the adult, so that surgery on this indication cannot be justified except possibly for children. His investigation showed that the pain-easing effect is only slightly greater for surgical than for conservative treatment. "No parallelism between the roentgen-anatomic and functional results has been seen; good functional results were observed when the transplants were fractured or resorbed, and poor results when the grafts were well fused. . . . In adults, the effect of the Albee graft is not due to its taking on any of the body weight or to its preventing

the slipping (since slipping does not occur); but in its producing an extraarticular arthrodesis on the intervertebral joints...". On the basis of 50 cases of spondylolisthesis in the age range 5—20 years and 110 operated cases over 20 years of age, Taillard (1955) concluded that the transplant cannot prevent slipping or mobility in the segment but that a bony union does have a good effect on the pain. Young girls with a pronounced wedge-shaped L 5 and a convex sacral base are liable to progressive slipping, which would justify anterior fusion in such cases. Discouraging results with dorsal transplants and metal plates for spondylolisthesis have been reported by d'Aubigné (1952) who considered it more logical to undertake interbody fusion and reported good functional results with a transperitoneal approach in 16 cases. In one out of five cases of ventral fusion, Sicard (1952) accidentally penetrated the cauda equina with a screw, causing neurological disorders; he argues that, since dorsal fusion gives good results, young people with a purely functional condition should not be exposed to the risk inherent in ventral fusion. A modified operation for spondylolisthesis has been developed by Marino-Zucco (described by Montiselli & Maresca, 1957): The loose arch is temporarily removed, the superior and inferior facets are denuded of cartilage and the pseudoarthrosis is excised. Costal strip are placed between the intervertebral joints and the loose arch is refixed with short screws through both transplant and facet. Boucher & Vancouver (1959) recommend fixation with long screws pointing ventrally distally and laterally, so that they penetrate the vertebral body and the alae of the ilium respectively via the pedicles.

Chaklin (1937) used a paravertebral approach for interbody fusion in 6 cases of spondylolisthesis. Hirsch (1966) has described a method for ventral, extradiscal bridging from L. 5 to the sacrum, used successfully on 3 young girls with pronounced slipping.

A few cases of spondylolisthesis have been successfully reduced but subsequently became dislocated again in spite of fusion (Watson-Jones, 1938; Friberg, 1939). Treatment by open reduction and interbody osteosynthesis has been reported in 6 cases (Denecke, 1957). The sacrum was exposed from a dorsal incision and from an incision between the rectum and sacrum, the disc was extirpated together with a wedge-shaped segment of the sacrum and L 5, after which L 5 was forced into place with a special clamp and fixed with two screws from S 2 to L 3. This method met with considerable opposition on the grounds that the extent and risks of the operation were out of proportion to the patient's disorder (Erlacher, 1957).

### *Scoliosis.*

The surgical treatment of scoliosis (idiopathic as well as paralytic and congenital) is faced with special problems owing to the progression that occurs during growth (Risser & Ferguson, 1936). There is a tendency to increased torsional deformity with Albee's graft in growing individuals, since the transplant does not grow in step with the spine itself (Tavernier, 1934). The method used most for scoliosis has been Hibbs' fusion (Hibbs, 1924; Hibbs, Risser & Ferguson, 1931). In a report on 117 cases of scoliosis operated according to Steindler, i.e. a combination of Hibbs' and Albee's methods, an X-ray examination showed that pseudoarthrosis had developed in 68.3 per cent of the entire series and in 83 per cent of the 80 cases involving the lumbar spine; the pseudoarthroses healed spontaneously when the patients had grown up and the scoliosis had spontaneously stabilised (Ponseti & Friedman, 1950). In a series of 208 cases operated on according to Hibbs at the New York Orthopaedic Hospital, the incidence of pseudoarthrosis as demonstrated at re-operation was 12.9 per cent for idiopathic scoliosis and 33.3 per cent for paralytic (Jónsson, 1953). Five years after the operation, 65 per cent of the cases had lost not more than one-tenth of the primary correction while the remainder had lost more than one-tenth. Gruca (1958) held that passive methods are incapable of arresting scoliosis in growing individuals with muscular imbalance; union was not achieved in any of the cases in which an attempt was made to prevent progress of the scoliosis by transplanting a rib along the transverse processes. At the same time he regards extensive massive fusion as unphysiological therapy for children. He therefore aims at a dynamic balance of the forces in the spine, which he achieves by means of steel springs between the spinous processes; if the scoliosis is pronounced, distraction with turn-buckles is also employed. An other corrective technique, with long, powerful steel rods and hooks between the lamina, has been used by Harrington since 1955. A combination of Hibbs' and Cobb's method (Cobb, 1952, does not aim at ankylosis of the intervertebral joints but adds autogenous bone) has been reported by Moe (1958), who ascribes loss of primary correction to pseudoarthrosis or too short a fusion. The correction achieved in a series of 266 patients was 40—45° and roughly half of this for pseudoarthrosis. With the technique he used early on, the incidence of pseudoarthrosis was 56 per cent for idiopathic scoliosis and 65 per cent for paralytic. Later, with Cobb's method, the former figure was reduced to 7 per cent and the latter to 36 per cent (subsequently to 14 per cent by including the facets). In the discussion after Moe's paper, Blount pointed out that by improvements in technique, Moe had managed to reduce the incidence of pseudoarthrosis:

"To be truly strong the fusion area should extend from the cartilaginous cap of one transverse process across to the cartilaginous cap of the other and should extend anteriorly to include the articular facets. This rod of bone must be of sufficient diameter to resist bending forces that produce stress fractures months or years later." According to Blount, the treatment of scoliosis cannot be regarded as satisfactory until pseudoarthrosis has been almost entirely eliminated. Blount et al. (1958) hold that surgery is indicated for progressive scoliosis irrespective of age. Although fusion in children admittedly inhibits growth, this is preferable to the effects of progressive gibbus. They have not noted any significant increase of the scoliosis after fusion.

### *Low back pain.*

Even before the spread of disc surgery in the nineteen thirties (Mixer & Barr, 1934) good results were reported with lumbar fusion for low back pain with or without sciatica. In many cases, the back pain was attributed to some congenital defect or anomaly demonstrated by roentgenography and held to cause lumbosacral instability (Johanson, 1920; Schamburrow, 1926; Chandler, 1929; Hibbs & Swift, 1929; Ferguson, 1934; Wagner, 1935; Kimberley, 1937).

It was emphasised that fusion may be indicated for persistent back pain even though the X-ray findings may be negative (Schamburrow, 1926). Williams & Yglesias (1933) held that a lowered interspace causes subluxation in the intervertebral joints and constriction in the foramina; the nerve is pressed against the facets, eliciting pain which increases with movement. They accordingly recommend fusion and, if the sciatica persists, facetectomy. Ghormley (1933) pointed out that arthritic changes are common in the intervertebral joints and are presumably bound to elicit discomfort in the same way as in other articulations, i.e. aching, pain on movement, swelling and fixation. He argued that the lumbosacral facets, which are positioned to prevent ventral displacement, are particularly exposed to continuous strain in their role as stabilisers of the spine. His recommendation is fusion according to Hibbs. Asymmetric facets as a cause of lumbosacral pain with or without sciatica has been discussed by Goldthwaith (1911), Danforth (1925), Putti (1927), Brailsford (1928—1929), Ayers (1935) and Key (1948). Chandler (1929) noted that, after fusion, sciatica disappeared to a lesser extent than did back pain. During a wave of enthusiasm, practically all low back pain with and without sciatica was attributed to prolapse of a disc (Dandy, 1941, 1944; Young & Burns, 1951, and others). It was found, however, that the back pain often persisted with a higher frequency than the sciatica after simple

extirpation of the disc [Briggs & Milligan (1944), Friberg & Hirsch (1946), Ghormley (1957), Hirsch & Nachemson (1963)] and fusion was once again considered. Persistent back pain was reported in 38.5 per cent of 217 disc operations at the Mayo Clinic and fusion was recommended as a secondary measure in special cases (Love 1947). Friberg & Hirsch (1946) note that disc degeneration is a common condition which is only occasionally complicated by prolapse. Surgery for a prolapsed disc simply means that the pressure on the root is removed, while the pathological changes in the disc are left unchanged. They noted a 30 per cent incidence of persistent spinal ailments and recommended fusion as a secondary procedure for persistent back pains or as a primary measure for severe lumbago with a negative myelogram and exploration. Armstrong (1958) writes that, in theory, it would be best to perform arthrodesis immediately in all cases as a combined operation, but adds that "demonstrative better results than those following simple removal of the nucleus cannot be supported by the published results of operated series. In fact, the results of extirpation of the nucleus combined with immediate arthrodesis seem to be if anything a little worse than those produced by simple removal of the diseased nucleus." Consequently, Armstrong reserves fusion "for a late and second stage procedure in selected patients". A combined operation produced good results in only 14 per cent of the cases in an insurance company's records (Marble & Bishop, 1945). Bony union was achieved in only a few out of 100 cases of dorsal interbody fusion but the clinical results were held to justify the method (Du Toit, Domisse & Müller, 1956). Out of 50 patients undergoing lumbosacral fusion, 14 had bony union and 8 were pleased with the result (Attenborough, 1955). Bony fusion has been said to result in such complete immobilisation, that prolapse of a disc cannot occur within the fusion (Ghormley, 1933; Dandy, 1944; Unander-Scharin, 1950; Cloward, 1953). Yet prolapse of a disc after bony fusion has been described by several writers (Love, 1947; Hensell, 1958).

### Pseudoarthrosis

In practice, the only way of assessing osseous union after surgical fusion is by X-ray examination. Some uncertainty remains, however, even after functional tests with flexion, extension and lateral flexion (Kimberley, 1937; Bosworth, 1945, 1952; Carr & Hyatt, 1955; McBride & Shorbe, 1958; Domisse, 1959; Overton, 1959). A definite assessment can be made only by exploration Smith, 1923; Jónsson, 1953; Watkins, 1953, 1959; Thompson & Ralston, 1949; Rolander, 1964).

Table 1.

*Pseudoarthrosis in fusion of L 4 — S 1.*

Author	No. of operations	Technique	Incidence of non-union (per cent)
Kimberley (1937)	93	Hibbs	31.2
Cleveland, Bosworth & Thompson (1948)	357	H-graft	17.4
Thompson & Ralston (1949)	169	Hibbs	23.6
Thompson & Ralston (1949)	40	Transfacet screws	55.1
Straub (1949)	80	Wilson's plate and cortical graft	14
Unander—Scharin 1950 b	80	Posterior, various methods	27.5
Unander—Scharin 1950 b	18	H-graft	5.6
Unander—Scharin 1950 b	7	Albee	88.9
Smith 1952	123	Hibbs	26
Watkins (1953)	10	Posterolateral, block	20
Hellstadius (1954)	57	H-graft	27
Shaw & Taylor (1956)	55	Only cortical	36
McBride & Shorbe (1958)	77	Facet block	36
Truchly & Thompson (1961)	41	Posterolateral, slivers	7.3
Howorth (1964)	33	Hibbs + screws through the facets	36

There is a wide variation between reports concerning the risk of pseudoarthrosis as assessed from clinical follow-up examinations. Yet without bony union, the clinical result in the form of relief from pain is often relatively good. According to Cleveland, Bosworth & Thompson (1948), 42 per cent of the patients had no pain in spite of pseudoarthrosis, while 5 per cent had persistent pain notwithstanding a bony union. Reporting 100 cases of fusion according to Chandler (1929), Newman (1955) found that 88 per cent of those with bony union had good clinical results compared with 53 per cent of those with pseudoarthrosis. Shaw & Taylor (1956) had good clinical results in 77 per cent of cases with pseudoarthrosis. Good results in 97 per cent of cases with bony union and in 67 per cent of those with pseudoarthrosis are reported by Eie (1964). Unander-Scharin (1950) reports graft complications in 21 per cent of the cured cases. At re-operation for suspected pseudoarthrosis, Thompson & Ralston (1949) found bony union in 8 out of 59 cases. Rövig (1949) reported 7 healed fusions in a group of 11 reoperated patients. Rolander (1964) found 10 cases of bony union among 35 fusions of L 4 — L 5 — S 1

re-operated for persistent ailments. Lange (1959) noted bony union with varying clinical results in 20 per cent out of 99 cases.

The frequency of pseudoarthrosis is consistently reported to be lower for fusion of the lumbosacral segment only than for extensive fusion. In a series of 230 cases, pseudoarthrosis was detected roentgenologically in 8.4 per cent of the fusions involving one segment as against 24.3 per cent of the two-segment fusions (Smith, 1952). For 251 cases with the facet block technique, McBride & Shorbe (1958) report figures of 9.5 and 36 per cent respectively. Bosworth (1952) reported that pseudarthrosis occurred in 3.8 per cent of 79 cases of fusion of L 5 — S 1 with an H-graft, 11.2 per cent in 223 cases of fusion of L 4 — S 1 and 45.5 per cent of 11 cases of fusion of L 3 — S 1.

Adkins (1955) writes that he has tried a variety of surgical techniques with discouraging results. Dorsal interbody fusion appealed to him most in theory and he performed a series of 70 operations but found bony arthrodesis in only one case. A similar experience has been reported by McBride & Shorbe (1958).

Spondylolisthesis has been described as a complication of dorsal fusion (Unander-Scharin, 1950 a; Andersson, 1956; Harris & Wiley, 1963).

### Clinical results following fusion

In order to make an objective assessment of the clinical effect of a method of treatment, comparisons must be made with an equivalent group of patients treated with some other method or left untreated. Comprehensive studies along these lines are lacking for lumbago. Attempts have however been made to select comparable groups retrospectively. Farrel & McCracken (1941) studied the case reports for a series of patients treated with fusion during the years 1914—40 and selected those for which the data suggested the diagnosis of a prolapsed disc; this group was then compared with one treated later with combined extirpation of the prolapsed disc and fusion. There was no clear difference between the results. Another study concerned 503 patients from 1939—47 with the clinical diagnosis of prolapsed disc (Millikan, 1954); the prolapse was extirpated in 329 cases and 100 received conservative treatment. No difference was found in the end results. Surgery was suggested as a selective treatment for patients with progressive paresis and for those with continuous or intermittent attacks that are not affected by conservative therapy. Similarly, Söderberg (1956) made a retrospective selection of 92 patients who, if treated more recently, would certainly have been recommended

for operation on a prolapsed disc. This group was compared with a later series in which the diagnosis of prolapsed disc was confirmed at operation and treated with simple extirpation. Here, too, there was no definite difference between the long-term results. An "impartial study" by a research committee of the American Orthopaedic Association (Nachlas, 1952) concerned 918 patients who had been operated on for back ailments in various parts of the U.S.A. during the period 1941—46. Of the patients available for a follow-up examination, 256 (group A) had been treated with simple extirpation of the prolapsed disc and 118 (group B) with a combined operation. The result was considered satisfactory for 59.80 per cent in group A and for 69.77 per cent in group B. The 10 per cent difference in satisfactory results is thus based upon selected material, with a follow-up of less than half of the individuals. In a study of 1,176 cases with a simple (84.8 per cent) or a combined (15.2 per cent) operation, Gurdjian et al. (1961) report excellent or good results for 67 per cent of both groups. Young & Love (1959) found that the results of a combined operation were 20 per cent better than with simple disc extirpation but they point out that the difference is not statistically significant.

### General indications for fusion

Indications for lumbar osteosynthesis have been reported by Poppem (1945): primary fusion in prolapsed disc with predominant back ailments, for signs of spinal instability, abnormal facets and particularly if the patient does heavy work. Platt (1948) recommends primary fusion at disc operation with a long history of back ache in patients with strenuous work. Pouyanne (1951) lists displaced vertebrae, limited arthrosis, dissatisfactory results after disc operation, old and rebellious lumbar pain, and as a precaution in hard workers. Wilson & Straub (1952) gives spondylolisthesis, disc prolapse, congenital anomalies, osteo-arthritis, instability, spinal fractures. Humphries, Hawk & Berndt (1957): lumbar disc degeneration with disabling back pain precipitated by movement of the back and relieved by a supporting brace or by lying down. Morgan (1957) considers that primary instability is the most common cause of low back pain and usually indicates fusion. Newman (1959): instability and localised severe degeneration in a disc or intervertebral joint. Truchly & Thompson (1962): primary and secondary instability. Howorth (1963) considers that fusion is indicated when there is instability or anomalies in the lumbosacral region with disabling pain unrelieved by adequate

conservative measures. Overton (1959) has summarised the indications for fusion as follows: "One basic requisite for a candidate for fusion is the presence of some mechanical derangement in the area of the spine to be fused."

## Anatomical and physiological considerations

The conditions for stabilising a ligamentous lumbar spine are determined by the anatomical design and the mechanical properties of the intervertebral discs, the various parts of the vertebrae and the material for osteosynthesis. For the descriptive and functional anatomy the reader is referred to the appropriate textbooks (e.g. Fick, 1904; Strasser, 1913; Braus, 1921; Rauber & Kopsch, 1920; Gray, 1962).

A motion segment (Junghanns, 1931) consists of two vertebrae and the intervertebral disc and ligaments between these. The vertebral body has a slightly concave silhouette and its horizontal section is usually shaped like a kidney. When studying physical properties, it should be noted that the cortical layer of the body is strikingly thin and pierced, particularly dorsally, by several nutrient foramina. The body's cranial and caudal surfaces are formed of concave, bony endplates. The border serves as a cortical reinforcement for the attachment of the end-plate to the periphery of the body; it is thickest ventrally and laterally, becoming narrower dorsally. The hyaline end-plate delimits the disc from the body of the vertebra.

The annulus is made up of concentric layers of collagenous fibres running helicoidally from one vertebral body to the next in such a way that the fibres in contiguous laminae lie at about  $100^\circ$  to each other (Horton 1958; Naylor, 1962; Galante & Hirsch, 1966). The fibres in the outer zone attach like Sharpey's fibre to the border of the vertebral body, while in the inner zone, they are joined to the hyaline cartilage (Hirsch & Schajowicz 1952). The collagenous fibres which correspond to those in fascia and tendon tissue are extremely strong and not very extensible (McMaster, 1933; Verzár, 1957, 1963). In the lumbar spine the annulus fibrosus is higher and thicker in front than behind (Todd & Pyle, 1928; Joplin, 1935; Inman & Saunders, 1947). As a result, the centre of the nucleus pulposus lies somewhat dorsal to the geometric centre of the disc (Schmorl, 1927; Böhmig, 1931). The nucleus pulposus or inner core of the disc consists of a three-dimensional network of collagen fibrils enmeshed in a mucoprotein gel which contains various mucopolysaccharides (Hirsch, Paulson, Sylvén & Snellman, 1951; Happey, MacRae &

Naylor, 1953; Naylor, 1962). It occupies about 30—50 per cent of the disc's area of cross-section (Perey, 1957; Nachemson, 1960; Eie, 1966). In sections from young individuals it protrudes above the cut surface of the disc. This has been taken as a sign of an inner pressure (Fick, 1904; Joplin, 1935; and others), which has been considered of decisive importance for the hydro-elastic function of the disc (Roux, 1895; Calvé & Galland, 1930; Petter, 1933; Joplin, 1935; Charnley, 1952). The cavity in the centre of the nucleus normally measures less than 1 cm<sup>3</sup> but becomes larger in degenerated discs (von Luschka 1856, 1858; Schmorl, 1927; Töndury, 1955; Fernström, 1960; Abel & Harmon, 1960; Teichert, 1962a), which may spontaneously appear to be filled with gas, i.e. the vacuum phenomenon at X-ray examination (Magnusson, 1937; Knutsson, 1940; Teichert, 1962 b), or be demonstrated by nucleography *in vivo* and on autopsy specimens (Hirsch, 1948; Lindblom, 1948, 1951; Hult, 1951, Romanus & Ydén, 1952; Nordlander, Salén & Unander-Scharin, 1958; Abel & Harmon, 1960; Fernström, 1960; Teichert 1962 a). In young individuals the water content of the nucleus (approximately 80 per cent) is about 10 per cent higher than that of the annulus but the difference diminishes with increasing age and in disc degeneration parallels a relative increase in the protein content (Püschel, 1930; Sylvén, Hirsch, Paulson and Snellman, 1951; Naylor & Smare 1953; Bush, Horton, Smare and Naylor, 1956; Mitchell, Hendry & Billewicz, 1961; Naylor, 1962).

The disc is covered ventrally by the anterior longitudinal ligament and dorsally by the thinner posterior longitudinal ligament. The vertebral arches of the motion segments are connected by the arcuate ligaments the supraspinous, interspinous and intertransverse ligaments. The ligamentum flavum attaches to the ventral surface of the articular processes and articular capsules, forming the dorsal limit of the vertebral canal. It is chiefly composed of highly elastic fibres (according to Krafka the modulus of elasticity of collagen fibres is 300 times that of elastic). In the lumbar spine of the dog, the extensibility of the ligamentum flavum is 63 per cent and its tensile strength is 671 g/mm<sup>2</sup> (Nunley, 1958). When the ligamentum flavum is sectioned horizontally it contracts (both *in vivo* at surgery and in dissection specimens), indicating that the lumbar discs are subject to a prestress (Fick, 1904; Malmros, 1942; Åkerblom, 1948; Nachemson, 1960; Riga & Robacki, 1965).

The other ligaments mentioned above consist chiefly of interlacing layers of collagenous fibrils and serve, together with the bony processes, as attachments for the spinal muscles.

The intervertebral joints are true diarthroses. In the lumbar spine their surfaces are cylindrical, set chiefly in the sagittal plane though usually

narrowing somewhat towards the back. In front, the cranial facets enclose the caudal, thereby preventing ventral translation (horizontal displacement, instability) of the upper vertebra in each pair (McNab, 1950; Lewin, 1964). Otherwise, the joints are designed to permit a relatively considerable degree of rotation around the sagittal and frontal and vertical axes (Güntz, 1934; Lewin, 1964, 1965). Like the intervertebral discs, the intervertebral joints are frequently the site of degenerative processes, which is one of the reasons why their load-bearing function has been discussed (Güntz, 1934; Shore, 1935; Severin, 1943; Gianturco, 1944; Ingelmark, 1956; Kelly, 1958; Lewin, 1964). In general it has been considered that the intervertebral joints serve as guides for the motion segment (Fick, 1904; Keyes & Compere, 1932; Armstrong, 1958; Nachemson, 1963).

The nucleus pulposus has been reported to act as a fulcrum for the segment's rotation (Fick, 1904; Steindler, 1955), which has an inconstant (momentary) axis of movement, normally centering on the nucleus (Dittmar, 1930) but displaced towards the intervertebral joints in disc degeneration (Gianturco, 1944; McNab, 1950).

#### *Nutrition and innervation of the vertebral body and disc.*

The vertebral body is supplied by two arteries, which run laterally and backwards midway down the body of the vertebra, through the intervertebral foramen and enter the dorsal aspect of the body. There are small caudad and cephalad periosteal branches, while larger branches are given off to the articular capsule and vertebral arch (Hanson, 1926). Numerous capillaries run under the end-plate of the vertebral body with branches perpendicular to it (Virgin, 1958; Wiley & Trueta, 1959).

In the embryo, the nucleus is supplied by a central axial artery running vertically from the osseous vertebra to the cartilaginous plate. There are also marginal vessels dorsally and ventrally (Böhmig, 1931; Hirsch & Schajowicz, 1952; Mineiro, 1965), which anastomose with one another and with the perichondral capillary system (Übermuth, 1930). The vessels become obliterated in the growing child, leaving scars in the hyaline end-plate. "The nucleus pulposus and the annulus fibrosus are completely without vessels during every phase of the individual's adult life" (Hirsch & Schajowicz, 1952). In the outer layers of the ligaments, there are a few small vessels but these do not penetrate the annulus.

The innervation of the lumbar segment is provided by the meningeal branch, which runs recurrently through the intervertebral foramen and divides into a cephalad and a caudad branch behind the pedicle, supplying the ligaments and periosteum as well as providing peri-

vascular branches to the epidural region and dura mater. Posterior branches run to the transverse process and articular processes as well as along the arch to the interspinous ligament (Pedersén, Blunk & Gardner, 1956). Tsukada (1938) reported neural elements in both the annulus fibrosus and the nucleus pulposus, while Roofe (1940) found them in the outer layer of the annulus fibrosus. Most studies, however, confirm the presence of nerves in the longitudinal ligament but not in the annulus (Keyes & Compere, 1932; Coventry, Ghormley & Kernohan, 1945; Wi-berg, 1949; Hirsch & Schajowicz, 1952; Mulligan, 1957; Jackson, 1966). Implantation of nucleus tissue in the rabbit produces an auto-immune response (Bobeckko & Hirsch 1965) with local inflammatory reaction. Rupture of the annulus fibrosus often leads to the formation of granulation tissue or fibrous connective tissue (Andraé, 1929; Eckert & Decker, 1947; Lindahl & Rexed, 1951), this can result in secondary vascularisation of the disc and might permit the ingrowth of accompanying nerves (Hirsch & Schajowicz, 1952).

Following improvements in staining techniques, the presence of sensible nerve endings in the peripheral parts of the annulus has been verified by Hirsch, Ingelmark & Miller (1963) using intravital methylene blue and by Jackson (1966) with cholinesterase and silver impregnation. Miller was also able to demonstrate nerve endings between the trabeculae of spongy bone. Milgram & Robinson (1966) showed nerve endings in the Haversian system of cortical bone. According to Jackson (1966) the cartilaginous end-plates of the vertebral bodies are accompanied by nerves terminating in very thin branches and frequently forming open loops in the vascular channels of the cartilage plates. This may be of special interest in view of the frequent and early occurrence of degenerative foci located in the greatest concavity of the end-plate, (e.g. Übermuth, 1930; Coventry, Ghormley & Kernohan, 1945; Töndury, 1955).

## **Previous studies of mobility and stability in the lumbar spine**

### *Studies of motion utilizing cadavers.*

The mobility of the spine has been repeatedly studied by means of measurements on cadavers ever since the time of Galen (for an extensive review see Andersson & Ekström, 1940-41).

The initial position for measurements has been defined by Strasser (1913) as the static equilibrium adopted by the upper vertebral body when it is uninfluenced by external forces or muscular forces. He determined the position of the upper body in relation to the sub-adjacent one in terms of the three angles between the mid-lines of the bodies projected in the

sagittal, the frontal and the horizontal planes. Virchow (1911, 1928) studied the segmental mobility on a ligamentous spine as follows: with the specimen's caudal vertebra held in the horizontal position, plaster casts were made of the specimen in the mid-position as well as after manual flexion and extension. The specimen was then divided in the sagittal plane and macerated, after which the section surfaces were painted white and marked with a sagittal line. The two halves of the specimen could now be placed separately in the plaster casts and moved between the three positions while measuring the change in angle. Virchow allows that the method is laborious, for which reason he only examined one specimen, only a part of the spine and only in the sagittal plane. Andersson & Ekström (1940—41) measured the range of movement for individual lumbar segments in the sagittal and frontal planes, using three specimens and varying loads. The range of movement was transferred onto a scale by means of a small mirror fitted ventrally and laterally respectively in the periphery of the vertebral body. These authors point out that previous results were somewhat arbitrary because the movement was obtained manually with a variation in the strength of the examiner's arm, so that the specimen's elastic limit was either not reached or exceeded. It proved difficult to achieve rotation in a well defined plane. The total movement ( $-5^{\circ}$  to  $+12^{\circ}$ ) was partly dependent upon the elasticity of the vertebral bodies. Rotation was found to occur around varying momentary axes, the positions of which were not determined.

Fick (1904) compared the mobility of the spine with the deformation of an elastic rod, the flexibility of which in all directions is directly proportional to the square of the height and inversely proportional to the square of the area of cross-section or the fourth power of the diameter. Lucas & Bresler (1961) determined the theoretical critical load ( $P_{cr}$ ) for a segmental column composed of alternating rigid and elastic elements and found good agreement with the empirical values for three human ligamentous spines.  $P_{cr}=1.95-2.62$  kg for the entire spine fixed at the sacrum only; with the upper vertebral body supported, this value is increased about tenfold.<sup>1</sup> They also calculated rotation/moment ratios for various levels of the spine. Evans & Lissner (1959, 1965) determined the energy absorption when specimens were loaded vertically and transversally. The highest value was found for vertical loading, with an average of 300 inch pounds (3.4 kgm). Ruff (1950) reported a figure of 4.5 kgm for specimens comprising six vertebrae and demonstrated that the moment of inertia is greater for flexion than for lateral bending.

<sup>1</sup> The critical load is the vertical load that causes stability failure or buckling of the rod (the spine).

*Roentgenologic studies of motion in vivo.*

The normal movement of the spine in vivo has been studied roentgenologically by a large number of authors (Calvé & Lelièvre, 1913; Junghanns, 1931; Backe, 1931; Dittmar, 1930—31 a, 1931 b; Elward, 1939; Alvik, 1949; Tanz, 1953; Leger, 1956; Allbrock, 1957; Schalimtzek, 1958; and others; see Table 2). A reliable assessment calls for extremely refined techniques. Subluxation between lumbar vertebral bodies with neural arches intact (pseudospondylolisthesis, retro- and anteposition) have been demonstrated by e.g. Junghanns (1931), Johnson (1934), Smith (1934), Severin (1943), Knutsson (1944), Melamed & Ansfield (1947) and Hagelstam (1949) and horizontal translation (instability) by Knutsson (1944), Gianturco (1944), Fletcher (1947) and Schalimtzek (1958). Knutsson (1944) considers that instability is an early sign of disc degeneration. Willis (1935) denies the occurrence of "backward displacement", which he considers to be an optical illusion. In X-ray examinations during movement in the sagittal plane, Hagelstam found up to 2 mm horizontal translation in normal cases; instability was demonstrated in case of lumbago-sciatica, but seldom exceeding 3 mm. Examining movement in the sagittal and frontal planes in a single case, Dittmar (1930) showed that sagittal and frontal rotation in the motion segment occur around different momentary axes. His technique for assessing the roentgenograms is the same in principle as that previously used by Virchow for autopsy specimens. Dittmar's calculations, however, are based on the assumption that the axis of motion, according to Fick, passes through the centre of the nucleus, (located in the posterior third of the disc, according to Schmorl, 1928). Rådberg (1954), in conjunction with discography, found that instability displayed before the injection (0.5 cc) disappeared afterwards but could be demonstrated again 24 hours later. During discography Roaf (1960) found that the position of the nucleus in the disc is not changed by eccentric loading of the specimen. Müller (1933), in an X-ray study of malrotation in scoliotic spines, found that there is an apparent lateral displacement due to the (longer) frontal diameter of one vertebral body being projected

Table 2. *Lumbar motion according to Backe, Dittmar and Leger.*

Level	Bending forward			Bending backward			Bending to the side		
	B.	D.	L.	B.	D.	L.	B.	D.	L.
L1-L2	2.0	3.0	6.5	6.6	5.5	9.5	3.5	3.25	8.0
L2-L3	3.0	8.3	10.5	8.0	4.0	7.5	4.0	2.75	9.0
L3-L4	3.0	8.3	12.5	9.0	5.5	5.0	5.4	5.75	9.5
L4-L5	3.7	14.3	17.0	10.2	3.5	4.0	4.7	4.75	7.0
L5-S1	2.2	—	12.0	16.4	—	9.5	3.4	—	1.5

over the (shorter) sagittal diameter of the other. Using a model of the spine, Tideström (1958) demonstrated how combinations of movements in the sagittal and frontal planes produce torsion in the spine without there being any rotation in the vertical axis of the segment. Hoag, Kosek & Moser (1960) have described a method for analysing movements in the spine, based upon Euler's theorem: If two solid bodies move in relation to one another in a plane, the movement can be described as a rotation in the plane about an axis perpendicular to this, the centre of the movement being obtained as the intersection of the normals to lines connecting the respective positions of two arbitrary points in two phases of the movement. They found that a centre of movement calculated in this manner lay dorsal of the centre of the disc in flexion and ventral in extension. They determined the range of movement by superimposing three roentgenograms, representing the mid-position and the two extremes in the plane.

#### *Role of the musculature.*

Electromyographic studies (Joseph, 1962; Asmussen & Klausen, 1962; Klausen, 1965 and Nachemson, 1966) have shown that in the upright posture very slight muscular activity is required to balance the spine, which thus adopts a position of equilibrium when influenced solely by the superimposed body weight. In the sitting posture there is a kyphosis of the lumbar spine and backward rotation of the pelvis, so that the centre of gravity lies 4.5—10 cm ventral to the sacral promontory. In the upright posture, the pelvis is rotated forwards with lordosis of the spine, so that the centre of gravity lies dorsal to the promontary (Åkerblom, 1948; Keegan, 1953 and Leger 1959). Loading of the trunk in the upright posture straightens out the lordosis (Asmussen & Klausen, 1962).

At the level of L 5, the superimposed body weight amounts to about 60 per cent of the total body weight (Ruff, 1950). The principles of simple levers have been applied to calculate the force required in the erector muscles to balance the body in forward flexion. The load on the disc of L 5 has been estimated by Strait, Inman & Ralston (1947) to five times the superimposed body weight. Similarly Steindler (1955) and Mattiash (1956) have calculated that a burden which is lifted with the body flexed and the arms hanging down exerts a load ten to thirty times as great on the lowest lumbar disc. Such calculations result in loads on the lumbar spine that are out of all proportion to its physical properties.

When heavy weights are lifted from the floor, the electromyographic activity during the first phase is low in the erector spinae and very high in the abdominal muscles (Floyd & Silver, 1955; Morris, Benner & Lukas,

1962, Ikata, 1966) but the intrathoracic and intra-abdominal pressure, measured directly with a manometer, is greatly elevated (Davis, 1956, 1959 a, b; Bartelink, 1957; Morris, Lukas & Bresler, 1961; Eie & Wehn, 1962) and this is calculated to relieve the load on the lumbar discs by 30—40 per cent. The aorta, too, has been held to play a considerable role in stabilizing and relieving the spine in vivo (Schantz, 1931). Using chronocyclophotography, Davis et al. (1965) demonstrated that "lumbar movements usually consisted initially of slight flexion, being followed by continuous lumbar extension . . . When lifting with bent knees the delay in onset of continuous lumbar extension was proportional to the weight of the load".

The lumbar intradiscal pressure has been measured in various postures in vivo (Nachemson, 1965). Bending forwards from the upright posture (body weight 70 kg), the total load on the disc of L 3 was calculated to 150 kg and was somewhat greater than this for the sitting posture bending forwards. When the subject held 10 kg in each hand, the load on the disc was increased by 70 kg.

## Previous studies of physical properties of vertebrae and discs

### *Bone tissue and vertebral bodies.*

The reaction of bone to mechanical forces has been the subject of repeated study (for reviews see Evans, 1957, and Knese, 1958). Bone may be regarded as a heterogenous or anisotropic material, composed of collagenous fibrils and apatite crystals, varying in its porosity and moisture content (Dempster & Liddicoat, 1952). Bone has been described as a multiphase system comparable with concrete or fiberglass (Knese, 1958; Currey, 1964; Mack, 1964). Its structure is determined by the arrangement of the collagenous fibrils, the basic principle being the spiral. The individual fibrils lie in concentric layers, those in contiguous laminae lying at an obtuse angle to one another. Knese asserts that the collagenous fibrils in bone are prestressed.

The physical properties of cortical bone have been investigated with reference to elasticity, viscosity and plasticity by Sedlin (1965) and by Sedlin & Hirsch (1966). These properties have been described by Sedlin in a rheologic model for cortical bone.

In loading tests on a cube of spongy bone from an adult lumbar vertebra, Rauber (1876) reported a breaking strength of 84 kg/cm<sup>2</sup>. In loading tests on whole bodies from lumbar vertebrae, Messerer (1880) found that the breaking strength varied between 22 and 78 kg/cm<sup>2</sup>. The first satisfactory report of compression tests on a sizable material of vertebral

bodies (52 vertebrae from 50 individuals) was published by Lange (1902). Each specimen consisted of three vertebral bodies (with the vertebral arch removed) and the intermediate intervertebral discs. The body at each end had its outer half sawn off horizontally and the specimen was loaded between two mutually independent metal plates, using a 250 kg lead weight which was lowered onto the loading plate with a double-armed lever. Two markers 13—14 mm apart were applied ventrally in the sagittal plane of the middle vertebral body. By placing an extensometer against the two pins, the deformation resulting from increments to the load could be read off from a scale between the long arms of the extensometer. Lange pointed out that his method gives the deformation between fixed points in the object measured and he rejected all methods that require the use of external reference points (e.g. a cathetometer, mirror devices, dial indicator between the loading plates). After the test, the vertebral body's area of cross-section was traced and determined by weighing. The breaking strength varied between 15 and 56 kg/cm<sup>2</sup> and the elastic limit between 5 and 30 kg/cm<sup>2</sup>. The modulus of elasticity was calculated to approx. 12,000. It seems, that Lange was unable to avoid buckling of the specimens since the distance between the measuring points sometimes increased.

Göcke (1926, 1931) compressed lumbar vertebrae from autopsy specimens in an Amsler materials testing machine and compiled stress-strain diagrams. Breaking strength was said to be 57—70 kg/cm<sup>2</sup> and the compression at the breaking point 15.5 per cent. The diagram was markedly S-shaped with a large initial deformation, suggesting adaptation at the loading surfaces (since the deformation was measured between the jaws of the loading apparatus). Fully comparable loading tests, with similar results have been undertaken by Perey (1957), Decoulx & Rieunau (1958) and Eie (1966). Ruff (1950) determined the ultimate strength of specimens comprising three vertebrae and the intermediate discs. Because the specimens tended to jack-knife, the surfaces of the outer vertebrae were sawn obliquely so that only the ventral part of the vertebrae received the primary load.

In loading tests on vertebrae with intermediate discs, the weakest part of the system has proved to be the end-plate (Friberg, 1941; Perey, 1957; Brown, Hansen & Yorra, 1957; Decoulx & Rieunau, 1958; Hardy, Lissner, Webster & Gurdjian, 1958).

In order to elucidate the aetiology of spondylolisthesis, Turner & Markellow (1930) made unsuccessful attempts on 20 autopsy subjects to produce isolated fracture of the laminae by direct blows to the lumbar spine or by forced extension and flexion. Rove & Roche (1953) repeated the

attempt in vain on 50 stillborn babies, whereas Hitchcock (1940) required little force to produce bilateral or unilateral laminar fractures by a combination of flexion, lateral flexion and torsion on specimens from 8-months foetuses and babies up to 10 months.

Arima (1959) loaded a two-dimensional model spine of photo-elastic material and showed that maximal stress was concentrated in the region corresponding to the isthmus.

Loading tests on individual processes of the vertebral arch have been made by Tylman & Ramotowsky (1961), Harrington (1962) and Waugh (1966) in order to find suitable attachments for devices to correct scoliosis. The spinous and transverse processes could be loaded with 15 kg at the most, while the pedicles could take more than 100 kg without fracturing.

#### *Loading tests on discs.*

Loading tests on discs have been undertaken with all or part of the adjacent vertebrae retained as a support. The vertical compression has been measured between the jaws of the loading apparatus, the vertebrae being regarded — for the loads in question — as solid, non-compressible parts of the specimen (Göcke, 1932; Virgin, 1951; Ingelmark & Ekholm, 1952; Hirsch & Nachemson, 1954; Brown, Hansen & Yorra, 1957; Virgin, 1958; Eie, 1966). The bulge of the annulus fibrosus during vertical loading has been measured by Hirsch & Nachemson (1954) and by Brown, Hansen & Yorra (1957), who report that both compression and bulging are somewhat greater in degenerated than in healthy discs. Göcke (1932) found that in young individuals with a high water content in the nucleus, the disc displayed considerable elastic deformation on loading; In adults the elasticity was complete, at least for loads under 70 kg. Damage inflicted upon the annulus fibrosus and end-plates did not affect the elastic function of the disc. Virgin (1951) repeated this test and verified Göcke's results, emphasising that the stress-strain diagram indicates a viscous elasticity. Complete recovery is modified by the duration of the force. "The intervertebral disc reaches its greatest state of efficiency in adult life — that is, when the nucleus pulposus has disappeared as an entity. The function of the disc appears not to depend upon the presence of the nucleus: rather does the presence of the nucleus indicate immaturity of the disc." Hirsch (1951) used an elastometer to record the tension in the annulus fibrosus during vertical loading. The results for degenerated discs varied greatly and it was concluded that the structural changes in the intervertebral disc altered the conditions in the motion segment, permitting pathological movements.

Nachemson (1960) developed a method for the direct measurement of

intradiscal pressure and found that the pressure per unit area in the nucleus pulposus of healthy or only slightly degenerated discs is about 50 per cent higher than the applied load, while in degenerated discs it is lower or inconstant. Parallel compression of the disc gave lower pressure measurements than oblique loading from in front, behind or the sides (Nachemson, 1963).

The intervertebral disc is the primary load-carrying structure between the vertebrae. There is "no support for the idea that factors other than the discs themselves play any part in carrying loads applied vertically to the cross-section through the vertebral column" (Hirsch & Nachemson, 1954).

### The stabilizing effect of fusion — previous reports

There is an extensive literature on the survival and conversion of bone transplants (Chase & Herndon, 1955; Urist, 1960). Autopsy specimens after fusion (Bachlechner, 1921; Debrunner, 1921; Görres, 1922; Biesalski, 1923; Smith, 1923; Joisten, 1929; Odelberg-Johnson, 1934 and others) have been found to display bony union of varying stability. No true tests of strength were made until Eie (1966) was able to investigate the bending strength of two complete specimens of the spine with healed fusion of L4—S1. He fixed the sacrum in a vise and loaded the cranial vertebral body during forward flexion. One of the specimens ruptured at the disc between L 3 and L 4 at a load of 58 kg and a lever of 10 cm (moment force 585 kg cm) and the other fractured through the sacrum at 35.8 kg with a lever of 19.5 cm (moment of force 716 kg cm). He concluded that the fusion area is stronger than other parts of the spine. Unfortunately, the indications for the fusion operations are not reported, neither is the surgical technique nor the fusions' sagittal extension in the segment.

In order to test the mechanical effect of fusion, Hoessly (1916) performed experiments on the dog. In a control group, a vertebral body was chiselled out transperitoneally, which regularly resulted in a gibbus. In the experimental animals, fusion of two segments was performed with a paraspinal bone transplant. When the vertebral body in the centre of the fusion was resected two months later, no deformity arose. Specimens from the experimental group could be loaded vertically up to 30—40 kg. Albanese (1922) made similar experiments on the dog and verified Hoessly's results. Haas (1936) performed fusions on three series of dogs, which were sacrificed 30 days later. With fusion between the spinous processes only, no changes were observed in the intervertebral joints. With fusion between

laminae, movement was prevented and the intervertebral joints were partially destroyed. With fusion of the intervertebral joint on one side, marked changes were found on the unoperated side as well.

According to Haas (1940), growing dogs display a tendency to lordosis after fusion, whereas injury to the epiphyseal plates results in kyphosis. Dorsal fusion was performed together with curettage of the epiphyseal plates and vertebral bodies in 10 dogs and no deformity was found post-operatively. He concluded that the fusion had prevented kyphosis. In a subsequent experiment on 6 dogs, Haas (1946) resected as much of the annulus as possible transperitoneally and scraped the end-plates with a curette. The five dogs sacrificed after 122—146 days all had bony union and no movement could be found between the vertebral bodies, although there was a slight play in the intervertebral joints.

Kurtz & Horwitz (1936) tried out Hadras' method with metal loops round the spinous processes. They reported good primary fixation in 8 dogs but this did not last in any of the animals owing to resorption of bone around the loops.

Using autopsy specimens from 6 individuals aged 18—68 years Albanese (1922) prepared 10 specimens consisting of three vertebrae and the intermediate discs; on these he imitated osteosynthesis by placing metal rods paraspinally and fixing them together with screws. Having resected the middle vertebral body, he loaded the specimen from a lever. At a load of 60—78 kg one of the specimens fractured through the pedicles and the other through the apex of the spinous process.

Azéma (1932) performed loading tests on two specimens comprising L 2 to the sacrum from men in their forties. The sacrum was held in a screw vise and subjected to dynamic force along its longitudinal axis: the specimen buckled but there was no sign of vertebral displacement. The isthmus was then severed on both sides, whereupon the same force produced a 5 mm ventral displacement above the defect. After this, the lower three vertebrae were fixed to the sacrum with two metal plates. The same flexion and displacement was produced with a static load of 30 kg and the author concluded that Albee's method is insufficient in spondylolisthesis. The other specimen had metal plates attached to it between the transverse process of L 3 and the sacrum. Although flexion and displacement was produced after severance of the isthmus, it was less pronounced than in the preceding experiment. The osteosynthesis was considered to correspond to Lance & Auroousseau's technique, which was preferred to that of Albee.

The fixation potential of metal rods has been investigated by Witt et al. (1959) for vertical loading of specimens consisting of the pelvis, sacrum,

lumbar spine and lower thoracic spine. Long metal rods or Küntscher nails were fixed with cerclage or screwed to the spinous processes, transverse processes or vertebral bodies or else they were introduced intraosseously down the vertebral bodies. It was considered that reliable fixation of a section of the spine could be achieved only with two strong steel rods (Lane's plates) screwed paravertebrally and involving several segments. This also produced a remarkable straightening of the unfixed parts of the spine. The method cannot be applied in practice in vivo. Paraspinal fixation gave acceptable stabilisation except against torque. Harris & Wiley (1963) imitated bony union in autopsy specimens by embedding the vertebral arches in methyl acrylate. A combination of flexion and torsion produced spondylolisthesis, though usually as a secondary phenomenon in larger injuries. They considered that the weakest part of the fusion was the isthmus and that spondylolisthesis probably represents a stress fracture. Six specimens were examined but no details of the method were reported.

Arima (1958) studied the distribution of stress in photo-elastic models of a vertebral segments, with three different types of fusions, with the segment in the mid-position and in various degrees of ventral flexion. On the assumption that the isthmus is the weakest region of the fusion, fixation between pedicles and intervertebral joints was recommended for fusion in the mid-position or slight kyphosis. As kyphosis increases, a ventral graft places greater stress on the isthmus than before the operation. In pronounced kyphosis (gibbus) no type of fusion is effective.

In experiments on plastic models of the spine, Pennal et al. (1964) demonstrated that screws through the articular processes do not give reliable fixation of the motion segment. Little violence was needed to produce a fracture through the facets. Stability was improved, however, by a combination of paraspinal metal rods, while a contoured plate against the lamina proved four times as efficient as screws alone. These authors report similar results with experiments on autopsy specimens.

Unander-Scharin (1950) investigated the effect of dorsal fusion as a means of relieving the tension on the disc. Nine autopsy specimens comprising the lumbar spine and sacrum were subjected to osteosynthesis with metal rods fixed through the spinal processes of L 4, L 5 and S 1. The specimens were loaded vertically before and after the osteosynthesis with 12.5, 25 and 37.5 kg. During loading a pelotte was held against the annulus fibrosus with a force of 1, 2 and 3 kg respectively. The pelotte's penetration of the annulus increased within the fusion and decreased in the other, free discs; this was taken as a sign of load-relieving effect within the fusion and increased stress on the free discs.

### III Materials and methods

Preparatory investigations were first made into the possibilities of imitating fusion in a satisfactory manner on fresh spinal specimens. Once this had been done, loading tests were conducted in an Amsler materials testing machine in conjunction with measurements of intradiscal pressure according to Nachemson. It was soon found that the results varied greatly according to the type of fusion employed and the way in which the load was applied (Rolander, 1961, 1963). Specimens consisting of more than one segment could not be prevented from buckling, which meant that the distribution of the applied load could not be defined. The deformation of the disc as well as of the vertebrae was such that it could not be followed with measuring dials attached to the loading device.

Experience from preliminary investigations on some thirty spinal specimens has resulted in the assembly of the apparatus described below and the definitive design of the method.

#### Preparation of the specimens

##### *Preparation of the specimens*

During routine autopsies at the department of pathology, Sahlgrenska Sjukhuset, specimens consisting of the entire lumbar spine were taken, if possible together with the upper part of the sacrum. The specimens were hermetically sealed in plastic bags and stored in a deep-freeze at  $-29^{\circ}$  C. Prior to testing they were left to thaw at room temperature, removed from the plastic bag and dissected free from fat and muscle, taking care to preserve the ligaments. Each lumbar spine was divided as a rule into two specimens, each consisting of two vertebrae with the intermediate disc and ligaments. Specimens incorporating two or more discs were sometimes used for special purposes. The outer end-plates of the vertebrae were scraped clean of disc tissue, after which the bottom half of the caudad body was embedded with plastic in a metal form designed for use with the loading apparatus described below. In order to avoid play as a result of shrinkage, the embedding material was permit-

ted to spread over the edges of the metal form and was also transfixed with steel nails running diagonally through the sides of the form. Polyester was used for embedding the specimen, with kaolin as a filler and reinforced with fiberglass. The cranial surface of the upper vertebral body was also covered with plastic to make a completely flat, horizontal loading surface (checked with a spirit level). No effort was made to line up the upper or lower plane of the disc horizontally. When the casting started to harden, the specimen was once more sealed into a plastic bag and stored at  $+6^{\circ}\text{C}$  in order to reduce the temperature rise during the hardening process. A piece of moist blotting paper was placed next to the specimen, though not touching it, so as to maintain a high relative humidity. The plastic casting having cooled, a fixture was used — with the specimen still wrapped in foil — to drive four centre nails into each vertebra: one in the spinous process, one in the ventral periphery of the body and one in the lateral periphery on either side of the body. The nails were placed so that each quartet lay in a horizontal plane, with a distance of 20—25 mm between the corresponding nails in the two vertebrae (depending on the height of the disc). The ventral and dorsal nails represent points in the sagittal plane of symmetry, while the lateral nails lie in a frontal plane at right angles to the sagittal plane (see Figs. 1, 15 and 16).

Various methods were tried to imitate healed fusion. Metal plates and screws proved inadequate, since the screws created structural faults and the specimen could not be loaded up to physiological levels. The best results have been achieved with plastics (Mandarino, 1960; Rietz, 1964). All plastics, however, are sensitive to fat during hardening and will not adhere properly to fresh bone. Nevertheless, good fixation can be obtained if, during hardening, the plastic material shrinks somewhat round the embedded parts of the bone. Polyurethane expands during hardening and consequently is unsuitable. Although epoxy-resin has many advantages, hardening either takes an excessive time or is highly exothermic. Polyester (Soredur H40), which has an elastic modulus for bending of  $39.000\text{ kg/cm}^2$ , gives suitable shrinkage. The hardening time is easily controlled but with the quantities required for experimental fusion ( $50\text{--}150\text{ cm}^3$ ) the maximum temperature is about  $90^{\circ}\text{C}$ . By taking a number of special precautions, however, hardening could be achieved without exceeding physiological temperatures measured immediately ventral of the fusion. Thus, the casting was made in a plastecine mold which screened the rest of the specimen; kaolin was used as a filler; the casting was applied in layers and the specimen was stored at a low temperature during the exothermic period of hardening (Fig. 2).

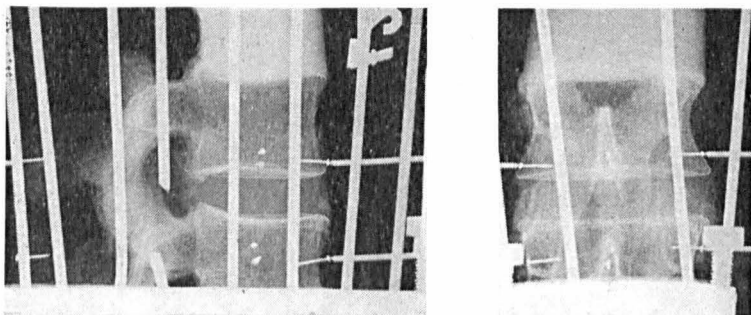


Fig. 1 (a, b).  
*Lateral and antero-posterior X-ray views of a specimen (nr 14 L2—L3) in the compression apparatus.*

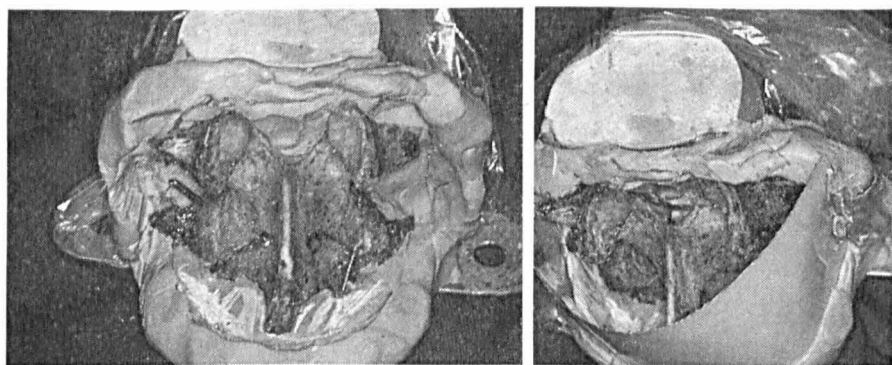


Fig. 2 (a, b).  
*Specimen nr 14 L2—L3 seen from the posterior-superior aspect in preparation for casting. The anterior elements of the specimen are isolated by plastecine and the remainder of the casting mold is made up of a piece of X-ray film.*



Fig. 3. *The complete casting of a fusion type 3 (c.f. Fig. 4).*

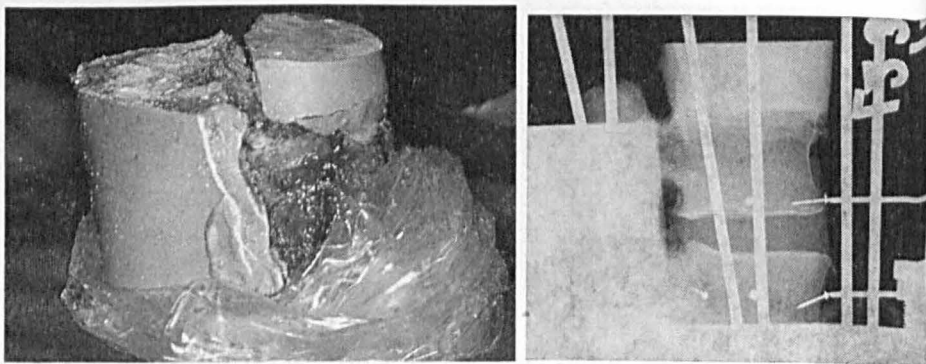


Fig. 4 (a, b). *Fusion type 3, specimen nr 14 L2—L3.*

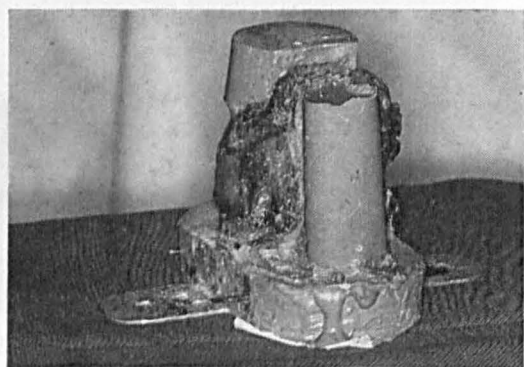
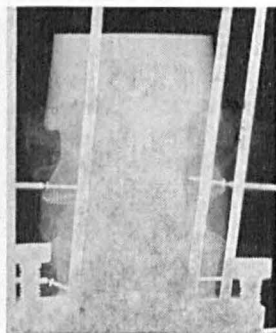
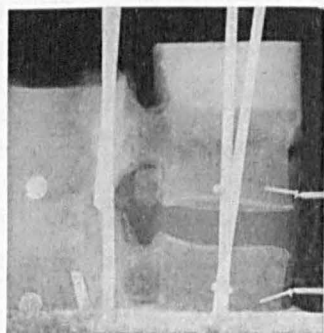
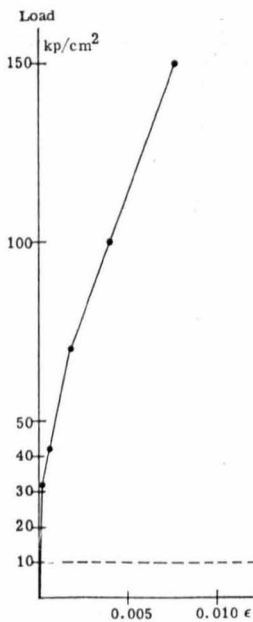


Fig. 5 (a, b, c). *Fusion type 1, specimen nr 23 L2—L3.*





Position of extensometers.

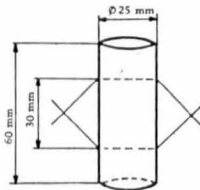


Fig. 6.  
Stress strain relation for compression of a plastic (polyester) cylinder.

The fusion was cast onto the vertebral arches in such a way that these were fixed to one another and to the base plate of the specimen in an approximately cylindrical form, as illustrated in Figs. 4—5. In order to reinforce the adhesion to the bone and prevent the specimen from being pulled out of the casting by flexion forces, the spinous processes and other relevant parts of the posterior segment were transfixed with screws before casting. The fusion was not more than 8 cm high and at least 3 cm in diameter. It may be assumed, that there is a wide range of stability of fusions achieved under intravital conditions. The experimental fusions were dimensioned so that there was no measurable deformation within the fusion mass (see Fig. 6) at the loads used.

Three types of experimental fusion were produced:

Type 1, involving only the spinous processes,

Type 2, involving the spinous processes, laminae and intervertebral joints,

Type 3, involving the spinous processes, laminae, intervertebral joints and transverse processes.

## Experimental devices

The investigations were made with the following apparatus.

### 1. *Compression apparatus* (Fig. 7).

The compression apparatus has a cast iron base, four steel corner pillars and, on top, a steel plate 10 mm thick. A stage in the base can be adjusted with micrometer screws in two directions at right angles to one another in the horizontal plane and can also be rotated about a vertical axis. In addition, the stage can be rotated on a horizontal axis so that it slopes to a variable degree to the horizontal plane. The specimen in the metal form described above is securely bolted to the stage. In the centre of the top plate of the apparatus there is a piston, the connecting rod of which runs in a stable ball bushing. The piston is driven by compressed air from a gas-tube, the rate of loading being controlled manually with standard valves.

The load is applied from the piston via a measuring head (Fig. 8) with two electro-dynamometers (Bofors KRK-1), each with a range of 0—100 kp. The loaders are fastened with turn-buckles to a plate of hardened steel 10 mm thick, down the middle of which there is an edge designed to impart a linear, vertical load. The angle of this edge to the horizontal plane is adjustable with a screw. The loading unit is rotatable about the piston, its movements being indicated on a graduated dial. Between the top of the specimen and the loading edge there is a steel face-plate and on this a trolley resting on four ball-races. With this arrangement, the specimen's freedom of movement with respect to rotation and horizontal translation is limited to a plane perpendicular and at right angles to the loading edge. Consequently, the loading force exerted on the specimen can be clearly defined in terms of size, position and direction. Each load can be reproduced even though the specimen has been removed from the apparatus in the interval.

### 2. *Electrodynamometers*.

The principle of the dynamometer is based upon the deformation of a ring which is loaded at two diametrically opposite points. This induces elongation at the periphery and this is converted into its electrical equivalent by means of strain gauges. The force to be measured is transmitted via two end-blocks; these have some lateral play and are consequently almost completely insensitive to bending moments. The electro-dynamometers are wired as balanced bridges and calibrated with standard precision resistances (Fig. 9).

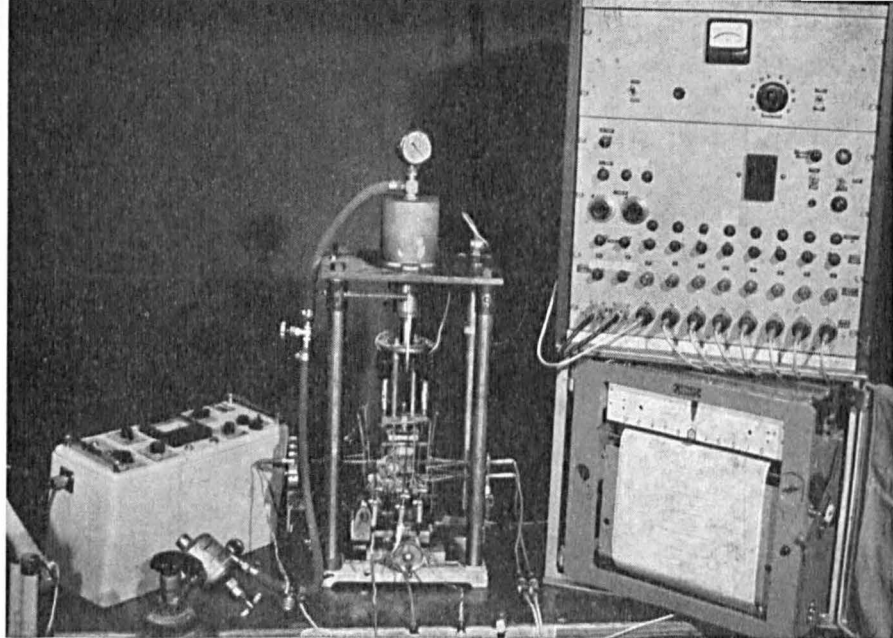


Fig. 7.  
*Complete testing apparatus with the amplifier for the disc pressure transducer on the left, loading device in the center and carrier frequency system, monitor, and recorder on the right.*

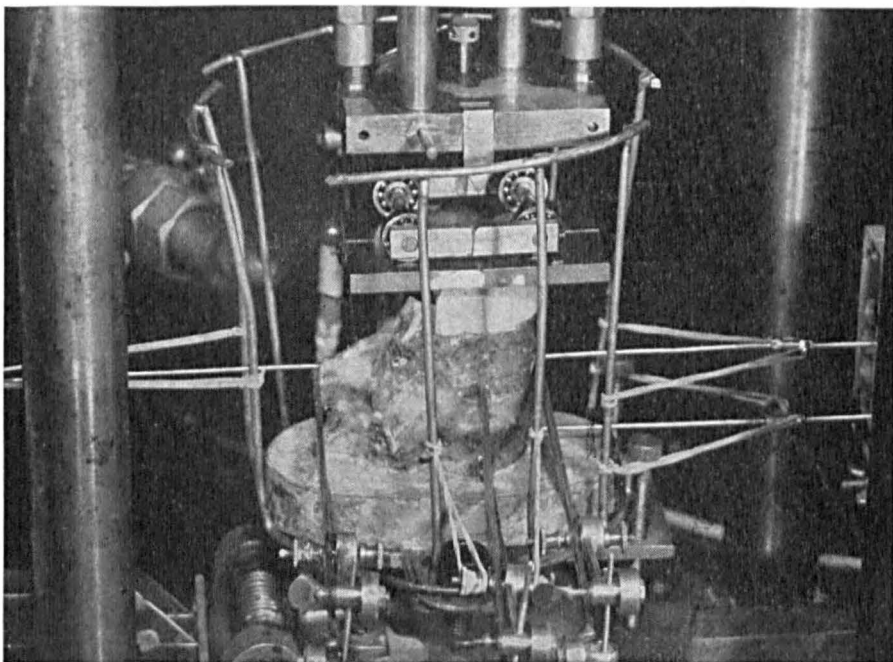


Fig. 8.  
*The specimen fixed beneath the loading head with the pressure transducer visible in the background on the left, and the applied displacement gauges and extensometers seen surrounding the specimen.*

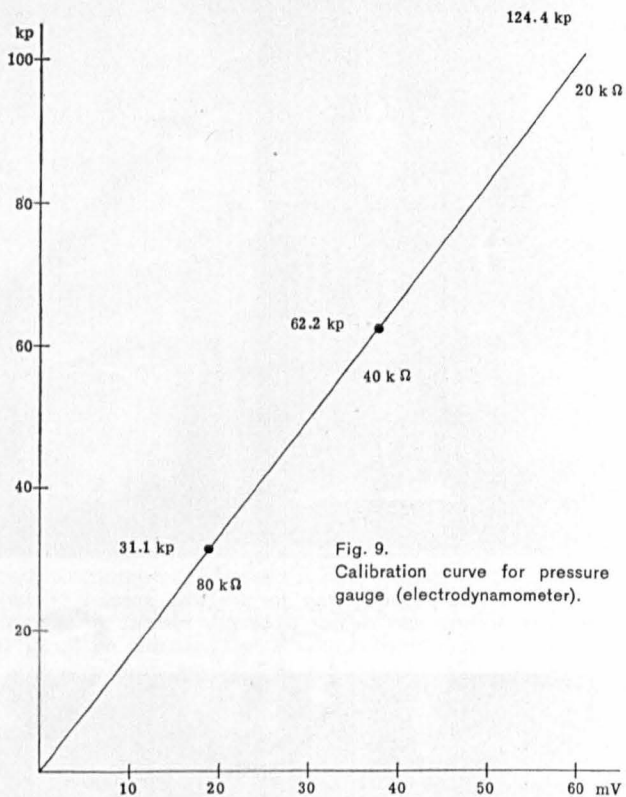


Fig. 9.  
Calibration curve for pressure gauge (electrodynamometer).

Fig. 12.  
Extensometer

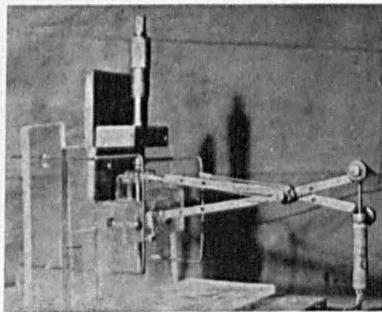
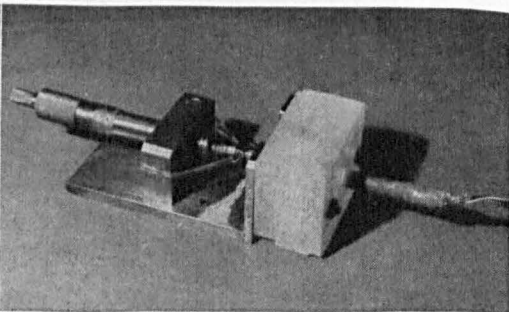


Fig. 10.  
Displacement gauge



*Specially designed apparatus for mechanical calibration with micrometer.*

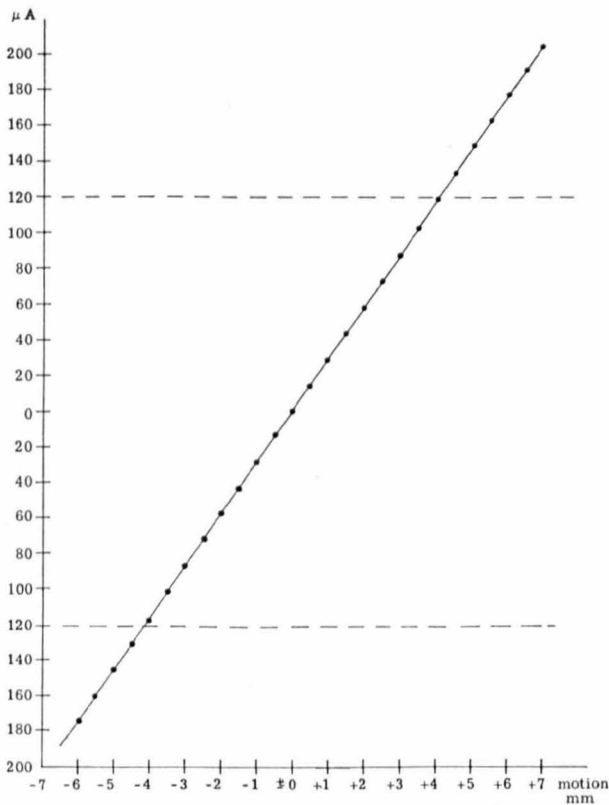


Fig. 11.  
Calibration curve for differential transformer nr 1.

### 3. Displacement gauges (Fig. 10).

For the measurement of displacements, a gauge of the induction type was constructed (Svensk elektronikonsult, Göteborg), known as a differential-transformer. The transformer is wound onto a teflon bobbin in which there is a movable soft iron core with a brass shaft and a measuring tip of anti-magnetic stainless steel. The differential-transformer is 40 mm long with an external diameter of 8 mm. Including the leads it weighed 10 g. The millimeter thread of the bobbin can be used for simple mechanical calibration since one revolution of the differential-transformer in the housing corresponds to a 1 mm displacement of the core. The gauge is however wired as a balanced bridge and by virtue of its electrical design, it is simpler to calibrate with a fixed precision resistances. The linear deviation for the range of measurements in question is less than 1 per cent (see Fig. 11). The gauges have been calibrated

regularly against a micrometer without it being found necessary to undertake any correction of the precision resistance. Three gauges of this type have been used for registering the movements of the specimen in the horizontal plane (translation).

#### 4. *Extensometers.*

The design and mechanical calibration of the extensometers produced for measuring displacement in the vertical plane are illustrated in Fig. 12. The extensometer is shaped like a scissors, with pointed ends to the "blades" and a differential-transformer (see above) mounted at the ends of the "handles". It is of brass, 15 cm long, with a total weight of 50 g. All its joints are fitted with ball-bearings. The position of the central axis makes it possible to suspend the extensometer in rubber bands against the specimen with a satisfactory balance and minimal measuring pressure. The extensometer can be zeroed in keeping with the initial distance between the measuring tips. Its range of linear measurement is the same as for the differential-transformer when used by itself. Five extensometers of this type have been used for the measurements: three to measure the vertical deformation of the disc, one to show the movement between the spinous processes and one to measure any deformations in the periphery of the upper vertebral body.

#### *Recording devices.*

The two dynamometers and eight motion gauges were connected to a specially designed, servodriven switch monitor (AB Svenska Philips and Svensk Elektronikkonsult, Göteborg). A carrier frequency system (Philips BF 2) is connected manually or automatically at a stage rate of 0.3—1 gauge/sec, each channel having a special unit for balancing and zeroing, an amplifier and a calibration resistance. The signals are transmitted to a one-channel potentiometer recorder (Philips PR 2210 A-21). The monitor also connects two reference channels and two unutilized steps, so that a single cycle (loading interval) lasts 14—46 sec. The recording paper is 250 mm wide and the error of the writer is 0.25 per cent of full deflexion. A paper speed of 75 mm/min was used throughout. As a rule, the displacement gauges were calibrated so that full deflexion on the writer corresponded to  $\pm 5$  mm, the figure for the dynamometers being  $\pm 100$  kp. The reading error is  $\pm 5/1000$  mm and  $\pm 0.1$  kp respectively.

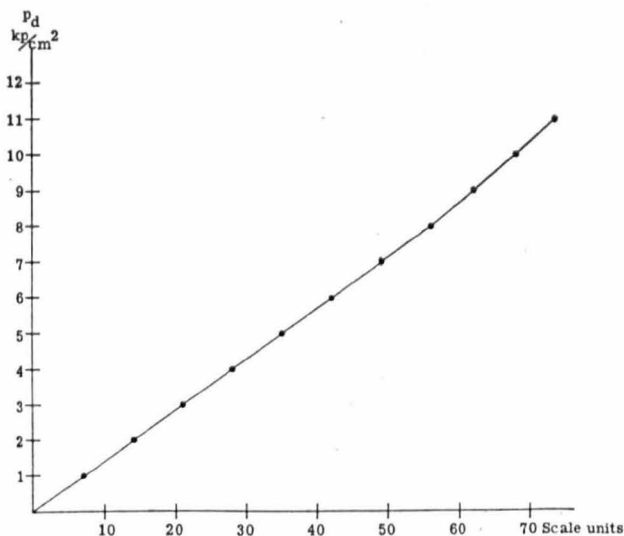


Fig. 13.  
Spec. nr 19, L3-L4  
Calibration curve for intradiscal pressure.

#### *Intradiscal pressure gauge.*

Intradiscal pressure was measured by the method described by Nachemson (1960). The discs is perforated with a needle, diameter 1.1 mm, closed at the end and fitted with a pressure-sensitive polyethylene membrane. The deformation of this membrane is transmitted via a closed, water-filled system to a mechano-electrical transducer of the Statham type (modified by Svema-Elementa, Sweden). The movement of the membrane is transmitted by the column of water to the copper membrane of the pressure transducer and converted via strain gauges into electrical equivalents and read off directly from the measuring bridge. The pressure transducer is calibrated against known pressures in a pressure chamber before and after each experiment. The error of the method has been calculated by Nachemson to approximately 3 per cent (Fig. 13).

#### *X-ray unit.*

The unit used was a portable machine with a 2 mm focus. The focus-film distance was 250 cm and the film-target distance 6 cm. Pictures were taken of the entire lumbar spine before dissection and also of each specimen in the loading apparatus without and with fusion in the sagittal and frontal planes and, at the end of the experiment, a picture in the specimen's longitudinal axis (Figs. 1 and 15). The enlargement is less than

3 per cent. The X-ray pictures were used for measuring the initial angle of the disc ( $\alpha_0$ ) as formed by the tangents to the projections adjoining surfaces of the vertebral bodies (Fig. 16). This angle has been given a positive sign in flexion and a negative in extension. A linear measure was provided in the X-rays by the projection of a bolt with a millimeter thread, which gave a scale divided into half millimeters. The linear dimensions of the vertebrae were measured from the frontal and sagittal projections with a pair of dividers (see Fig. 16, p. 44).

#### *Planimeter.*

After the experiments, the disc was sectioned horizontally and placed against a sheet of glass. The outline of the horizontal section was then copied onto tracing paper (Fig. 15) for calculation of its area with an Amsler planimeter to an accuracy of 1/10th cm<sup>2</sup>. The planimeter was checked by measuring a known surface of the same order of magnitude before and after each measurement of a disc. The planimeter was also used to calculate the mean height of the disc.

### **Description of the loading test**

The specimen, embedded in its metal form, is firmly bolted to the stage of the loading apparatus and encircled with a "cage" of brass rods. The clamps for the horizontal displacement gauges are then adjusted so that measuring rods of suitable length can be fitted horizontally in the specimen's sagittal plane and held against the centre nails with rubber bands between the cage and the shaft of the iron cores. Two gauges are lined up with the ventral measuring points on the bodies of the upper and the lower vertebra respectively, a third being lined up with the spinous process of the upper body. The extensometers for the measurement of vertical displacement are attached to the cage with rubber bands in a similar manner so that their measuring points are held against the pairs of centre nails on the two vertebrae. Thus one extensometer rests against the ventral aspects of the two vertebrae, one against each of their lateral aspects and one against the spinous processes. In addition, one extensometer is placed with both its measuring points against the upper vertebral body. In each case, the caudal centre nail serves as a reference point for the vertical displacement between the points of the extensometer. The extensometers are balanced by adjusting a lead weight suspended from the upper "handle" and the rubber bands are tensed just sufficiently to hold the measuring points against the centre nails. The loading stage has a very slight play which proved difficult to eliminate. It is, however, recorded by the motion gauge against the lower

vertebral body and the readings from the motion gauges against the upper vertebra can be corrected accordingly. It follows that all measurements are derived from points on the specimen and no external references are required.

The loading stage — with the specimen and motion gauges — is now adjusted so that the plane of the loading edge coincides with the frontal plane through the four lateral centre nails in the specimen. The steel plate and trolley are placed on top of the specimen, a trial load is applied and the angle of the loading edge to the horizontal plane is adjusted to obtain even compression in the frontal plane.

The disc is perforated anterolaterally or posterolaterally, the pressure-sensitive needle is inserted so that its pressure receptor lies in the centre of the disc and the pressure transducer is clamped to its stand.

The motion gauges and dynamometers are zeroed and calibrated. With the first dynamometer connected to the writer (channel 9, Fig. 14), the air valve of the compression apparatus is opened and the load is read

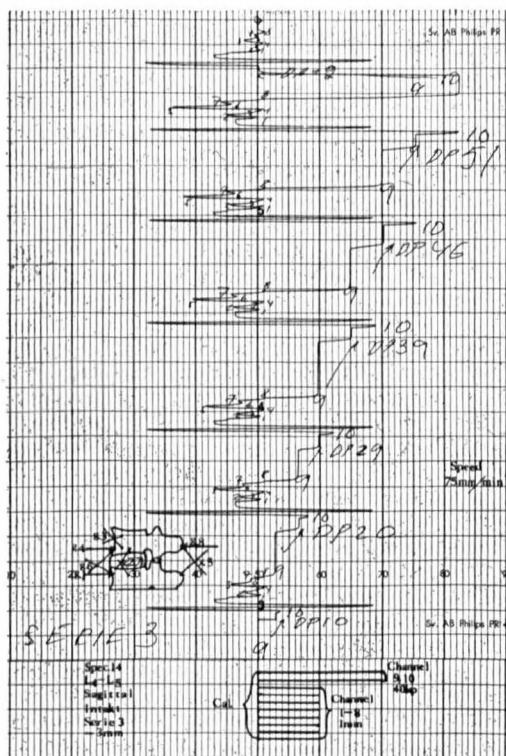


Fig. 14. Reproduction of a recording from a single loading sequence (series).

off. Once the desired load has been obtained, the air valve is closed and the switching unit is set for automatic registration of all the gauges. When the writer registers channel 9 a second time, the switching unit is turned off. The load is now increased one interval and the new readings of the gauges are recorded in the same manner as before. The intradiscal pressure at each load is also read off and recorded. The load is increased by stages to a maximum of 200 kp. The vertical gauge on the body of the upper vertebra is checked to ensure that there is no displacement of the body. Should any displacement occur, the specimen is unloaded. After unloading, recordings are made of residual displacements.

Once the residual displacement at the end of the first loading sequence has been recorded, the specimen and loading stage are shifted in the sagittal plane so that the same sequence of measurements can be repeated with ventrally (+) or dorsally (—) eccentric loads, the change in position as a rule being 5 mm at the time. A record is also generally kept of the degree of eccentricity (in millimeters from the initial position) at which the applied load results in compression of the specimen without altering the angle of the disc in the sagittal or frontal plane ("balanced position").

After the loading sequences in the sagittal plane have been completed, the specimen is turned  $90^\circ$  prior to studying rotation in the frontal plane (lateral flexion). For this, the vertical motion gauges are placed against the same measuring points as previously, whereas the horizontal gauges now coincide with the frontal plane, one against the lower and one against the upper vertebral body's right-hand measuring point and one against the upper vertebral body's left-hand measuring point. The measuring sequences described above are now repeated, first with the loading edge in the sagittal symmetry plane, then eccentrically to the right (+) and left (—).

Special measures such as division of ligaments, fixation of intervertebral joints with screws or resection of such joints, can be undertaken without removing the specimen from the loading apparatus and further loading sequences can be performed directly. The specimen has to be removed, on the other hand for the casting of fusion. The plastic cast is left to harden for at least two hours before the specimen is reinserted in the loading apparatus, after which the loading sequences can be continued under the same conditions as before.

Upon the completion of measurements on fused specimens, the disc is excised (as a rule this can be done without detaching the motion gauges) and the specimen is then loaded until it fractures.

Before being excised, the disc is generally injected with chromopaque. The area of the resected disc's horizontal cross-section is measured with the planimeter as described above. The pathological condition of the disc is assessed by macroscopic inspection.

After the vertebral specimen has been examined roentgenographically, it is sawn through for investigation of the fractures and to check that the fusion cast has not loosened from the bone or base plate.

### Terms and definitions

1. The *measuring points* of each vertebra have been numbered as shown in Fig. 15.
2. The distance between points 1 and 5 (L) has been measured on sagittal X-rays with an accuracy of 0.5 mm (allowing for roentgenographic enlargement) and rounded off to the nearest millimeter.
3. The *initial height* of the disc ( $h_1, h_2, h_3, h_4$ ) has been measured on X-rays as the distance between the edges of the vertebrae on the vertical line connecting each measuring point and its corresponding reference point. The *mean height* of the disc has been calculated by measuring the surface of the disc in the lateral X-ray with a planimeter and dividing the result by the sagittal diameter ( $d_s$ ).

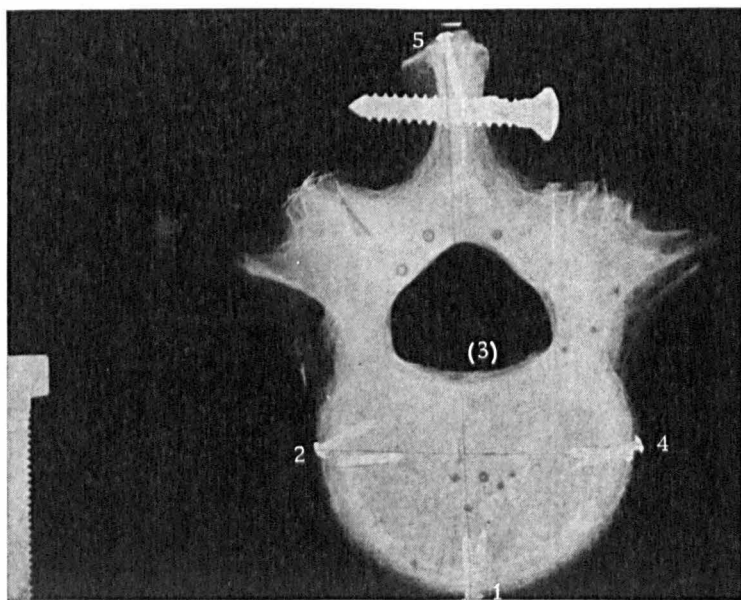


Fig. 15.  
Radiographic view of specimen nr 17 L1—L2 taken from above, demonstrating placement of measuring points 1—5 in the vertebra .

4. The area of the excised disc's horizontal cross-section ( $A \text{ cm}^2$ ) was traced off and calculated with the planimeter. The sagittal ( $d_s$ ) and frontal ( $d_f$ ) diameters of this section were also measured (see Fig. 17).
5. The intersection of the sagittal and frontal diameters has been called the disc's *geometric centre* ( $c$ ).
6. The *initial angle* of the disc in the sagittal ( $\alpha_0$ ) and frontal ( $\beta_0$ ) planes has been measured on the sagittal and frontal X-rays with a protractor as the angle between the tangents to the contiguous surfaces of the adjoining vertebral bodies (Fig. 16).
7.  $v_1$  and  $v_2$  are the angles of these sagittal tangents to the horizontal plane, with a positive sign when the tangent slopes ventrally and a negative when it slopes dorsally.
8. The change of angle in the sagittal plane ( $\alpha$ ) that arises when the specimen is loaded has been given a positive sign for flexion (positive

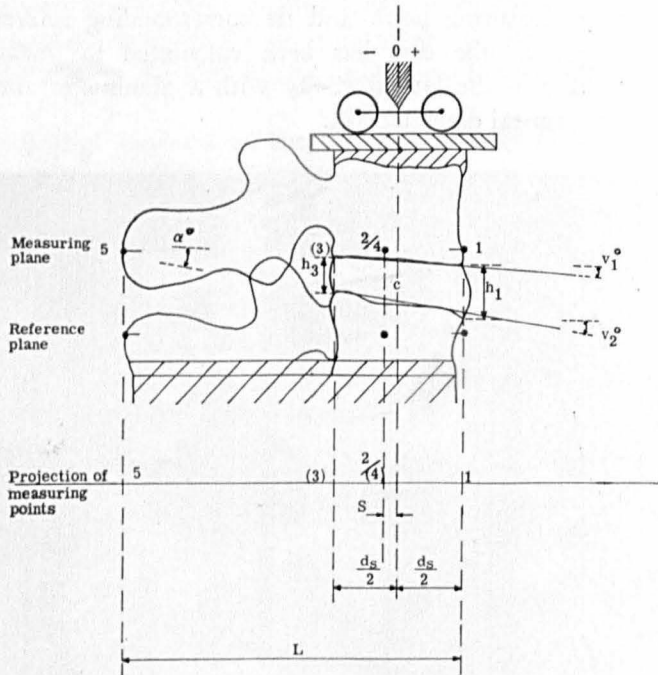


Fig. 16.  
Schematic lateral view of the specimen in the loading apparatus with dimensions applied.

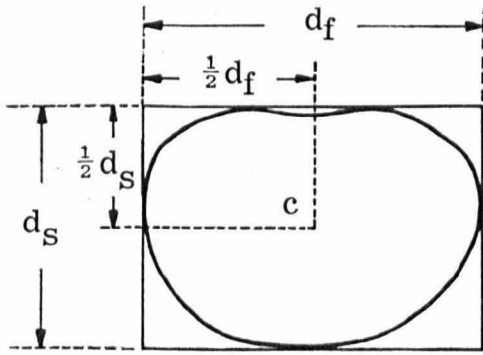


Fig. 17.  
Direct tracing of the sectioned disc (Spec. nr 17 L1—L2) with dimensions applied.

sagittal rotation) and a negative for extension (negative sagittal rotation).  
9. The change of angle in the frontal plane ( $\beta$ ) has been given a positive sign for lateral flexion to the right (positive frontal rotation) and a negative to left (negative frontal rotation).

10. Rotation around the longitudinal axis-torque- ( $\gamma$ ) is counted positive in the clockwise direction.

11. The *vertical displacement* ( $\delta_v$ ) of a measuring point is the recorded change in the distance between the measuring arms of the extensometer and carries the number of the measuring point ( $\delta_{1v}$ ,  $\delta_{2v}$ ,  $\delta_{4v}$ ,  $\delta_{5v}$ ) the sign being negative for a decrease and positive for an increase of this distance.

12. The *horizontal displacement* of a measuring point is designated in a similar way ( $\delta_{1h}$ ,  $\delta_{2h}$ ,  $\delta_{4h}$ ,  $\delta_{5h}$ ), with a positive sign for displacement ventrally and to the right and a negative for displacement dorsally and to the left.

13. S is a correction factor for measuring points 2 and 4 (see Fig. 16).

14. The *unit displacement* ( $\varepsilon$ ) is the quotient of the vertical deflection and the initial height for a loading interval and is designated according to the measuring point ( $\varepsilon_1$ ,  $\varepsilon_2$ ,  $\varepsilon_3$ ,  $\varepsilon_4$ ).

15. The lumbar spines used in this study have been numbered consecutively, each specimen being designated by this number and the vertebrae involved, e.g. no. 13, L 3 — 4. The discs are identified by the number of their cephalad vertebra.

16. Loading of the specimen has been done in stages from zero to a maximum, unloading has been done straight to zero. The displacements arising at each loading stage have been recorded for the individual measuring points. The loading sequences have been numbered consecutively

Scale: Each unit represents 0.5 mm displacement ( $\delta_x$  and  $\delta_y$ ) of the measuring point and 10 mm distance along the specimen.

Nr 14  
L4-L5

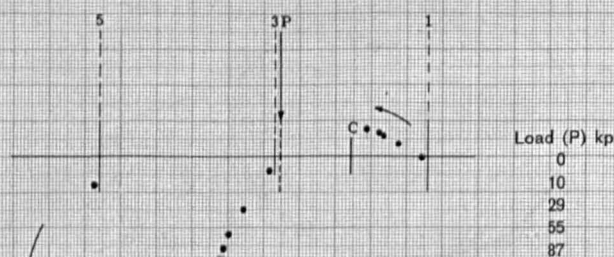


Fig. 18 a.  
Motion in the sagittal plane represented by horizontal and vertical displacement of points 1, 3 and 5 in an intact specimen with increasing load applied 20 mm behind the geometric centre.

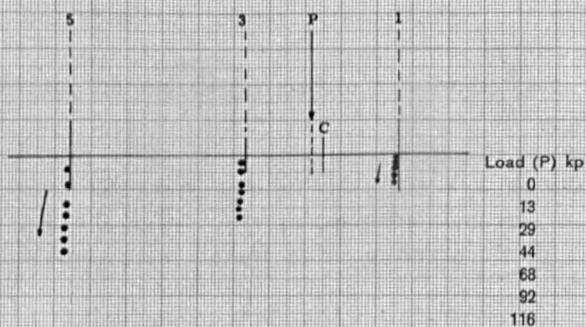


Fig. 18 b.  
load applied centrally (-3 mm).

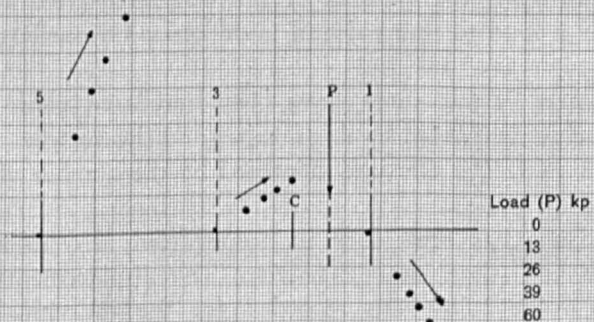


Fig. 18 c.  
load applied 10 mm in front of the geometric centre.

Fig. 19 a.

Motion in sagittal plane represented by horizontal and vertical displacement of points 1, 3 and 5 in a fused specimen with increasing load applied 20 mm behind the geometric centre.

Load (P) kp  
0  
(16)  
26  
50  
(73)  
100

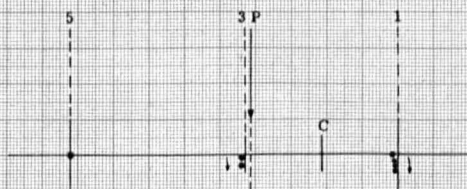


Fig. 19 b.

load applied centrally (-3 mm).

Load (P) kp  
0  
10  
21  
45  
66  
86  
106

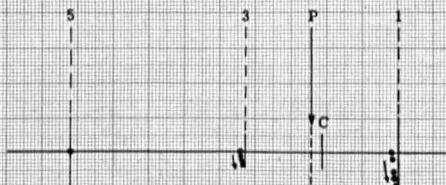


Fig. 19 c.

load applied 10 mm in front of the geometric centre.

Load P kp  
0  
12  
26  
41  
62  
82

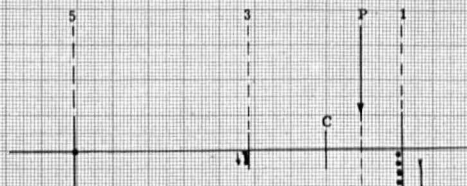
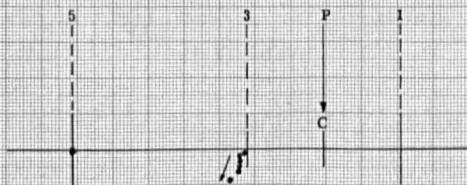


Fig. 19 d.

Fused spec. after excision of the disc; loaded centrally ( $\pm 3$  mm).

Load P kp  
0  
6  
20  
36  
52  
74  
99  
118  
134  
145



for each specimen, together with data characterising the experiment, i.e. loading in the sagittal plane or the frontal plane, position of the loading edge (eccentricity) and state of the specimen (disc removed, fusion, etc.).

17. *The eccentricity of the load* is the distance in millimeters from the geometric centre of the disc to the plane of the loading edge, with a positive sign ventrally and to the right of the centre and a negative dorsally and to the left. The eccentricity is also given non-dimensionally as the quotient of the above distance and half the diameter of the disc (see Fig. 16).

18. At a certain eccentricity, characteristic of each disc, loading elicits no tendency to rotation. This eccentricity has been termed the "*balanced position*".

19.  $M_0$  is the distance in the sagittal plane from the "*balanced position*" to the geometric centre.

20. The *load* (P) is given in kp (the unit of force that approximately corresponds to the unit of mass kg) or as the loading intensity =  $P/A$  kp/cm<sup>2</sup>.

21.  $\sigma/\epsilon$  is a ratio to compare different specimens for defined loads and measuring points.

22. The intradiscal pressure ( $p_d$ ) has been measured in kp/cm<sup>2</sup>.

### Method of analysis of the obtained data

All the measurements recorded by the writer (Fig. 14) were tabulated and graphs were drawn for each loading series to depict the displacement of the measuring points in the horizontal and vertical planes. The initial position of each measuring point is represented by the origin and its displacement is plotted against the corresponding stage of loading. The movement of the segment (deformation of the disc) is illustrated by plotting the measuring points in the sagittal and frontal planes on a common x axis showing their true distances from each other and the position of the loading edge. The vertical and the horizontal displacements are reproduced on an enlarged scale by way of illustration. Fig. 18 shows the rotation of an intact segment in the sagittal plane for central loading as well as for ventral (+) and dorsal (—) eccentricity.

Similarly, the segment's motion after fusion is illustrated by Fig. 19. Point 5 is embedded in the fusion cast and shows no displacement, while point 1 indicates compression for both negative and positive eccentricity. The deformation of the fused specimen after excision of the disc is exemplified in Fig. 19 d.

Scale: Each unit represents 0.5 mm displacement ( $\delta_x$  and  $\delta_y$ ) of the measuring point and 10 mm distance along the specimen.

Nr 13  
L1-L2

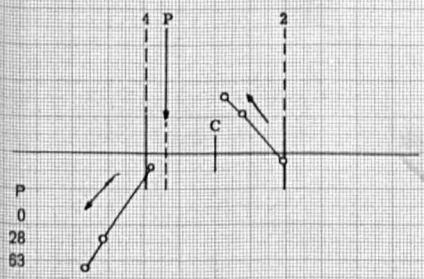


Fig. 20 a.  
Motion in the frontal plane (lateral bending) represented by the horizontal and vertical displacement of points 2 and 4 in an intact specimen with increasing load applied 14 mm to the left.

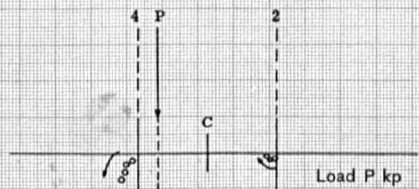


Fig. 21 a.  
Motion in frontal plane (lateral bending) represented by horizontal and vertical displacement of points 2 and 4 in a fused specimen with increasing load applied 14 mm to the left.

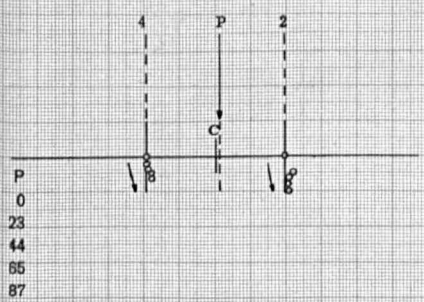


Fig. 20 b.  
load applied centrally (+1 mm).

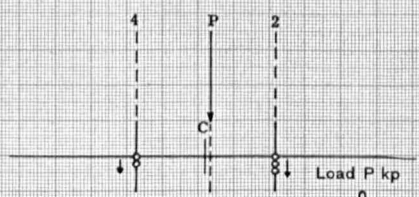


Fig. 21 b.  
loaded centrally (+1 mm).

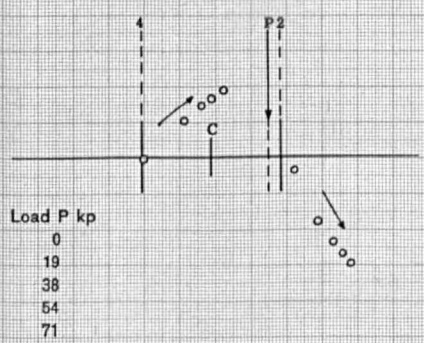


Fig. 20 c.  
load applied 16 mm to the right.

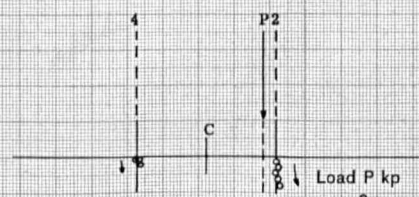


Fig. 21 c.  
load applied 16 mm to the right.

Fig. 22 a  
Spec. nr 14, L4-L5  
Intradiscal pressure (pd) in an intact specimen with increasing load applied in the sagittal plane at three different eccentricities, given in brackets for each curve.

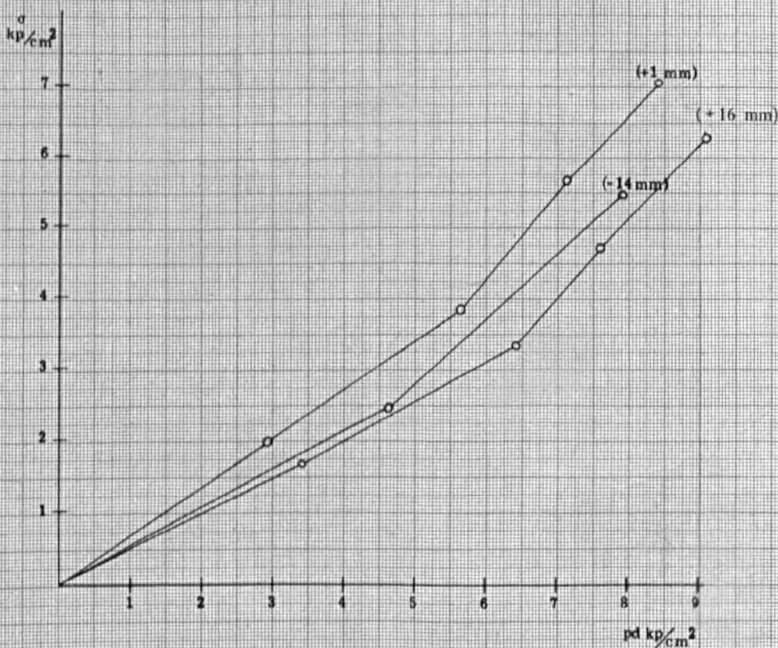
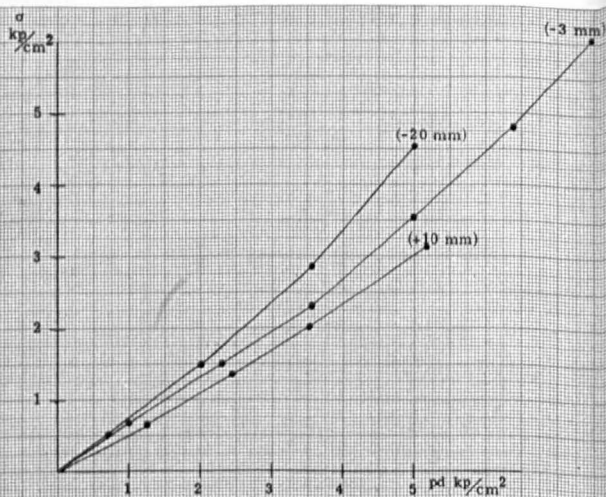


Fig. 22 b.  
Spec. nr 13, L1-L2  
Intradiscal pressure (pd) in an intact specimen, tested in the frontal plane with increasing load applied at three different eccentricities (given in brackets for each curve).

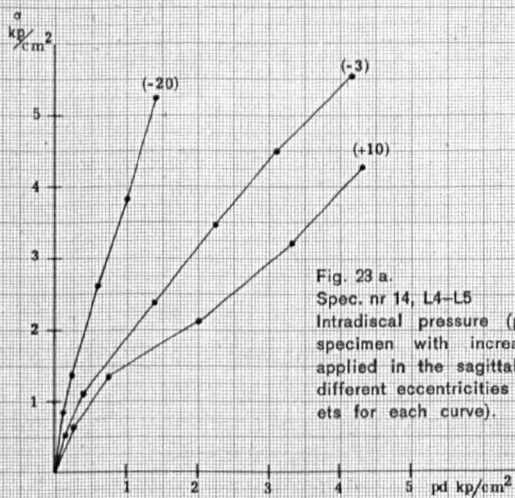


Fig. 23 a.  
Spec. nr 14, L4-L5  
Intradiscal pressure (pd) in a fused specimen with increasing load ( $\sigma$ ) applied in the sagittal plane at three different eccentricities (given in brackets for each curve).

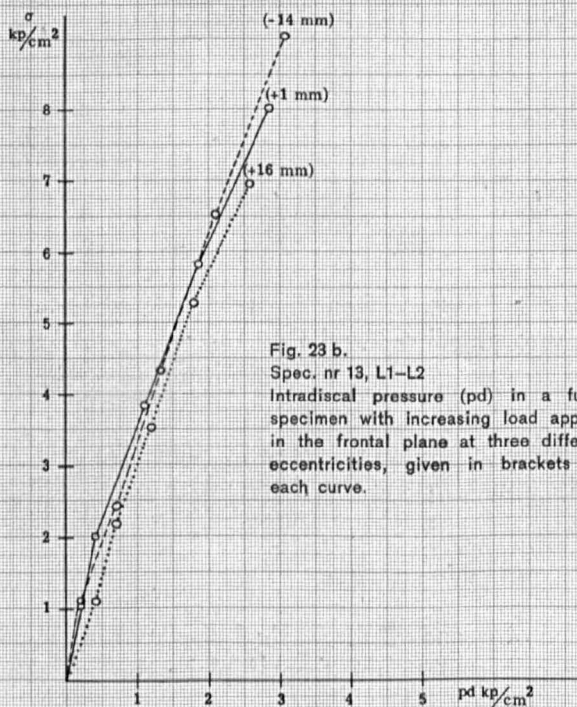


Fig. 23 b.  
Spec. nr 13, L1-L2  
Intradiscal pressure (pd) in a fused specimen with increasing load applied in the frontal plane at three different eccentricities, given in brackets for each curve.

In the same manner, Fig. 20 depicts horizontal ( $\delta_h$ ) and vertical ( $\delta_v$ ) displacement of points 2 and 4 for balanced loading and for lateral flexion to either side, while Fig. 21 shows the displacement for loading after fusion.

The momentary centre for the movement in the sagittal and frontal planes for successive stages of loading has been calculated by analytical plane geometry from the coordinates for points 1 and 5:

$$y - y_1 = -\frac{x_2 - x_1}{y_2 - y_1} (x - x_1) \quad (1)$$

as exemplified in Fig. 36, p. 75.

The intradiscal pressure ( $p_d$  kp/cm<sup>2</sup>) for each loading series is included in the graphs as a function of the external load ( $P$  kp or  $\sigma$  kp/cm<sup>2</sup>), see Fig. 22. For intact specimens the intradiscal pressure usually is lowest with "balanced loading", while a load applied eccentrically gives a higher intradiscal pressure in the centre of the disc. After fusion (Fig. 23), the intradiscal pressure is lowest for dorsal loading (near the fusion) and increases if the load is shifted ventrally or to either side.

The successive changes in angle have been calculated in the sagittal ( $\alpha$ ) and frontal ( $\beta$ ) planes from the vertical displacement at the measuring points.

$$\tan \alpha = \frac{\delta_1 - \delta_5}{L} \quad (2 a)$$

$$\tan \alpha = \frac{\delta_1 - \frac{\delta_2 + \delta_4}{2}}{\frac{d_s}{2} + S} \quad (2 b)^1$$

$S$  is the distance in millimeters from the geometric centre of the disc to the frontal plane through points 2 and 4.

$$\tan \beta = \frac{\delta_2 - \delta_4}{d_f} \quad (3)$$

Given the change of angle in the sagittal plane ( $\alpha$ ) and the sagittal diameter ( $d_s$ ), one can calculate the deformation of the disc's posterior border ( $\delta_3$ ):

$$\tan \alpha = \frac{\delta_1 - \delta_3}{d_s}; \quad \delta_3 = \delta_1 - d_s \tan \alpha \quad (4)$$

For the calculation of  $\epsilon_2$  and  $\epsilon_4$ , the vertical displacement at points 2 ( $\delta_2$ ) and 4 ( $\delta_4$ ) were corrected to the frontal plane through the geometric centre of the disc:

$$\delta_2 \text{ corr} = \delta_2 - S \tan \alpha \quad (5)$$

<sup>1</sup> All results are given according to formula 2 b if not otherwise remarked.

Thus the initial position of the upper vertebral body is represented by a horizontal ellipse, with the short sagittal diameter ( $d_s$ ) between points 1 and 3 and the long diameter ( $d_l$ ) between points 2 and 4. During loading this plane rotates in relation to the corresponding horizontal reference plane through the lower vertebral body. Its position at each stage of

Fig. 24 a.  
Spec. nr 14, L4-L5  
Vertical displacement ( $\delta_V$ ) of points 1, 2, 3 and 4 at increasing load and constant eccentricity (-16 mm) in an intact specimen, tested in the sagittal plane.

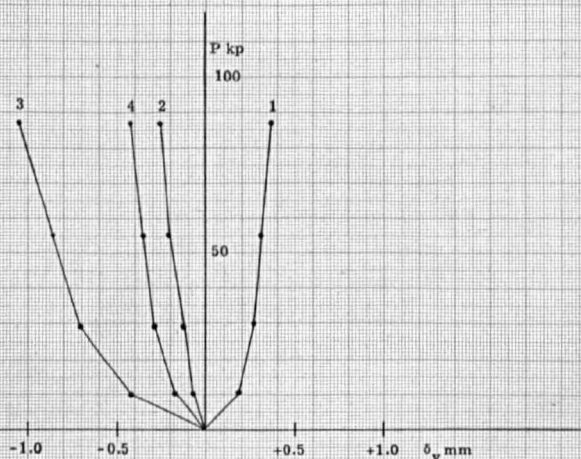
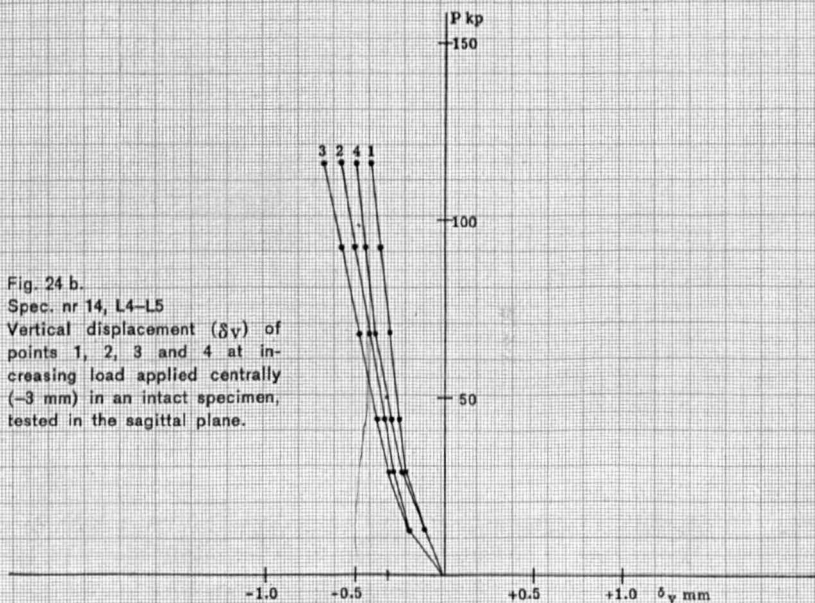
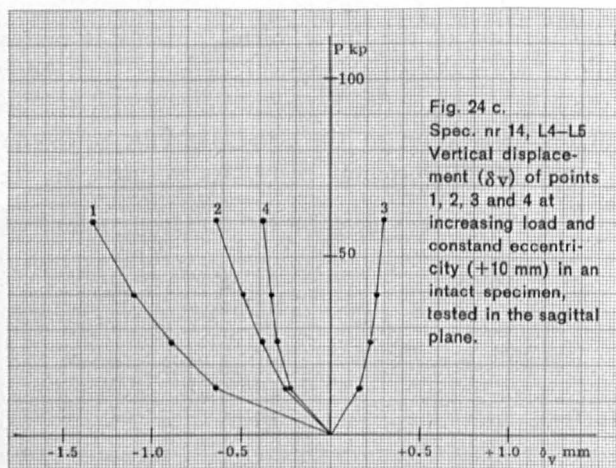


Fig. 24 b.  
Spec. nr 14, L4-L5  
Vertical displacement ( $\delta_V$ ) of points 1, 2, 3 and 4 at increasing load applied centrally (-3 mm) in an intact specimen, tested in the sagittal plane.





loading can be indicated by the vertical displacement at the four measuring points in relation to the load applied (Fig. 24) or by the displacement at one point and the change in the angle of the plane ( $\delta_{1v}$  and  $\alpha$  or  $\delta_{2v}$  and  $\beta$ ), as illustrated by Fig. 25.

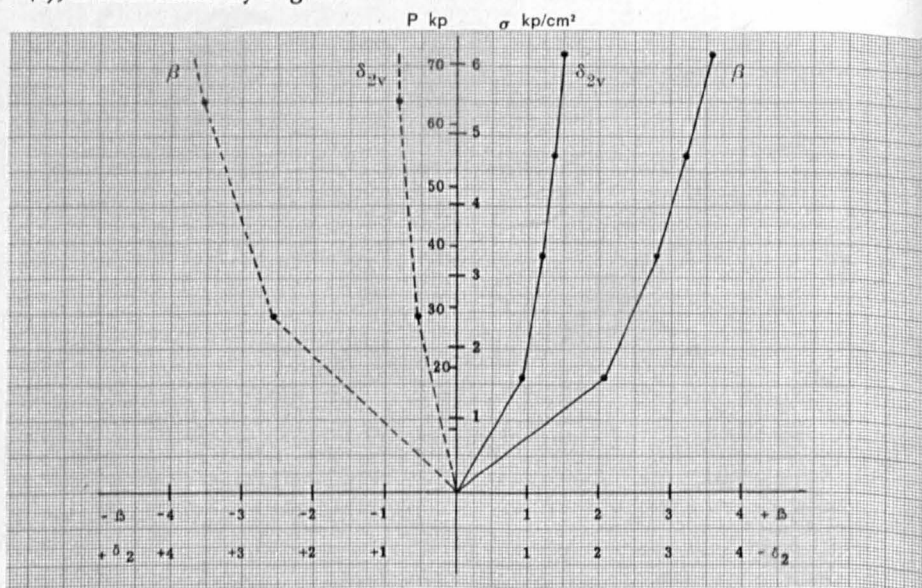


Fig. 25. Spec. nr 13, L1-L2

Change of angle ( $\beta^\circ$ ) in frontal plane (lateral bending) and vertical displacement ( $\delta_{v2}$ ) of right lateral margin of vertebra (point 2) in an intact specimen tested in the frontal plane with increasing load at eccentricity -14 mm (---) and +16 mm (—).

The relationship between the change in angle and the displacement on the one hand and the eccentricity at constant load on the other is illustrated in Fig. 26 for intact specimen and in Fig. 27 for the same specimen after fusion.

Fig. 26 a.  
Spec. nr 14, L4-L5  
Change of angle in the sagittal plane at three constant loads and various eccentricities in an intact specimen.

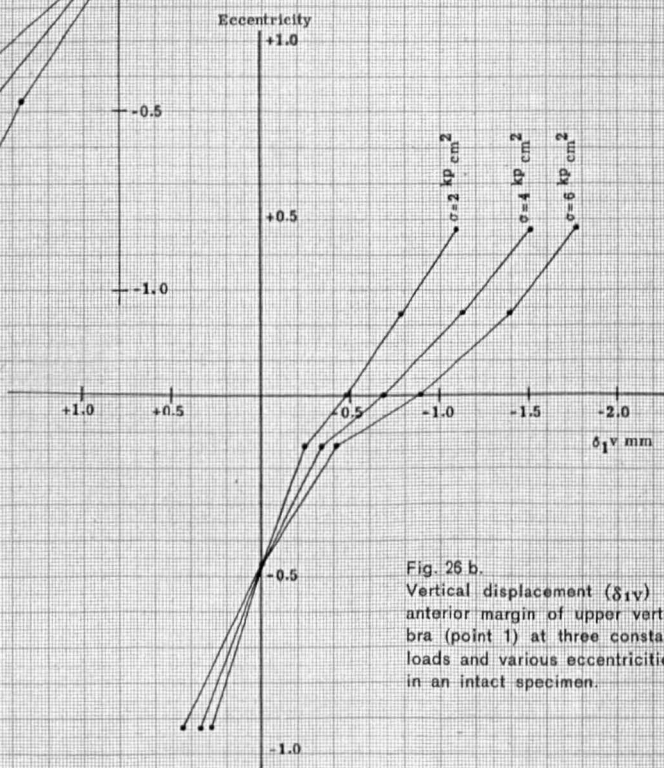
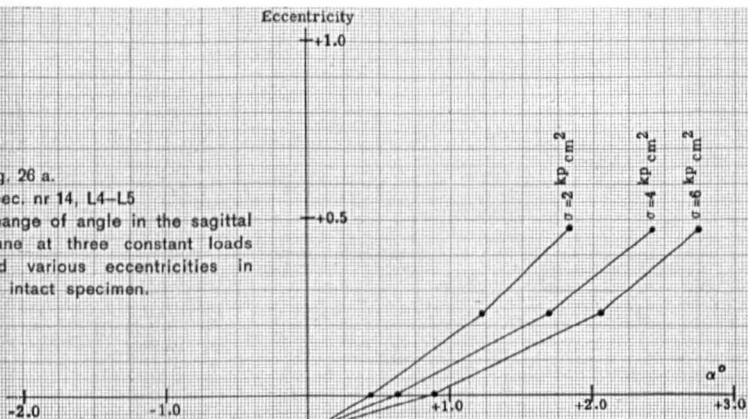


Fig. 26 b.  
Vertical displacement ( $\delta_{1v}$ ) of anterior margin of upper vertebra (point 1) at three constant loads and various eccentricities in an intact specimen.

Fig. 27 a.  
Spec. nr 14, L4-L5  
Change of angle in the sagittal plane  
at three constant loads and various  
eccentricities in a fused specimen.

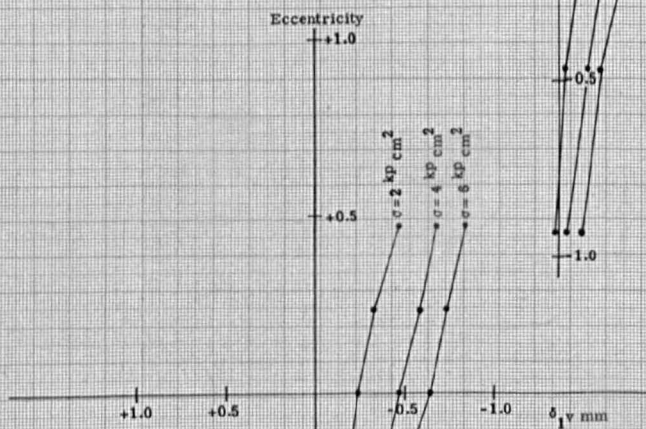
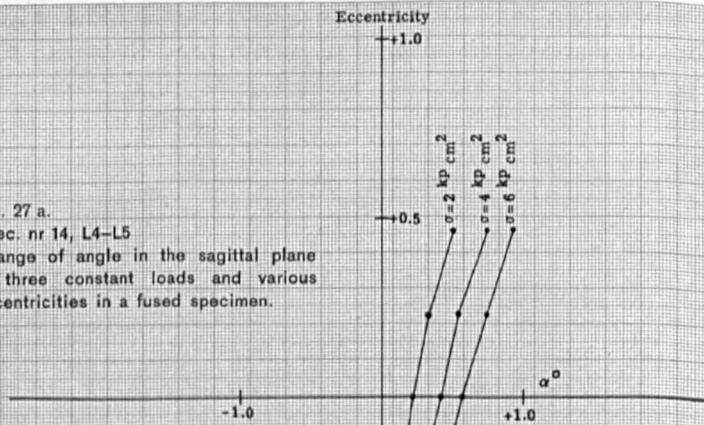


Fig. 27 b.  
Spec. nr 14, L4-L5  
Vertical displacement ( $\delta_{1V}$ ) of anterior  
margin of upper vertebra (point 1) at  
three constant loads and various eccen-  
tricities in a fused specimen.

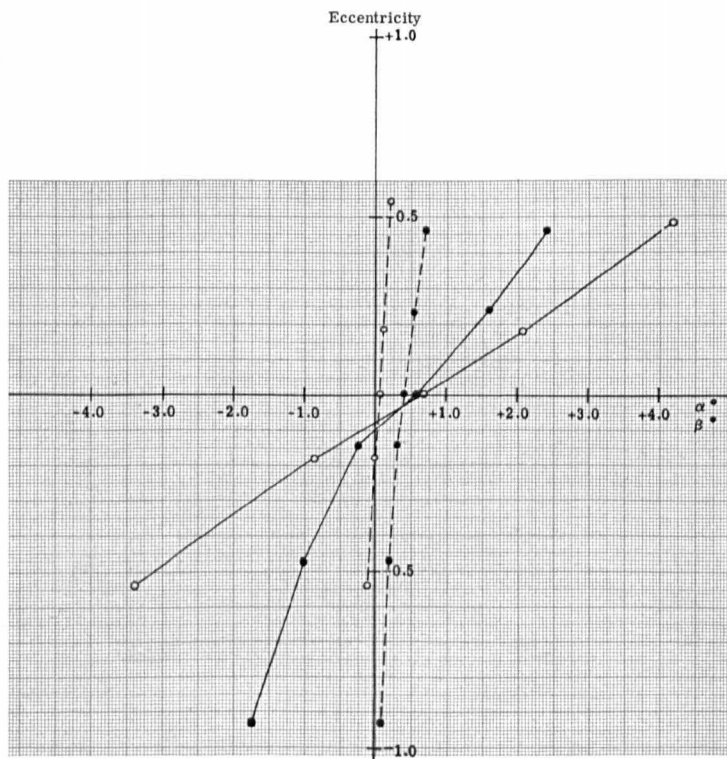


Fig. 28.

Nr 14, L4-L5

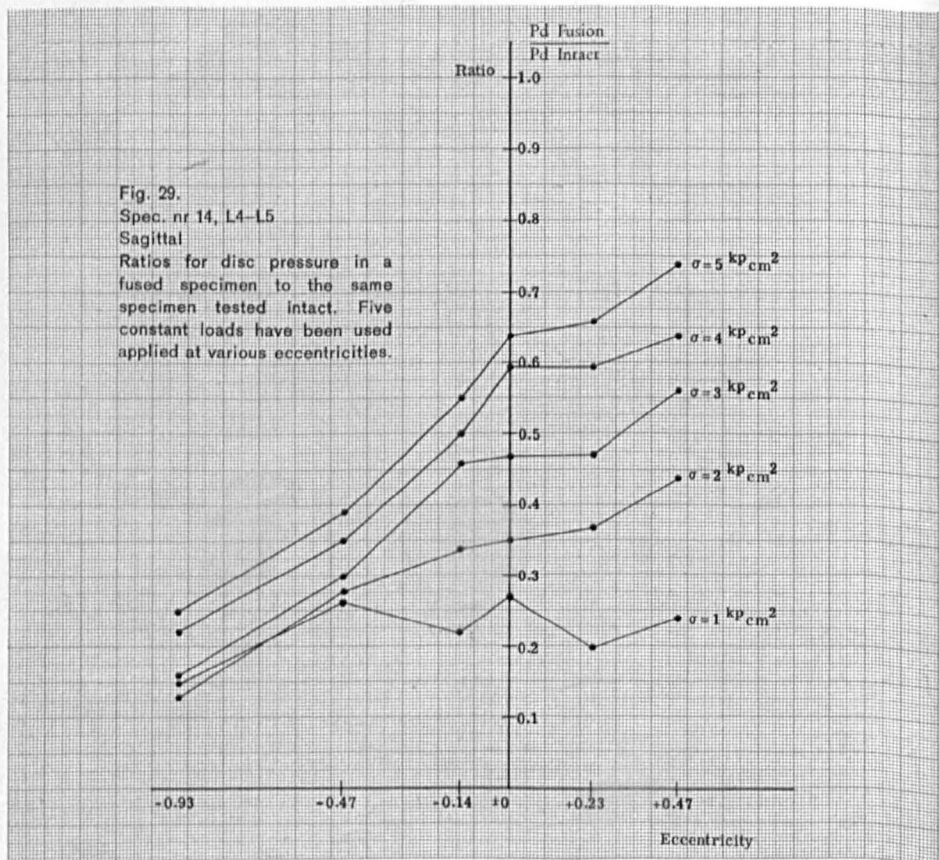
Change of angle in one specimen with constant load ( $\sigma=4$  kp/cm<sup>2</sup>) applied at various eccentricities in sagittal ( $\alpha^\circ$ ) and frontal ( $\beta^\circ$ ) planes both intact and after fusion.

- = Sagittal
- = Frontal
- = Intact
- - - = Fusion

In order to visualize the three-dimensional movement of the segment during various loading conditions and after different treatments of the specimen, graphs such as those shown in Fig. 28 were compiled for a particular load per unit area (4 kp/cm<sup>2</sup>), with the change in angle ( $\alpha$  and  $\beta$ ) and the relative displacement at a point in the plane ( $\epsilon_1$  and  $\epsilon_2$ ) plotted against the degree of eccentricity during loading in the sagittal and frontal planes for an intact specimen and after fusion.

Comparisons between intact specimens and specimens with fusion or some other procedure are made on the basis of the ratio between the respective

values at the same load for  $\alpha$ ,  $\beta$ ,  $\delta_h$ ,  $\delta_v$ ,  $\varepsilon$  and  $p_d$ , as shown in Fig. 29; in this way one can demonstrate the percentage effect of the fusion on the various properties.



## Discussion of the method

The method described above is in many respects a compromise solution. Although problems which have cropped up during the development work have been mastered to some extent by modifications to the apparatus etc., certain difficulties have necessitated a revision of the original aims.

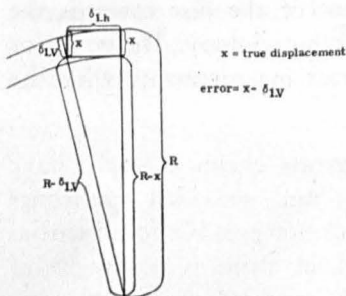
Concerning the apparatus, it would have been preferable to make simultaneous recordings of the displacement of several points on the vertebral

body, the vertical and horizontal displacement of the disc towards the vertebral foramen and the protrusion of the disc's periphery. The posterior region of the disc was not available for direct measurements with the vertebral arch intact.

The simultaneous registration of data via separate channels would have simplified the analysis of the measurements and provided recordings during a continuously increasing load. This was not possible for financial reasons. With recordings over a single channel there is a danger of errors due to hysteresis. On the other hand, repeated recordings at a constant load did not result in significant differences. The routine acquired from numerous experiments has meant that variations in the rate of loading are remarkably small (cf. Fig. 14) and probably irrelevant for the displacements in question, particularly as the method of registering the data allows sufficient time for the specimen to become stabilised in a new state of equilibrium.

The intradiscal pressure was recorded at the centre of the disc. It was found that during eccentric loading, the recorded pressure varied in different parts of the disc. Consequently, one would like to use several pressure receptors and record the pressure in different parts of the disc simultaneously, besides making simultaneous recordings at several levels in specimens comprising a larger number of segments. The disc pressure method requires repeated calibrations against known pressures during the course of the experiment and the data has to be rejected if the calibrations deviate more than 5 per cent (cf. p. 39). A transducer was modified for the measurement of differential pressure but the attempt had to be abandoned owing to the difficulty of regulating the counter-pressure with sufficient precision. Trials have also been made with a strain gauge attached directly to a metal membrane at the measuring point; so far, however, such a device has not proved serviceable. The method employed in the present study is intended for the measurement of hydrostatic pressure, which cannot a priori be considered to be obtained in severely degenerated discs. Nevertheless, the pressure has been recorded if it proved reproducible in repeated series. This data is not, however, intended to represent hydrostatic pressure, equal throughout the nucleus, but simply as an expression of the deformation of the nucleus' tissue in the centre of the disc.

There is an error in measurement inherent in all motion gauges (Fig. 30). For rotation of the specimen about a horizontal or vertical axis, the new position of the horizontal motion gauge's measuring point lies on the arch of a circle having a radius equal to the length of the measuring arm; for the horizontal gauge this is approximately 80 mm. Since the vertical



$$(R-x)^2 + \delta_{1h}^2 = (R-\delta_{1V})^2$$

$$X = R \left( 1 - \sqrt{1 - \frac{2\delta_{1V}}{R} + \frac{\delta_{1V}^2 - \delta_{1h}^2}{R^2}} \right)$$

$$X \approx R \left( 1 - 1 + \frac{\delta_{1V}}{R} \right) = \delta_{1V}$$

Fig. 30.  
Measuring error in the extensometers.

displacement is maximum  $\pm 5$  mm, the correction for the horizontal deviation is given by the sine of a very small angle and thus does not affect the recorded value. Similarly, for horizontal displacement of the measuring point, the vertical motion gauge indicates the point's deviation along the arch of a circle with a radius equal to the distance between the tips of the gauge's legs; this distance is  $25 \text{ mm} \pm 5 \text{ mm}$ . Owing to the relatively short radius for the vertical gauge, a large horizontal deviation can result in a large percentage error in the vertical displacement. However, the horizontal deviation has been small both in absolute and in relative terms (Figs 45 thru 47).

Calculation of change in angle of the segment makes use of the frontal diameter ( $d_f = 51 \pm 7 \text{ mm}$ ) and the sagittal diameter ( $d_s = 39 \pm 6 \text{ mm}$ ) and the distance between points 1 and 5 ( $L = 81 \pm 13 \text{ mm}$ ). An error of  $\pm 1 \text{ mm}$  in measuring  $d_s$  gives an error for the angle  $\beta$  of less than 2 per cent. The same error for  $d_s$  gives an error for  $\alpha$  of less than 3 per cent ( $\alpha$  calculated from  $L$  yields less than 1.5 per cent). If, in addition, one allows for a maximum error of  $\pm 0.03 \text{ mm}$  in measuring the vertical displacements, the calculations of  $\beta$  and  $\alpha$  incorporate errors of  $\pm 0.04^\circ$  and  $\pm 0.05^\circ$  respectively. This means that the calculated value of  $\delta_3$  contains a relatively large percentage margin of error for small angles (less than 1 degree) and consequently it has not been used for comparisons between specimens.

$\epsilon$  is the ratio between two units of length ( $\delta_v/h$ ) for each stage of loading. A strictly mathematical calculation requires the use of logarithmic values for addition over several intervals. The non-logarithmic values have in fact been used but this only affects the fifth place of decimals, whereas the results have been taken to three places of decimals only.

The area of the unloaded disc ( $A$ ) is included in the calculation of the load per unit area ( $\sigma = P/A$ ) which is an expression for the mean load on the surface  $A$ . On vertical compression of the disc,  $A$  increases by up to approximately 5 per cent (Nachemson, 1960). This means that

for an increased total load,  $\sigma$  is somewhat larger than the mean load on the disc (calculated from the true area) and less, to roughly the corresponding extent, than the mean load on the end-plate and the vertebral body.

On loading, the distribution of forces within the specimen is uneven. One obtains a statically indeterminate system for the calculation of these internal forces in a section. Such a calculation cannot be made without knowledge of the physical properties and geometry of the specimen. Approximate calculations of the distribution of forces have been tried (with arbitrary assumptions concerning the geometry and physical properties) in order to study the order of magnitude of forces active in different parts of the system. However, these calculations contained so many suppositions that their value was questionable.

As already mentioned, checks were made during the loading tests to ensure that there was no appreciable vertical compression in the vertebral body; otherwise the vertical displacement of the measuring points could not be equated with the vertical deformation of the disc between measuring point and reference point. In fact, there is unlikely to be any appreciable vertical deformation of the vertebral body, judging from compression tests made with heavy loads on specimens in an Amsler materials testing machine and measurements of deformation with the extensometers already described (Fig. 31).

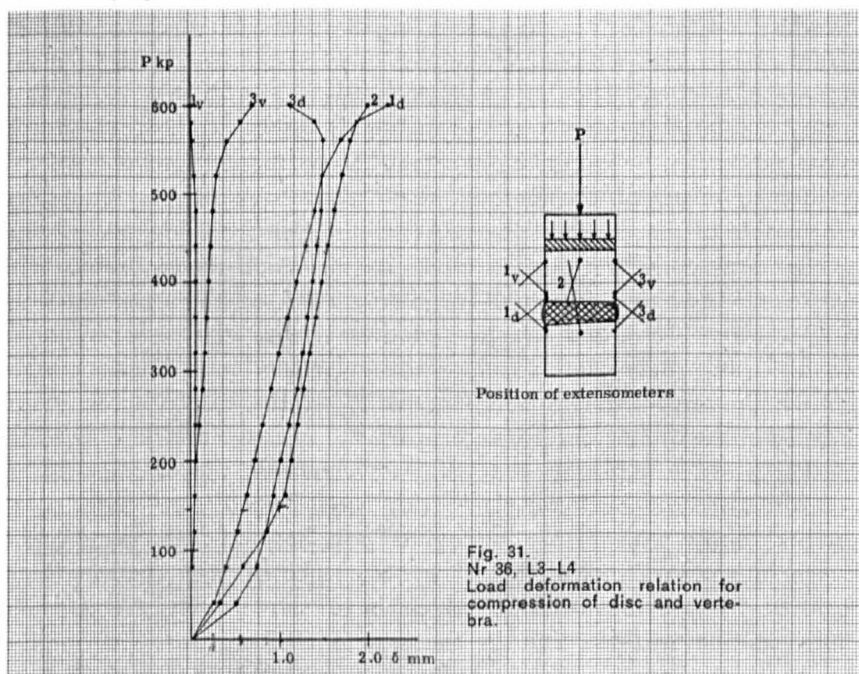
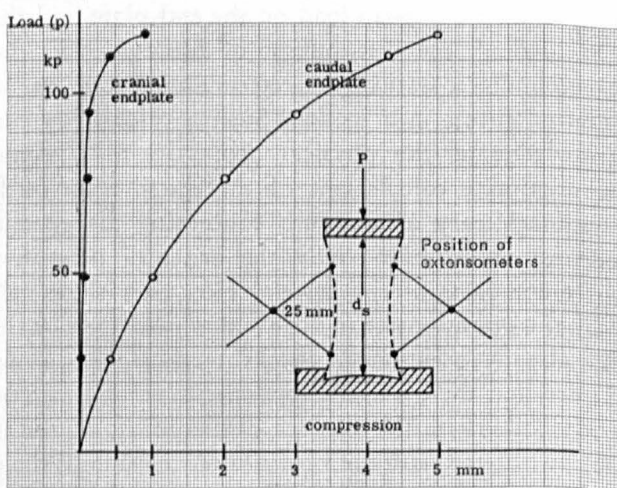


Fig. 32.  
 Nr 38, vertebra L2  
 Compression along the sagittal  
 diameter of vertebra.



From the calculations of the angle  $\alpha$ , it was found that both negative and positive changes in this during eccentric loading were larger as calculated according to formula (2 a) than according to the normal method (2 b). This difference increases with increasing eccentricity and also with increasing intensity of the load. Thus, although there was no appreciable change in the vertical height of the vertebral body, after eccentric loading the measuring points no longer lie in the same plane. Since the difference cannot be ascribed to errors of the method, there must have been a "concealed" deformation of the vertebral body. As will be seen from Fig. 32, in which the vertebral body was loaded along its sagittal diameter, shear forces possess a considerable potential for deformation of the vertebral body. In view of the form and structure of the vertebra, the periphery of the vertebral body may well change its angulation during shearing stress, viz. the posterior segment bends cranially in the case of positive and caudally in the case of negative eccentricity.

Another possible explanation for the difference in the calculated angle is deformation of the end-plate; this would tend to "explode" the vertebral body with protrusion of its periphery and a corresponding change in angle (Zarek, 1966). The occurrence of such deformation is suggested by previous studies, which have shown that the end-plate constitutes the weakest link in the system (Friberg, 1947; Friberg & Hirsch, 1950; Perey, 1957; Decoulx & Rieunau, 1958), as well as by

Fig. 31, where the end-plate fractures at the load at which the deformation curves for disc and vertebral body tend towards one another.

Post mortem changes constitute an elusive source of error in all studies on autopsy specimens. Since it was not always possible to test the specimens at the time of sampling, all specimens were immediately frozen in order to ensure maximum uniformity. Freezing is not considered to affect the physical properties of bone (Perey, 1957; Evans, 1957; Sedlin, 1965; Sedlin & Hirsch, 1966), intervertebral discs (Bartelink, 1957; Hardy, Lissner, Webster & Gurdjian, 1958; Nachemson, 1960) or ligament (Viidik & Lewin, 1965). No change in the extensibility and elasticity of human ligamenta flava was found after unprotected storage in a refrigerator (Åkerblom, 1948). The load-elongation correlation of rabbit ligaments tested fresh and after storage for 2—96 hours at room temperature was studied and no definite difference was found in tensile strength in spite of histological signs of autolysis, (Viidik, Sandqvist & Mägi, 1965).

The physical properties of both bone (Rauber, 1876; Evans & Lebow, 1952; Smith & Walmsley, 1959; Sedlin, 1965; Sedlin & Hirsch, 1966) and ligament (Walker, Harris & Benedict, 1964; Viidik, Sundqvist & Mägi, 1965; Viidik & Lewin, 1965; Galante & Hirsch, 1966) are sensitive to dehydration and increases in temperature. Fresh bone is a poor thermal insulator (Thompson, 1958; Sedlin, 1965) probably owing to its high moisture content. The physical properties of rat tail tendon were not affected by a change from freezing at  $-35^{\circ}\text{C}$  to  $+37^{\circ}\text{C}$  but irreversible changes occurred above approximately  $40^{\circ}\text{C}$  (Rigby, Hirai, Spikes & Eyring, 1959). The critical temperature for collagen is reported to be  $47-48^{\circ}\text{C}$  (Delaunay et al, 1956; Verzá, 1957).

In the present study, consideration has been paid to these factors as described on pp. 29—30.

In several preliminary trials the specimen was stored in a refrigerator for up to one week after testing without and with fusion and then re-tested in the reverse order, i.e. first *with* fusion and then with the fusion removed. The results showed no appreciable difference in respect of either deformation in the disc or the intradiscal pressure. It was also found that, with the type of loading in question, repeated loading series do not affect the physical properties, thereby confirming previous investigations on comparable specimens (Göcke, 1931; Virgin, 1951; Hirsch & Nachemson, 1954; Nachemson, 1960; Sedlin, 1965; Sedlin & Hirsch, 1966).

## Material

This experimental study was made on 71 samples of human lumbar spines, obtained from 38 autopsy subjects ranging in age from 4—76 years. The postmortem examination and specimen sampling

Table 3.

### *The Study Group.*

Subject no.	Autopsy no.	Age Sex	Body-weight	Length	Time in hospital days	Cause of death
1	II-98	44 F	—	—	3	Perf. ulcer. (op)
2	I-586	6 M	17	—	4	Cardiac failure (op)
3	I-607	4 M	—	—	1	Malignant laryngitis
4	II-101	65 F	—	—	12	Pulm. embolism.
5	L-100	64 M	—	—	0	Suicide
6	I-717	40 M	—	—	1	Acute myocarditis
7	L-49	34 M	—	—	0	Suicide
8	I-1094	74 M	60	170	0	Cardiac failure
9	I-1194	44 F	59	165	9	Uremia
10	I-1199	54 F	53	160	6	Bronchopneumonia
11	II-250	64 F	—	—	31	Reticle cell sarcoma
12	L-84	67 M	—	—	(513)	Bronchopneumonia (senility)
13	I-1390	53 F	—	—	7	Bronchopneumonia
14	L-86	48 M	—	—	0	Cardiac failure
15	I-1458	61 M	72	—	15	Acute leukemia
16	I-1467	65 M	86	170	1	Myocardial infarction
17	I-1468	70 F	78	160	2	Myocardial infarction
18	II-272	76 F	—	—	10	Circulatory failure
19	II-276	58 M	—	—	1	Myocardial infarction
20	I-1481	58 M	—	—	1	Myocardial infarction
21	I-1483	61 F	61	160	5	Cerebral contusion
22	I-1511	43 M	70	185	1	Bronchopneumonia
23	I-1513	44 M	59	158	14	Bronchopneumonia
24	II-280	30 M	61	—	14	Inestinal carcinoma
25	I-105	64 M	—	—	1	Uremia
26	II-27	56 M	—	—	6	Pulmonary carcinoma
27	II-29	62 M	—	—	1	Pulmonary carcinoma
28	I-201	52 F	48	—	10	Hepatic failure
29	L-25	32 F	—	—	0	Electric shock
30	I-302	31 M	64	175	14	Uremia
31	I-379	42 F	68	170	2	Suicide (barbit. poison)
32	N.L.	5 M	—	—	0	Subdural hemorr. (op)
33	I-1239	50 F	—	—	72	Bronchopneumonia
34	II-252	56 M	49	—	25	Pancreatic ca.
35	II-255	46 M	—	—	10	Pulm. embolism.
36	I-1254	41 M	—	—	0	Subdural hemorr.
37	I-525	62 M	—	—	0	Myocardial infarction
38	I-553	73 M	—	—	1	Myocardial infarction

were performed within three days after death. The subjects utilized represent a largely random selection of the autopsy material available at this institution. Efforts were made to limit sampling to subjects up to 60 years of age, with a brief period of hospitalization and without suspicion of gross osseous changes in the spine. The need to obtain specimens at definite times meant that this delimitation could not always be applied (Table 3, p. 64).

It was frequently found that the anterior surface of the disc had been damaged during the autopsy, particularly the disc L 5 — S 1. The rejection of segments damaged in this way determined the level from which the samples were taken.

Specimens from all the lumbar spines obtained during the period when the present experiments were conducted have been tested consecutively and all of them are included in the results. Examinations were made for roentgenographic signs of disc degeneration (Knutsson, 1954, 1957), spondylitic spurs, anomalies, asymmetrical joint facets or other changes in the vertebrae. Only one lumbar segment (no. 16, L 4 — L 5) presented appreciable asymmetry of the intervertebral joints. Since the mechanical effect of such asymmetry is the subject of much discussion in the literature (Putti, 1933; Ghormley, 1933; Wiles, 1935; Güntz, 1937; Ingelmark, 1956; Nachemson, 1960; Lewin, 1964), a T 12 — L 1 segment (specimen no. 19) which displayed such asymmetry was also included. No other anomalies were found in the segments presented here. Specimen no. 19 displayed roentgenographic signs of residual tuberculous spondylitis with partial union L 2 and L 3. The roentgenographic changes are indicated in the master table (Table 4, pp. 68—71) and arbitrarily graded.

The degree of degeneration in the excised discs was assessed by macroscopic inspection in accordance with established standards (Lindblom, 1944; Friberg & Hirsch, 1950; Lindblom, 1951; Virgin, 1951, 1958; Naylor & Smare, 1951; Ingelmark & Ekholm, 1952; Hendry, 1958; Nachemson, 1960; and others).

*Group 0.* Macroscopically normal discs without signs of ruptures or other structural changes. Both the annulus fibrosus and the nucleus pulposus are shiny white. The nucleus appears homogeneously gelatinous and is clearly delimited from the annulus fibrosus.

*Group 1.* Discs with a normal appearance in general but with a somewhat more fibrous structure in the nucleus. A distinct boundary between nucleus and annulus. Some cases present a slight yellowish discolouration (Fig. 33).

*Group 2.* Clear deterioration of the central structures of the nucleus, which is definitely drier than normal and usually discoloured. There may be

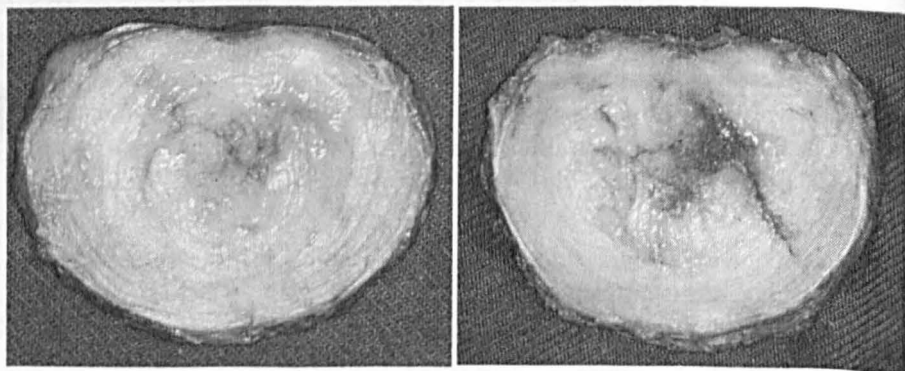
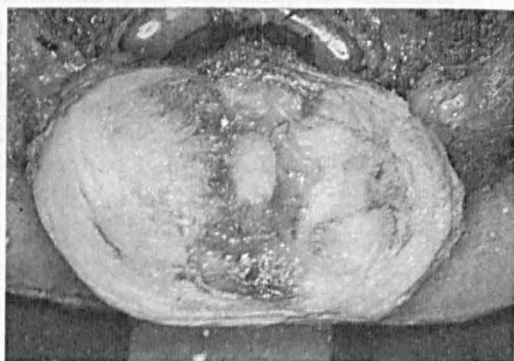


Fig. 33 thru 35. *Demonstrating various degrees of disc degeneration.*

- a) *Spec. nr 13 L3—L4 — Degeneration group 1.*
- b) *Spec. nr 15 L3—L4 — Degeneration group 2.*
- c) *Spec. nr 13 L5—L1 — Degeneration group 3.*



isolated fissures in the annulus. The boundary between annulus and nucleus is not particularly distinct (Fig. 34).

*Group 3.* Marked degenerative changes in the nucleus as well as the annulus fibrosus, with ruptures and sequestra in the nucleus or the annulus and/or scarring of the nucleus (Fig. 35).

Group 0 constitutes healthy discs from generally young individuals, while Group 1 represents higher age groups for which the findings may be considered normal.

Groups 2 and 3 comprise discs with increasing degrees of degeneration in which hydrostatic conditions cannot be held to be obtained.

All specimens were subjected to a varying number of loading series with registration of the displacement at a minimum of 5 measuring points.

Some of the senile specimens fractured during the experiment, which could not then be concluded according to plan. Most of the specimens were subjected to eccentric loading in both the sagittal and the frontal plane. Fusion was performed on 33 specimens, other measures being carried out on the remainder.

Measurements of intradiscal pressure were recorded for 34 specimens but rejected in the remainder, either when the pressure proved not to be reproducible for the same load in repeated series or because of deviations greater than 5 per cent at calibration before and after the experiment. Characteristic data for each specimen and the tests performed are listed in Table 4 (pp. 68—71).

Some 1500 loading series, with an average of 7 loads per series, were conducted on the specimens reported here. This makes about 90,000 primary data which together with approximately the same number of calculated values, form the basis for the results reported below. Some 4000 graphs of the types illustrated provided a satisfactory basis for studying individual specimens but are not suitable for reporting the material as a whole. The large quantity of results made it advisable to use a computer. However, the number of individuals is relatively small and consequently an analysis of the results should not be based on too many sub-groups. Specimens are included from children, adults and aged individuals, with the age group 40—50 predominating. The specimens were classified as normal (gr. 0—1) and degenerated (gr. 2—3), without otherwise considering the age distribution. The risk of osteoporosis increases with age. However, osteoporotic specimens fractured when still "intact" and are thus hardly represented among the fusion cases, for which the strength of the bone tissue is of primary importance.

The level of the disc is important in that the range of movement increases in a caudal direction. The range of movement is dependent upon the height of the disc and the area of its cross section (Fick, 1904) and consideration has been paid to these factors.

All the specimens included in this report have contributed to the results for intact specimens and loading in the balanced position. In the case of eccentric loading, on the other hand, specimens incorporating more than one segment have been excluded. Such specimens buckle in both the sagittal and the frontal plane, making it difficult to define the eccentricity of the load.

Owing to the variations in the geometry of the different specimens, neither the eccentricity nor the load could be predetermined to equivalent figures for comparisons between specimens. Such figures can be interpolated graphically with considerable accuracy by combining different

Table 4.

## Specimen characteristics.

## Tests Performed.

Specimen Nr #	Sex	Age	Disc level tested	Disc degeneration (0-3)	X-ray changes (0-3)	Disc area cm <sup>2</sup>	Sagittal diameter (d <sub>s</sub> ) mm	Frontal diameter (d <sub>f</sub> ) mm	Height of disc (h <sub>m</sub> ) mm	Distance "balanced position" to geometric center (m <sub>0</sub> ) mm	Original disc angle in sagittal plane (α <sub>0</sub> ) degrees	Intact	Divided Ligaments	Screws through facets	Removal of articular processes	Injected disc cm <sup>3</sup>	Fusion	Fusion type 1-3	Fusion + excised disc	Additional moment	Special tests	Count of series	Max. load used kp	Remarks <sup>1</sup>	
1	F	44	L2	0	1	12.3	32	47	9	-	- 7°	S					S	2	S			6	100	2 segments	
2	M	5	L2	0	0	7.0	28	32	8.5	-	- 6°	X					X							Pd only	
2	M	5	L3	0	0	7.1	26	34	8.5	+1	- 4°	S					S	2	S	S		29	64	One spec.	
2	M	5	L4	0	0	7.6	27	35	8.5	-	- 4.5°	X					X								Pd only
3	M	4	L4	0	0	7.4	26	34	9.3	+6	-10°	S										45	71	One spec.	
3	M	4	L5	0	0	8.3	26	36	9.7	-6	-13°	S	S	F		1.0			S			45	71		
4	F	65	L2	2	0	18.5	45	54	10.3	-2	- 7.5°	S					S	1	S			10	105	2 segments	
4	F	65	L4	2	0	23.0	44	64	15.3	-	-10.5°	S					S	1						2 segments	
5	M	65	L1	1	0	19.5	39	58	10.0	-7	- 5°	S				S	S	1	S			24	154		
6	M	40	L4	1	0	23.8	45	66	15.5	-4	- 5.8°	S				S	S	1	S			24	167		
7	M	34	L2	1	0	15.5	39	50	7.3	-2	- 2.9°	S				S	S	2	S			23	200		
7	M	34	L4	1	0	17.8	40	58	10.0	-3	-15°	S	S				S	2	S			10	200		
8	M	74	L4	2	2	16.9	40	53	8.0	-2	- 2.7°	S		S		S	S					10	170		
9	F	44	L3	1	0	13.4	37	53	12.0	-8	- 6°	S	S	S		S	S	1(M)				42	200		

10	F	54	L4	2	0	14.9	36	51	11.3	+5	-11.5°	S						10	156
11	M	64	L2	3	2	17.0	39	58	9.3	-3	-7.5°	S						11	120
11	M	64	L4	3	2	14.0	36	58	10.8	-1	-16.5°	S						23	140
12	M	68	L4	3	1	19.2	41	60	10.0	-6	-11°	S						1	88
13	F	53	L1	1	0	11.5	30	39	8.3	-3	-6°	S						30	129
13	F	53	L3	1	1	16.0	40	42	11.0	-2	-8°	S						30	111
13	F	53	L5	3	1	16.6	39	50	9.0	±0	-15.5°	S						30	165
14	M	48	L2	1	0	19.1	41	53	11.7	-2	-11.5°	S						24	118
14	M	48	L4	1	2	19.1	43	56	12.8	-2	-12°	S						25	145
15	M	65	L1	1	1	15.4	38	49	10.3	±0	-7.5°	S						25	143
15	M	65	L3	2	1	17.8	40	52	13.0	-6	-9.5°	S						29	144
16	M	65	L2	1	1	18.7	41	50	11.3	-2	-10.5°	S						28	137
16	M	65	L4	1	2	21.2	46	51	12.0	-2	-17.5°	S						42	152
17	F	70	L1	1	1	9.2	31	40	7.3	-5	-5.5°	S						18	101
17	F	70	L3	2	1	10.7	31	46	10.0	-8	-9.5°	S						9	130
18	F	76	L4	2	1	15.0	35	51	11.5	-3	-8.0°	F						16	161
19	M	58	Tn12	1	2	14.2	36	49	8.0	-4	-6°	S						17	129
19	M	58	(L2)L3	2	2	20.0	41	59	13.0	-2	-5.5°	S						45	151
19	M	58	L5	2	2	24.5	46	57	13.0	-4	-18.5°	S						31	163
20	M	58	L2	1	1	18.4	40	48	11.3	-5	-7.3°	S						23	137
20	M	58	L4	1	1	21.9	44	52	14.0	-3	-10.5°	S						36	153
21	F	51	L1	1	1	13.0	36	42	10.7	-4	-9°	S						14	137
21	F	51	L3	2	1	10.7	31	46	10.0	-8	-9.5°	S						9	130
21	F	51	L5	3	1	16.6	39	50	9.0	±0	-15.5°	S						30	165
21	F	51	L2	1	0	19.1	41	53	11.7	-2	-11.5°	S						24	118
21	F	51	L4	1	2	19.1	43	56	12.8	-2	-12°	S						25	145
21	F	51	L1	1	1	15.4	38	49	10.3	±0	-7.5°	S						25	143
21	F	51	L3	2	1	17.8	40	52	13.0	-6	-9.5°	S						29	144
21	F	51	L2	1	1	18.7	41	50	11.3	-2	-10.5°	S						28	137
21	F	51	L4	1	2	21.2	46	51	12.0	-2	-17.5°	S						42	152
21	F	51	L1	1	1	9.2	31	40	7.3	-5	-5.5°	S						18	101
21	F	51	L3	2	1	10.7	31	46	10.0	-8	-9.5°	S						9	130
21	F	51	L4	2	1	15.0	35	51	11.5	-3	-8.0°	F						16	161
21	F	51	Tn12	1	2	14.2	36	49	8.0	-4	-6°	S						17	129
21	F	51	(L2)L3	2	2	20.0	41	59	13.0	-2	-5.5°	S						45	151
21	F	51	L5	2	2	24.5	46	57	13.0	-4	-18.5°	S						31	163
21	F	51	L2	1	1	18.4	40	48	11.3	-5	-7.3°	S						23	137
21	F	51	L4	1	1	21.9	44	52	14.0	-3	-10.5°	S						36	153
21	F	51	L1	1	1	13.0	36	42	10.7	-4	-9°	S						14	137
21	F	51	L3	2	1	10.7	31	46	10.0	-8	-9.5°	S						9	130
21	F	51	L5	3	1	16.6	39	50	9.0	±0	-15.5°	S						30	165
21	F	51	L2	1	0	19.1	41	53	11.7	-2	-11.5°	S						24	118
21	F	51	L4	1	2	19.1	43	56	12.8	-2	-12°	S						25	145
21	F	51	L1	1	1	15.4	38	49	10.3	±0	-7.5°	S						25	143
21	F	51	L3	2	1	17.8	40	52	13.0	-6	-9.5°	S						29	144
21	F	51	L2	1	1	18.7	41	50	11.3	-2	-10.5°	S						28	137
21	F	51	L4	1	2	21.2	46	51	12.0	-2	-17.5°	S						42	152
21	F	51	L1	1	1	9.2	31	40	7.3	-5	-5.5°	S						18	101
21	F	51	L3	2	1	10.7	31	46	10.0	-8	-9.5°	S						9	130
21	F	51	L4	2	1	15.0	35	51	11.5	-3	-8.0°	F						16	161
21	F	51	Tn12	1	2	14.2	36	49	8.0	-4	-6°	S						17	129
21	F	51	(L2)L3	2	2	20.0	41	59	13.0	-2	-5.5°	S						45	151
21	F	51	L5	2	2	24.5	46	57	13.0	-4	-18.5°	S						31	163
21	F	51	L2	1	1	18.4	40	48	11.3	-5	-7.3°	S						23	137
21	F	51	L4	1	1	21.9	44	52	14.0	-3	-10.5°	S						36	153
21	F	51	L1	1	1	13.0	36	42	10.7	-4	-9°	S						14	137
21	F	51	L3	2	1	10.7	31	46	10.0	-8	-9.5°	S						9	130
21	F	51	L5	3	1	16.6	39	50	9.0	±0	-15.5°	S						30	165
21	F	51	L2	1	0	19.1	41	53	11.7	-2	-11.5°	S						24	118
21	F	51	L4	1	2	19.1	43	56	12.8	-2	-12°	S						25	145
21	F	51	L1	1	1	15.4	38	49	10.3	±0	-7.5°	S						25	143
21	F	51	L3	2	1	17.8	40	52	13.0	-6	-9.5°	S						29	144
21	F	51	L2	1	1	18.7	41	50	11.3	-2	-10.5°	S						28	137
21	F	51	L4	1	2	21.2	46	51	12.0	-2	-17.5°	S						42	152
21	F	51	L1	1	1	9.2	31	40	7.3	-5	-5.5°	S						18	101
21	F	51	L3	2	1	10.7	31	46	10.0	-8	-9.5°	S						9	130
21	F	51	L4	2	1	15.0	35	51	11.5	-3	-8.0°	F						16	161
21	F	51	Tn12	1	2	14.2	36	49	8.0	-4	-6°	S						17	129
21	F	51	(L2)L3	2	2	20.0	41	59	13.0	-2	-5.5°	S						45	151
21	F	51	L5	2	2	24.5	46	57	13.0	-4	-18.5°	S						31	163
21	F	51	L2	1	1	18.4	40	48	11.3	-5	-7.3°	S						23	137
21	F	51	L4	1	1	21.9	44	52	14.0	-3	-10.5°	S						36	153
21	F	51	L1	1	1	13.0	36	42	10.7	-4	-9°	S						14	137
21	F	51	L3	2	1	10.7	31	46	10.0	-8	-9.5°	S						9	130
21	F	51	L5	3	1	16.6	39	50	9.0	±0	-15.5°	S						30	165
21	F	51	L2	1	0	19.1	41	53	11.7	-2	-11.5°	S						24	118
21	F	51	L4	1	2	19.1	43	56	12.8	-2	-12°	S						25	145
21	F	51	L1	1	1	15.4	38	49	10.3	±0	-7.5°	S						25	143
21	F	51	L3	2	1	17.8	40	52	13.0	-6	-9.5°	S						29	144
21	F	51	L2	1	1	18.7	41	50	11.3	-2	-10.5°	S						28	137
21	F	51	L4	1	2	21.2	46	51	12.0	-2	-17.5°	S						42	152
21	F	51	L1	1	1	9.2	31	40	7.3	-5	-5.5°	S	</						

Table 4.

## Specimen characteristics.

## Tests Performed.

Specimen Nr #	Sex	Age	Disc level tested	Disc degeneration (0-3)	X-ray changes (0-3)	Disc area cm <sup>2</sup>	Sagittal diameter (d <sub>s</sub> ) mm	Frontal diameter (d <sub>f</sub> ) mm	Height of disc (h <sub>m</sub> ) mm	Distance "balanced position" to geometric center (m <sub>0</sub> ) mm	Original disc angle in sagittal plane (α <sub>0</sub> ) degrees	Intact	Divided Ligaments	Screws through facets	Removal of articular processes	Injected disc cm <sup>3</sup>	Fusion	Fusion type 1-3	Fusion + excised disc	Additional moment	Special tests	Count of series	Max. load used kp	Remarks <sup>1</sup>
22	M	43	L2	1	1	19.0	44	49	9.3	-3	-8°	S					S	2	S			30	156	
22	M	43	L4	2	1	21.7	46	55	11.5	-5	-14°	S					S	1	S			38	158	
23	F	44	L2	1	1	17.6	39	49	11.0	-3	-4.5°	S					S	1	S			25	148	
23	F	44	L4	1	1	17.2	40	51	13.3	-2	-7.5°	S	S				S	1		S	S	58	144	
24	M	30	L3	0	0	18.6	41	55	10.5	-2	-8.5°	S					S		S	S		27	140	
24	M	30	L5	0	0	19.2	39	57	13.3	-1	-16°	S					S		S	S		24	132	
25	M	63	L2	1	1	14.0	36	48	9.3	-1	-6.5°	S	S				S					14	121	
25	M	63	L4	3	1	18.2	39	53	13.0	+1	-9.3°	S					S	1	S		S	38	138	
26	M	42	L2	1	1	22.9	45	52	13.5	-5	-8.8°	S					S	2	S			29	152	
26	M	42	L4	2	1	26.0	49	65	13.7	-3	-12.3°	S					S	2	S			35	141	
27	M	61	L2	2	1	22.0	44	59	10.3	-3	-4.5°	S	S				S	3	S	S	S	34	150	
27	M	61	L4	2	1	23.7	46	65	12.0	-3	-12.0°	S	S	S			S	2	S	S		31	140	
28	F	51	L2	1	1	20.4	42	58	11.5	±0	-6°	S					S					37	159	



graphs for each specimen. This has been done to a considerable extent but would prove excessively voluminous for all the parameters in the entire material. For the comparisons which may be said to deal with a behavioural pattern for lumbar spine specimens under the influence of varying forces, practical considerations have led to a grouping of both the loading intensity and the degree of eccentricity. The loading intensities were grouped into two intervals, 1 — 2 and 3 — 4 kp/cm<sup>2</sup>, and the eccentricity into 7 equal intervals, from —1 to +1. The higher loading interval corresponds approximately to the individual's total body weight, i.e. 40 per cent more than the superimposed body weight. The lower loading interval complements this, since many series, particularly those with great eccentricity, do not reach the higher load interval, and consequently there tends to be rather limited data for this.

The intervals of eccentricity are natural in relation to the geometric centre of the disc. In the case of the sagittal plane, however, the balanced position is an important factor since it is here that all parameters (except intradiscal pressure) change sign. Only one (degenerated) disc has the balanced position in the interval +0.15 — +0.45, while for 17 healthy and 14 degenerated discs it lies between —0.15 and +0.15 and for 11 healthy and 5 degenerated discs between —0.45 and —0.15.

The division of the material into intervals of loading intensity and eccentricity represents a compromise solution to a complex problem. It results in an unnecessarily large spread of measurement data and is to be

Table 5.

*Mean and standard deviation of 48 specimens (including two vertebrae and one disc) contributing to aggregate results:*

Disc area (A)	=	18.1 ± 3.2 cm <sup>2</sup>
Disc height (h <sub>3</sub> ), posterior	=	7.3 ± 0.6 mm
Disc height (h <sub>2</sub> =h <sub>4</sub> ), lateral	=	11.4 ± 2.0 mm
Disc height (h <sub>1</sub> ), anterior	=	13.8 ± 3.1 mm

Table 6. *Largest change in angle measured of intact specimens:*

		Forward	Backward
Sagittal ( $\alpha$ )	max.	+7.5°	— 6.3°
	min.	+1.1°	— 1.8°
		Right	Left
Frontal ( $\beta$ )	max.	+7.6	— 6.6
	min.	+1.2	— 1.2

accepted only under the above conditions; even so, it does not, of course, do full justice to the accuracy with which the measurements were made. All aggregate results are shown in the diagrams as shaded areas representing the standard errors ( $\pm SE$ ) of the mean ( $\bar{x}$ ); subgroups are indicated as separate mean and standard errors. In the tables, the number of measurements ( $n$ ) are given for each mean.

Some specimens prove to be particularly resistant to deformation and were therefore subjected to higher loads at greater eccentricity than was normally the case. In the graphs representing results for all the specimens, this is reflected by an overrepresentation of such specimens in the extreme intervals of eccentricity. In some intervals, for which only a few measurements were obtained, the general picture is liable to be distorted by extreme results for individual specimens. These specimens could, of course, have been excluded, but it was decided instead to give free rein to chance and to discuss the reason for such deviations in each case.

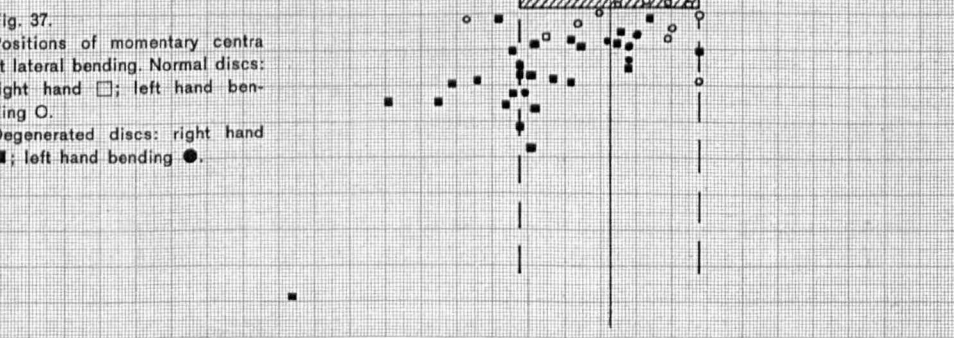
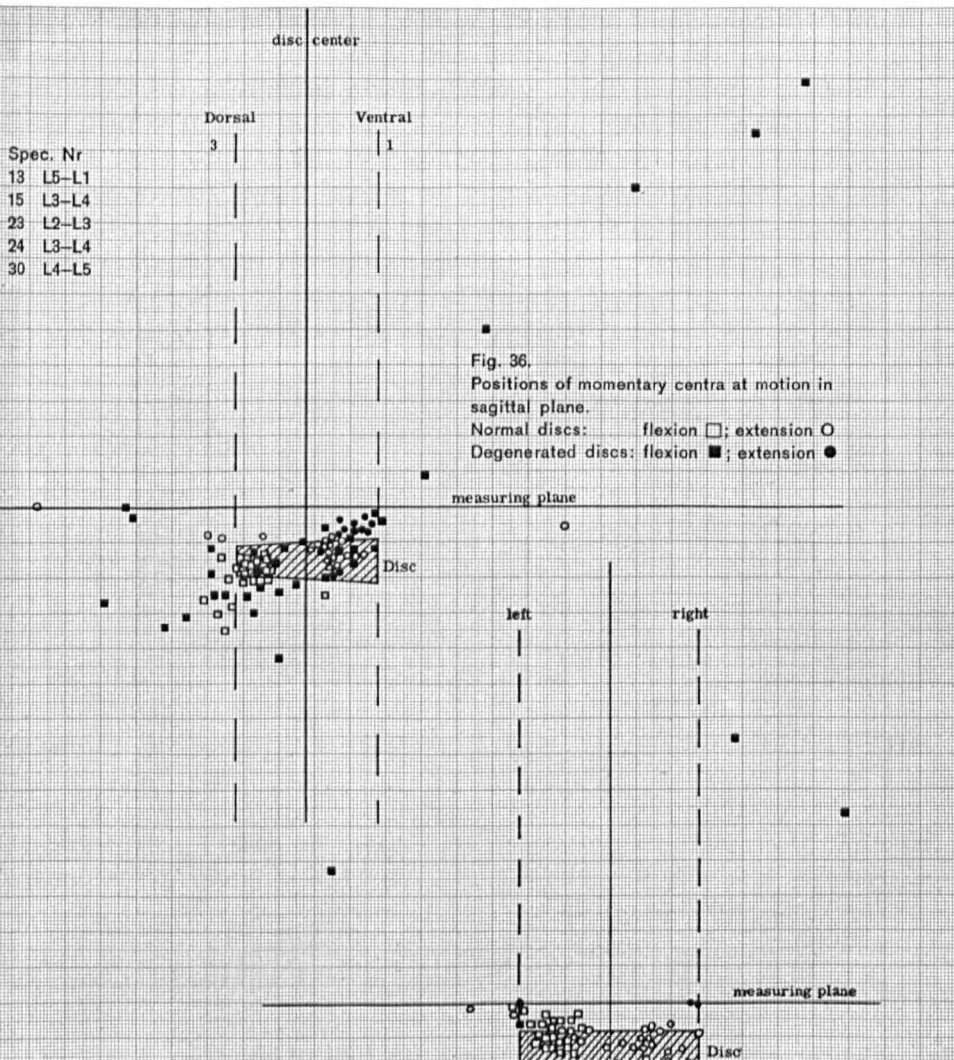
## IV Results and discussion

### Intact specimens

#### *Motion centre*

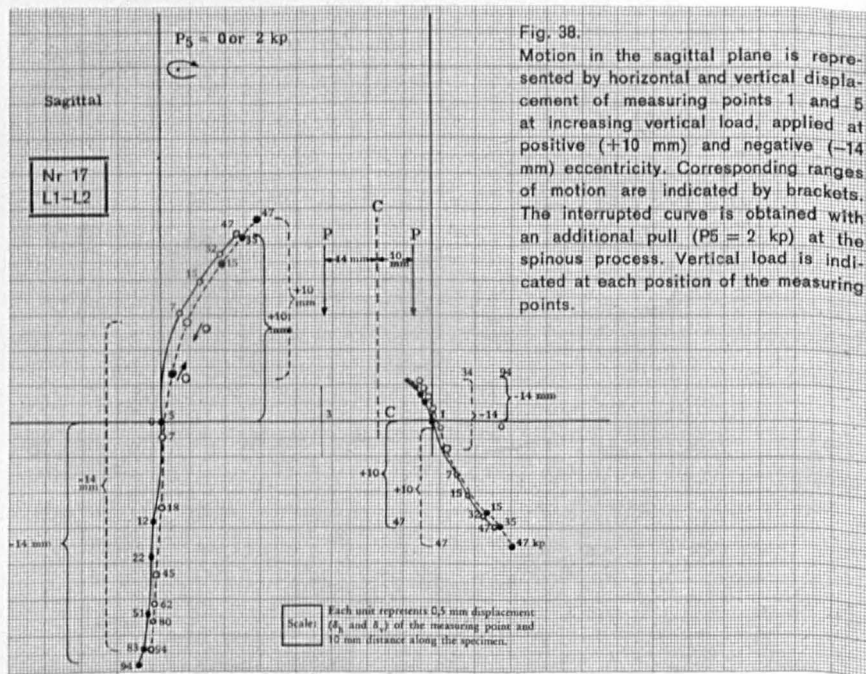
Joint function is usually described in anatomy as rotation around and translation along the body's three mutually perpendicular, primary axes: the longitudinal, sagittal and transverse. A lumbar motion segment (two vertebrae with the intermediate disc and ligaments) is considered to possess six degrees of freedom, i.e. both rotation and translation are represented (Broman & Hjortsjö, 1952). It has been held that all the axes of motion pass through the centre of the nucleus pulposus (Fick, 1904; Strasser, 1913; Calvé & Galland, 1930; Hagelstam, 1949; Broman & Hjortsjö, 1952) though with varying instantaneous centres (Dittmar, 1931). In the event of disc degeneration, the frontal axes of motion is reported to be displaced dorsally towards the intervertebral joints (Gianturco, 1944; MacNab, 1950). Knutsson (1944) considers that increased sagittal translation is an early sign of disc degeneration.

In accordance with the principle stated on pp. 22 and 52 (Hoag, 1960) the position of the instantaneous centres has been calculated at rotation in the sagittal and frontal plane. With this procedure, translation along the longitudinal axis (compression of the disc without accompanying rotation or translation along the other main axes) gives an instantaneous centre with an infinite  $x$  coordinate. Similarly, for translation in the horizontal plane the  $y$  coordinate is at infinity. It follows that the position of the instantaneous centre is discontinuous for central loading. Fig. 36 illustrates the position of the instantaneous centres in rotation in the sagittal plane (around frontal axes) for five specimens representing different levels of the spine and different degrees of disc degeneration. Hoag's statement is confirmed to the extent that healthy discs show a concentration of instantaneous centres for ventroflexion in the dorsal part of the disc and vice versa. The degenerated discs give a very large spread and many of their values lie outside the figure. At rotation in the frontal plane (Fig. 37) there is a corresponding tendency for the instantaneous centres to be concentrated to the left of the median for flexion to the right and vice versa, but in this case even normal discs display a wide spread. The spread



of the instantaneous centres might be interpreted as indicating a type of "instability" but not in the usual sense.

Seven specimens (cf. Table 4, p. 68), besides being subjected to a vertical compressive force in the usual way, also had a vertical lifting force applied to the spinous process of the upper vertebra; this gave a known increment to the positive moments acting in the sagittal plane. The horizontal and vertical displacements of points 1 and 5 were recorded during vertical loading with positive and negative eccentricity respectively, with and without the extra force applied to the spinous process. It will be seen from Fig. 38 that the relatively slight additional force makes a large initial



positive change of angle (see further p. 96). Here, the figure serves to show that both measuring points follow the same paths of motion for both types of loading and hence that the instantaneous centres for the interval of motion are nearly identical.

Although the movements of a lumbar motion segment are limited in extent, its pattern of motion is highly versatile. The centres of motion are infinite in number and can hardly be used as a basis for describing function. It has proved practical, however, to use the 6 degrees of freedom as a basis for describing the changes which occur when the specimens are subjected to various loading conditions.

## Longitudinal axis

### *Translation.*

Longitudinal translation implies vertical displacement ( $\delta_v$ ) that is equally large at all measuring points; this is referred to as balanced loading. Since, however, the initial height ( $h$ ) is different for the various measuring points, the relative displacement ( $\epsilon$ ) is not the same for them all. This position is unstable and may vary somewhat for different loads (Fig. 39). The stress-strain relations for all the discs tested, were obtained from the loads at which the change in angle in both the sagittal ( $\alpha$ ) and the horizontal plane ( $\beta$ ) was less than  $\pm 0.25^\circ$ . The relative deformation is represented by measuring points 1 and 2 (cf. Figs. 40 and 41).

The graphs indicate a viscoelastic stress-strain relationship, with increasing rigidity as the load rises. At a loading intensity of 5–6 kp/cm<sup>2</sup> the "compression" of the normal disc is 2.6 per cent and in disc degeneration 3.4 per cent. The corresponding figures reported by other investigators are approximately 10 and 15 per cent (Göcke, 1932; Virgin, 1951; Ingelmark & Ekholm, 1952; Hirsch & Nachemson, 1954; Brown, Hansen & Yorra, 1955; Ewans & Lissner, 1965). The difference (1:4) is ascribable to the fact that the latter measurements were made from external reference points. By measuring between points on the specimen itself, close to the limits of the disc, one reduces the influence of deformation in the bone tissue as well as errors due to adaptation between the specimen and the loading plates. The geometrical asymmetry of the specimen makes it necessary to have at least two measuring points in each primary plane. Moreover, direct measurements on the disc and vertebra must be made separately, due to differences in their materials (cf. Fig. 31). This naturally applies in particular to specimens composed of several segments (see p. 114). The total vertical compression of the disc is in actual fact still less than indicated above, since the disc in situ has a preload of approximately 1 kp/cm<sup>2</sup> (Petter, 1933). The disc tissue itself has been regarded as incompressible. Thus, the vertical deflexion is the result of an initial collapse of voids in the disc and an increasing bulge of the annulus fibrosus and end-plates. Since the bulging of the disc was not a major item in the present investigation, its order of magnitude was simply checked on three specimens with their arches removed. The vertical deformation was recorded at four measuring points in the usual way. The horizontal displacement gauges were positioned against minute centre nails, which had been fitted in the circumference of the annulus fibrosus at the sagittal and frontal diameters so as to correspond to measuring points 1 and 3, and 2 and 4 respectively. The increase in the sagittal and frontal diameters could then be measured during centric and excentric loading. The result

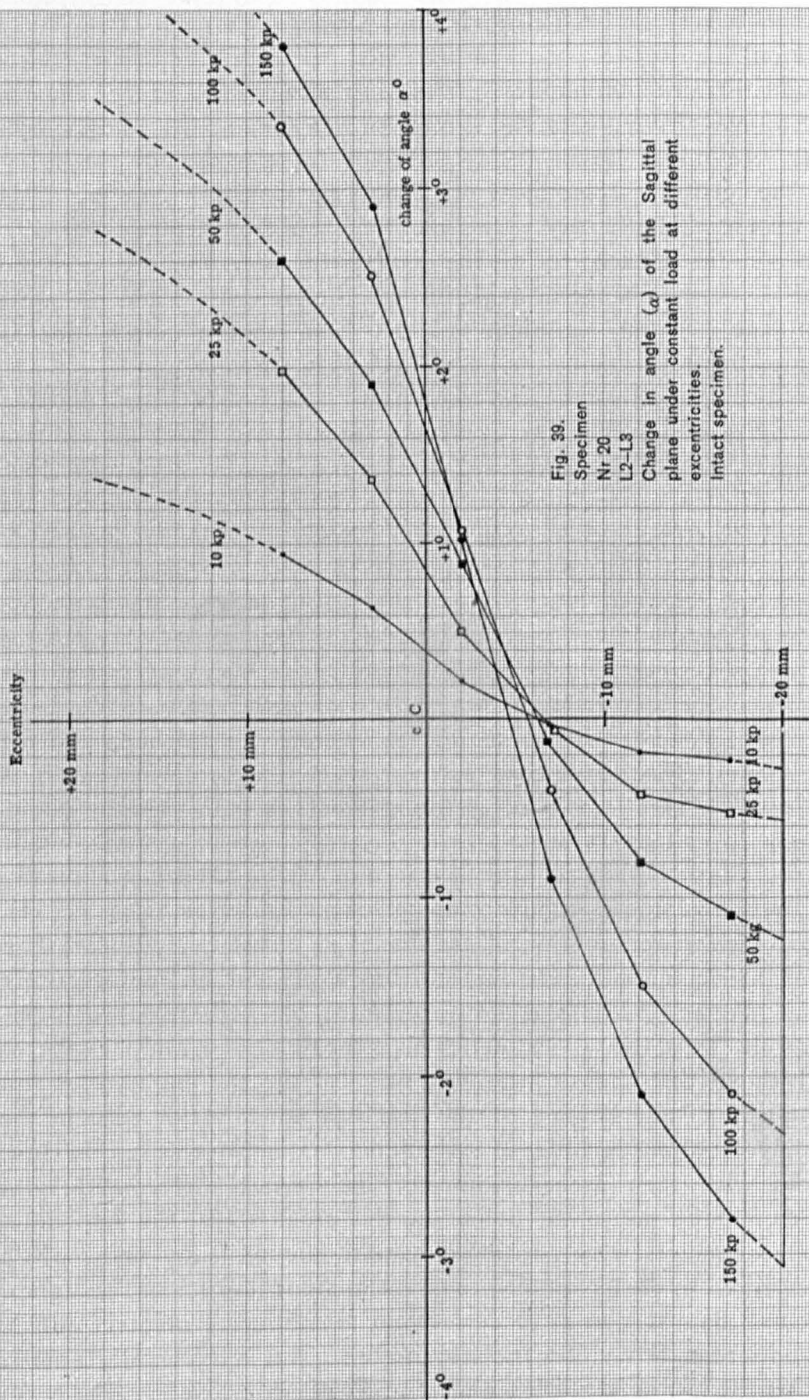


Fig. 39.  
Specimen  
Nr 20  
L2-L3  
Change in angle ( $\alpha_0$ ) of the Sagittal  
plane under constant load at different  
eccentricities.  
Intact specimen.

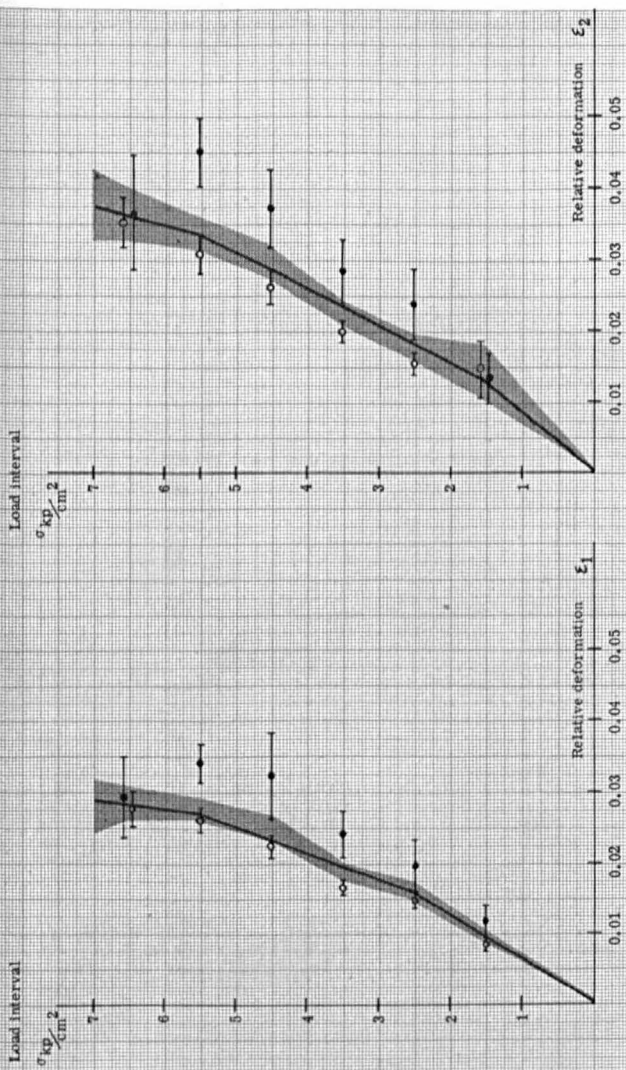


Fig. 40-41. Stress strain relation in all tested discs.  
 -O- = mean ( $\bar{x}$ ) and standard errors ( $\pm SE$ ) for normal and -●- degenerated discs.  
 Central loading  $\alpha$  and  $\beta$  within  $\pm 0.25^\circ$ .

Normal discs (α)			All discs (α+β)			Degenerated discs (β)		
$\bar{x}$	$\pm SE$	$n$	$\bar{x}$	$\pm SE$	$n$	$\bar{x}$	$\pm SE$	$n$
0.01	-0.004	10	0.01	-0.004	10	0.01	-0.004	10
0.02	-0.003	10	0.02	-0.003	10	0.02	-0.003	10
0.03	-0.002	10	0.03	-0.002	10	0.03	-0.002	10
0.04	-0.001	10	0.04	-0.001	10	0.04	-0.001	10
0.05	-0.001	10	0.05	-0.001	10	0.05	-0.001	10

of such a test on a specimen with class 1 degeneration is shown in Fig. 42. The sagittal and frontal diameters both increased by 1.3 mm in the loading interval 1 — 2  $kp/cm^2$  and by 2 mm in the interval 3 — 4  $kp/cm^2$ . The increase was the same for centric and excentric loading. In the two highly degenerated discs the increase was smaller in the sagittal diameter but somewhat larger in the frontal. These discs bulged considerably even before loading, while during loading it was obvious to the naked eye that they bulged more in some parts of the periphery than in others. The magnitude of the bulging was very similar to that reported by Hirsch &

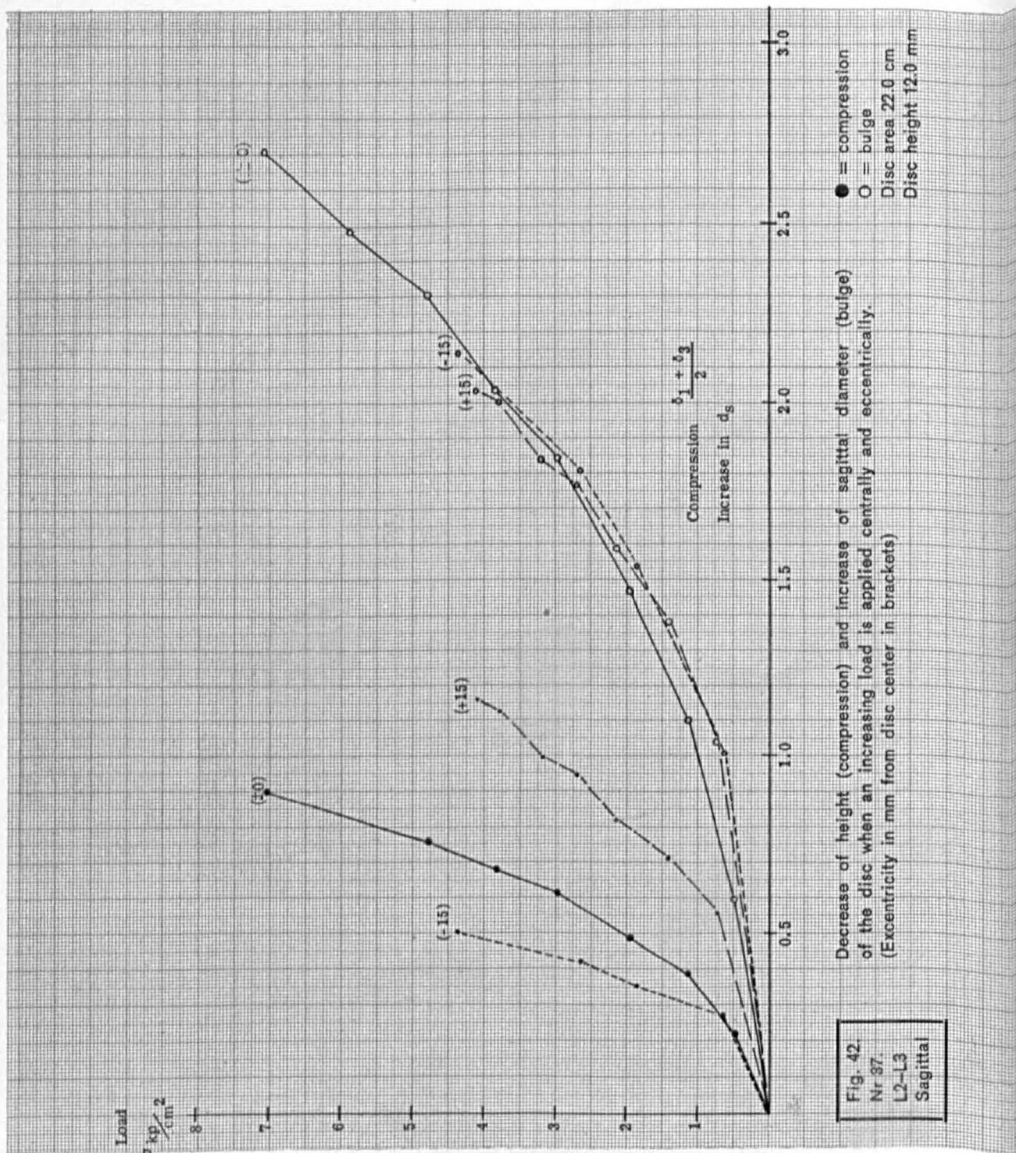
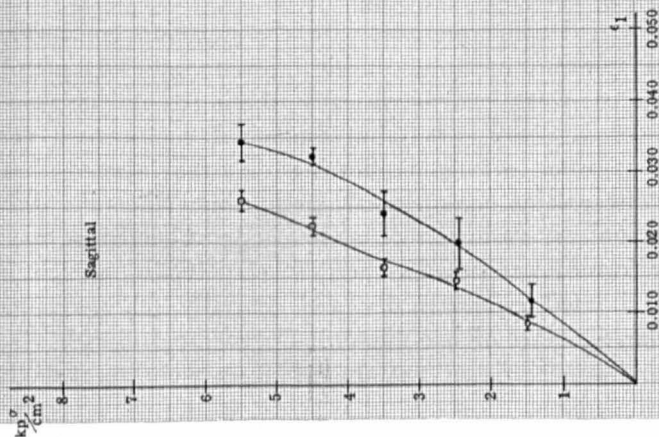
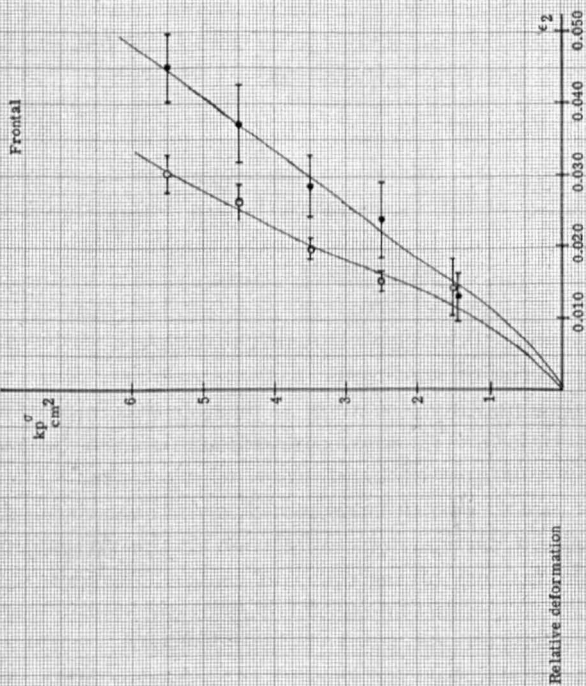


Fig. 42  
Nr 87  
L2-L3  
Sagittal

Nachemson (1954) and by Brown, Hansen & Yorra (1957). As a result of the bulging, the surface area of the healthy disc increased by approximately 6 per cent at loading intensity 1—2 kp/cm<sup>2</sup> and 7 per cent at 3—4 kp/cm<sup>2</sup>. The corresponding figures for the degenerated disc are 4 and 6 per cent. This gives an average of 5 per cent for the lower loading interval and 6.5 per cent for the higher (cf. Nachemson, 1960, who reports an average of 5 per cent for all loads).



$\beta$	Discs	$\bar{X}$	S.E.
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000



$\beta$	Discs	$\bar{X}$	S.E.
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000
1-1-15	9	0.000	0.000

Fig. 43-44  
Stress-strain relation  
all specimens  
—○— normal discs  
—●— degenerated discs  
central loading,  $\alpha$  and  
 $\beta$  within  $\pm 0.25^\circ$

The vertical deformation is statistically larger for the degenerated than the normal discs at all loading intervals (Figs. 43 and 44) at the 1 per cent level (Student's T-test). This greater compressibility also results in a larger residual deformation after the first series of loadings. After repeated loadings, however, the residual deformation is equally large in healthy and degenerated discs. The residual deformation in 52 intact specimens after the first and last series of loadings is given in Table 7 (in the case

Table 7.

*Residual deformation of the disc after the first and last loading serie on intact specimens.*

Serie	Degree of degeneration.	Mean for $\frac{\delta_{1v} + \delta_{3v}}{2}$	SE	n
First	0 — 1	0.065	± 0,015	33
„	2 — 3	0.119	± 0,025	19
Last	0 — 1	0.155	± 0,033	33
„	2 — 3	0.156	± 0,006	19

of the remaining specimens, the displacement gauges were zeroed between the first and the last series of loadings).

As much Chromopaque or Ringer solution as possible was injected into 25 discs (see Table 4, p. 68). The maximum amount varied between 0.3 and 3 cc except in the case of eight discs which leaked. There was practically no resistance to the injection, which caused the average height of the disc to increase approximately in relation to the volume injected; at the same time, the bulging of the disc was reduced (roughly measured with calipers). The maximum amount which could be injected was reached abruptly, without any gradual increase in resistance to the injection. The height of the disc could not then be further increased, even though maximum force was applied to the injection. On the other hand, the discal pressure varied synchronously with the injection force. The maximum intradiscal pressure measured during injection was 3.5 kp/cm<sup>2</sup>. When injected specimens were loaded vertically, the horizontal displacement was reduced (cf. Rådberg, 1954) but the initial compression and the residual deformation were large, indicating that the injected fluid had spread in the disc and/or been pressed out of this. When the discs were sectioned, the contrast medium was seen to have collected in what appeared to be preformed cavities (Teichert, 1962a, 1962b), which in normal discs were situated symmetrically and centrally (chromopaque has a large molecular diameter of one micron). Degenerated discs having irregular cavities and concentric or radiating fissures were accordingly stained with contrast medium.

Since the injection of contrast fluid changes the physical properties in the disc, discography could not be used as a routine in the present investigation but was performed after the other measurements on the disc had been concluded.

#### *Rotation-torque.*

Four specimens were used for this test (no. 24 L 3 — L 4 and L 5 — S 1; no. 31 L 3 — L 4 and L 5 — S 1). A threaded bolt, 10 cm long, diameter 6 mm,

was screwed horizontally through the upper vertebral body, parallel to the sagittal diameter. The specimen was placed in the loading apparatus with the displacement and pressure gauges applied in the usual way. A sagittal horizontal displacement gauge was fitted against measuring point 2 (the extensometer over the vertebra was omitted). Thin steel wires were then attached at either end of the bolt, 45 mm from the centre of the vertebral body, and pulled horizontally in opposite directions parallel with the frontal diameter. Each wire was hung vertically over a pulley and loaded with 4 kg, which gave a positive moment of 36 kpcm acting around the longitudinal axis. The angle of rotation ( $\gamma$ ) was read of the compression apparatus' protractor and was also calculated from the

$$\text{equation } \tan \gamma = 2 \frac{(\delta_{1h} - \delta_{2h})}{d_f} \quad (6)$$

The angles of rotation calculated in this way for the four discs were 0.33, 0.33, 0.54 and 1.18° (simultaneous central vertical loading reduced  $\alpha$ ). After removal of the intervertebral joint facets, the angle increased to 1.0, 2.3, 1.7 and 2.3° respectively. Fick (1904) gives the average for intact, lumbar segments as 2.5°. Andersson & Ekström (1940) found 0.6° at a torque of 48 kpcm and 1.9° at 200 kpcm. In the present study the accompanying change in angle of the horizontal plane was negligible. The calculation assumes that the rotation occurs around the longitudinal axis through the centre of the disc; this seems reasonable. Although the measurements incorporate certain uncontrollable errors, they do indicate the magnitude of the possible rotation and show that the intervertebral joints take up torque in the horizontal plane.

An interesting phenomenon, probably associated with the helicoidal arrangement of the fibres in the annulus, is that the average height of the disc increases when horizontal torque is applied — an increase that is approximately proportional to the degree of rotation. At the same time the disc pressure dynamometer gave a negative reading.

## Frontal and sagittal axes

### *Translation in the horizontal plane.*

Fick (1904) asserts that parallel displacement between vertebrae is severely limited but not entirely prohibited by the construction of the annulus. Brocher (1958) considers that a parallel displacement between vertebrae always indicates a pathological change of major clinical significance. Severin (1943) demonstrated roentgenologic retroposition in 50 per cent of degenerated discs. Knutsson (1944) developed a test of stability by using lateral X-rays at maximal flexion and extension. More than half of

58 discs with anatomical signs of degeneration showed "instability". Displacement in the direction of flexion was presented by 26 and in the opposite direction by four (paradoxical mobility according to Gianturco, 1944; Schalimtzek, 1958). In 18 cases Knutsson found roentgenologic instability out of 82 without other anatomical signs of disc degeneration. He considered this to be an early roentgenologic sign of disc degeneration. A similar investigation on spinal specimens was made by Friberg & Hirsch (1949), who correlated the X-ray findings with the pathological anatomy of the intervertebral discs. Hagelstam (1949) found that in roentgenologically normal discs the limits for parallel displacement were  $\pm 2$  mm while they were wider for degenerated discs but seldom more than 3 mm. He found that the error of measurement for roentgenological methods can easily amount to 1 mm. Direct measurements on specimens do not seem to have been made previously.

In the present investigation the parallel displacement is given as the x-coordinate of the measuring point. No specimen at any load or eccentricity gave a displacement of more than  $\pm 2$  mm, while only a few results exceeded  $\pm 1$  mm. Various initial angles of the vertebral bodies in relation to the horizontal plane ( $v_1$  and  $v_2 \pm 10^\circ$ ) did not influence the magnitude of the horizontal displacement. The direction of this displacement was liable to vary for loads near the centre but otherwise it followed the direction of rotation, so that positive rotation gave a positive horizontal displacement. Increased eccentricity resulted in increased horizontal displacement but could be achieved near maximal displacement with slight loads, suggesting that there is a certain play in the unloaded disc in the horizontal direction. With considerable eccentricity, however, there is a critical load for each disc at which the horizontal displacement reaches a certain maximum and then might change its direction upon further loading. In Figs. 45 and 46, points 1 and 2 represent motion in the horizontal plane for varying eccentricity and loads of 1—2 and 3—4 kp/cm<sup>2</sup>. For an eccentricity of -0.45 to -0.15 in the sagittal plane, the horizontal displacement is 0, increases and decreases linearly respectively at the neighbouring eccentricity intervals but curves away at greater eccentricities to a maximum at +0.45 to +0.75.

Parallel displacement along the frontal axis (Fig. 46) is of the same magnitude as in the sagittal axis.

The horizontal displacement is not to be regarded as an isolated motion but as an integrated function of the disc's deformation by the forces acting upon it. Fig. 47 shows a typical case of the relationship between the horizontal and vertical displacements of point 1 at different loads and eccentricities.

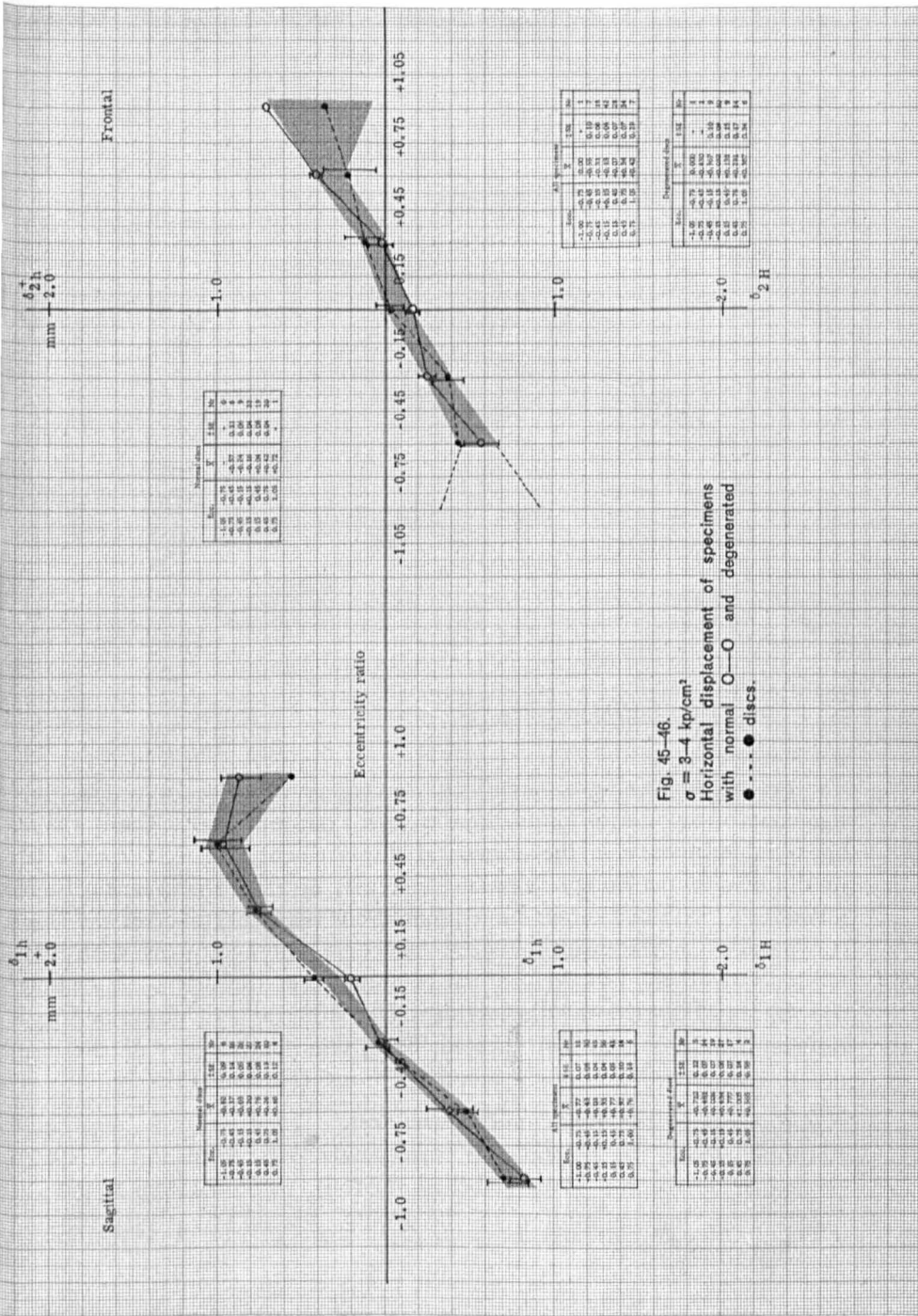


Fig. 45-46.  
 $\sigma = 3-4 \text{ kp/cm}^2$   
 Horizontal displacement of specimens  
 with normal O—O and degenerated  
 ●—●—● discs.

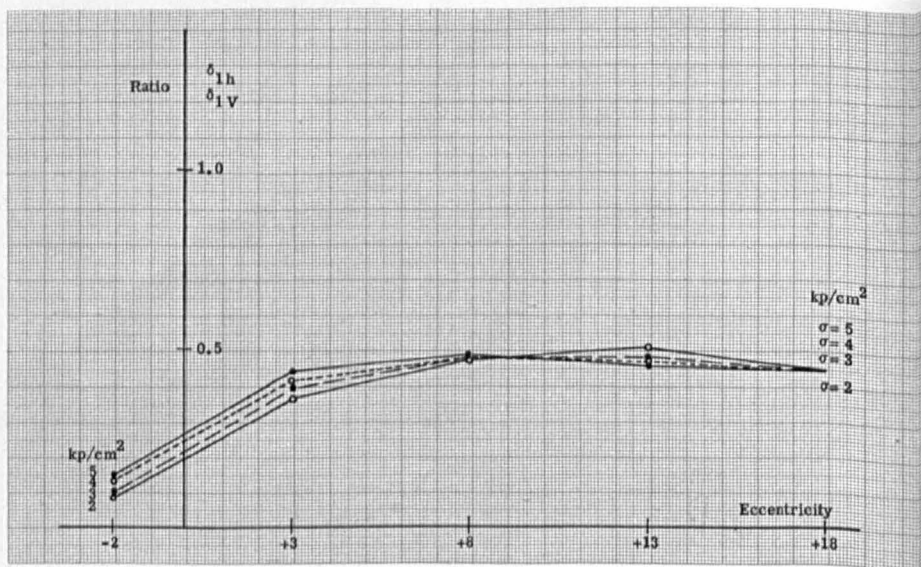


Fig. 47.

Nr 23, L2-L3

Ratio of horizontal to vertical displacement of measuring point one (1) using constant loads with different eccentricities, tested intact in sagittal plane.

The magnitude of the horizontal translation agrees with the limits reported by Hagelstam. In the present material and with the loading method used, no increased translation — instability — was found for degenerated discs.

To test the stabilizing effect of the interspinous ligaments, interarcuate ligaments and posterior joints, these were cut out separately. There was no appreciable increase in the horizontal displacement (Fig. 48). As the tilt of the disc to the horizontal plane increases, so does the shearing force. Chandler (1951) and others have pointed out the importance of the slope for parallel displacement between vertebrae. In agreement with Fick (1904) and others, however, it can be stated that the disc itself delimits the degree of horizontal displacement (the anterior and posterior longitudinal ligaments were not severed, being regarded as part of the disc) due to the construction of the annulus fibrosus (Horton, 1958).

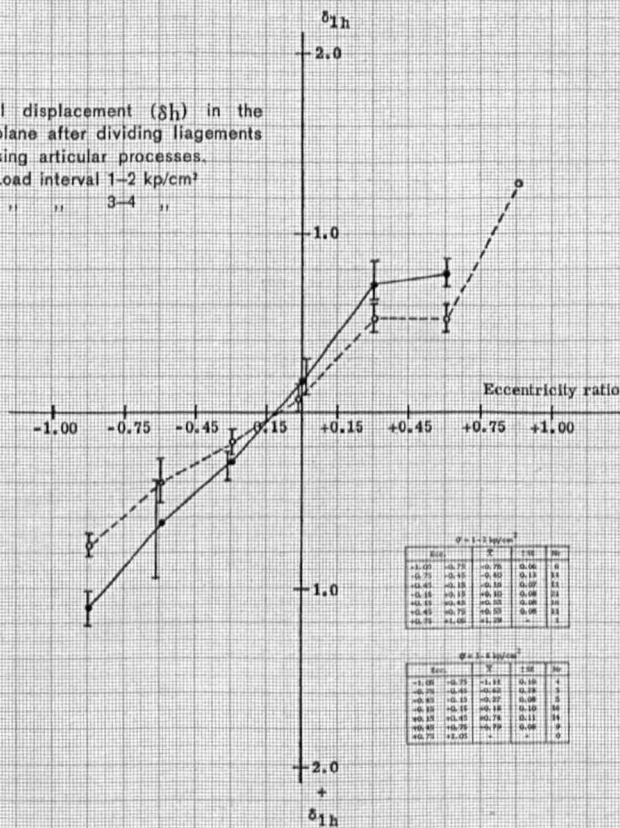
#### *Rotation around the frontal and sagittal axes.*

Rotation around the frontal axis corresponds to forward and backward flexion in the sagittal plane (labelled sagittal), while rotation round the sagittal axis implies motion in the frontal plane, i.e. lateral bending (labelled frontal).

The rotation in each plane has been compiled, in accordance with the principles given on p. 55 Fig. 26, as the relative displacement of a

Fig. 48.  
Horizontal displacement ( $\delta_{1h}$ ) in the  
sagittal plane after dividing ligaments  
and excising articular processes.

○—○ Load interval 1-2 kp/cm<sup>2</sup>  
●—● " " " 3-4 " "

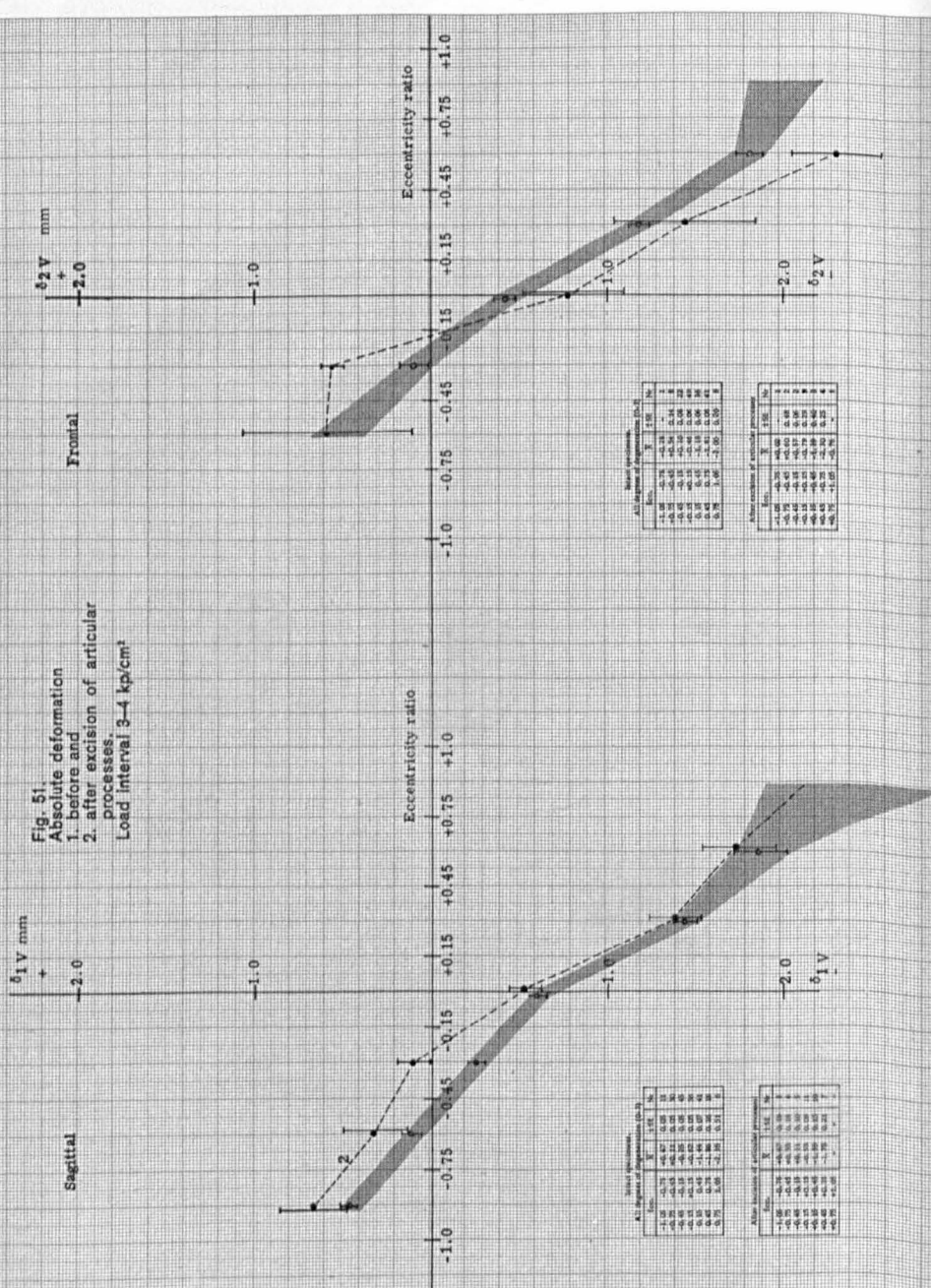


measuring point and the change of the angle in the plane. Motion in the sagittal plane is thus represented by  $\varepsilon_1$  and  $\alpha$  and motion in the frontal plane by  $\varepsilon_2$  and  $\beta$ . It should be borne in mind that, by definition, positive rotation (forward flexion and lateral bending to the right) is indicated with a positive sign for the change in angle (given in radians) while the deformation is described as negative when the distance between a measuring point and its reference point diminishes, and positive, when this distance increases. For a correct conception of the movement, each point on the deformation curve must be compared with the corresponding change in angle.

Figs. 49 a and 50 a illustrate rotation in the sagittal plane (dorsoventral flexion). The change in angle is 0 at an eccentricity of  $-0.12$ , i.e. a distance ( $m_0$ ) of 4.5 — 5 mm dorsal of the geometric centre. The relative deformation is then  $3 \pm 0.3$  per cent, which corresponds to a deformation







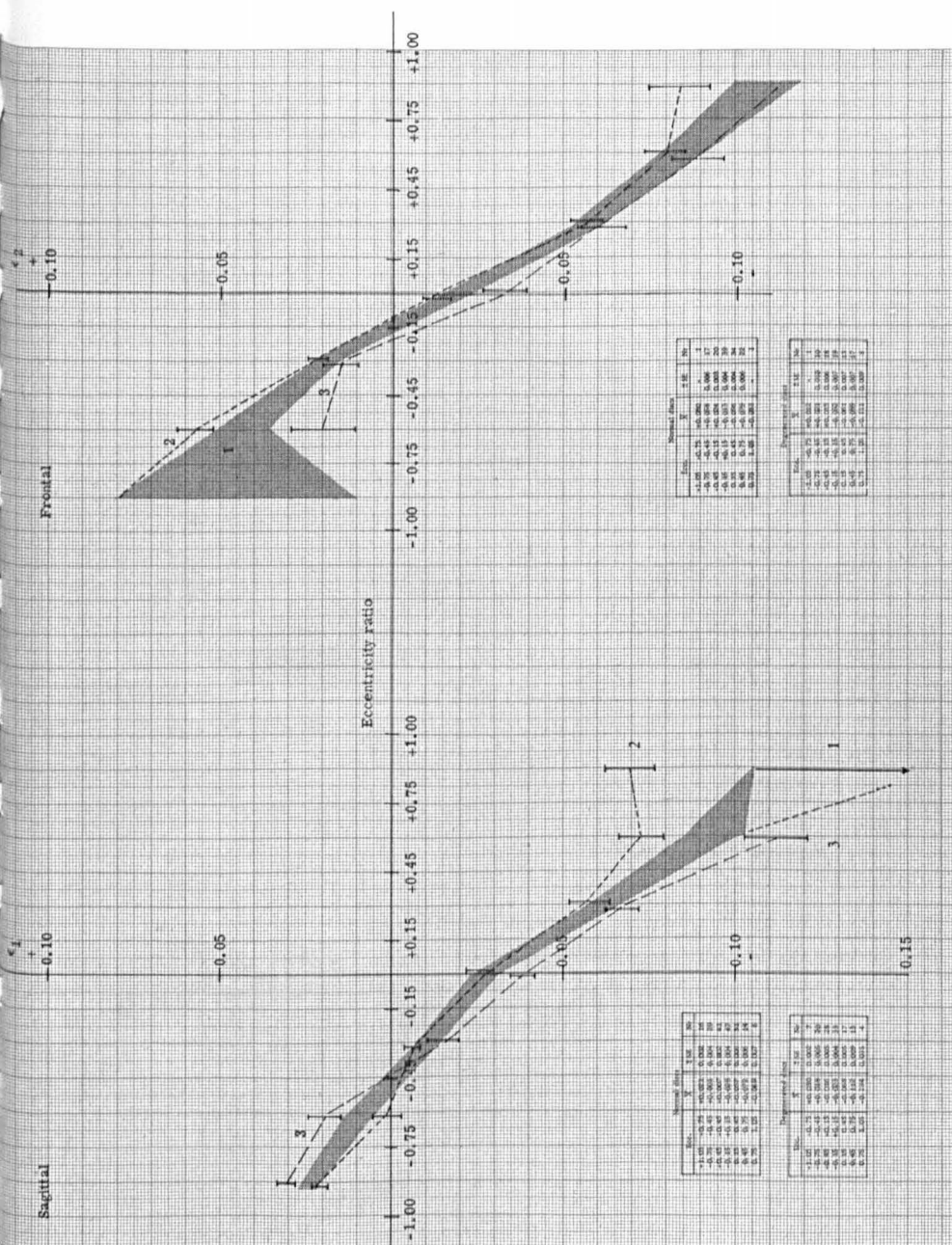
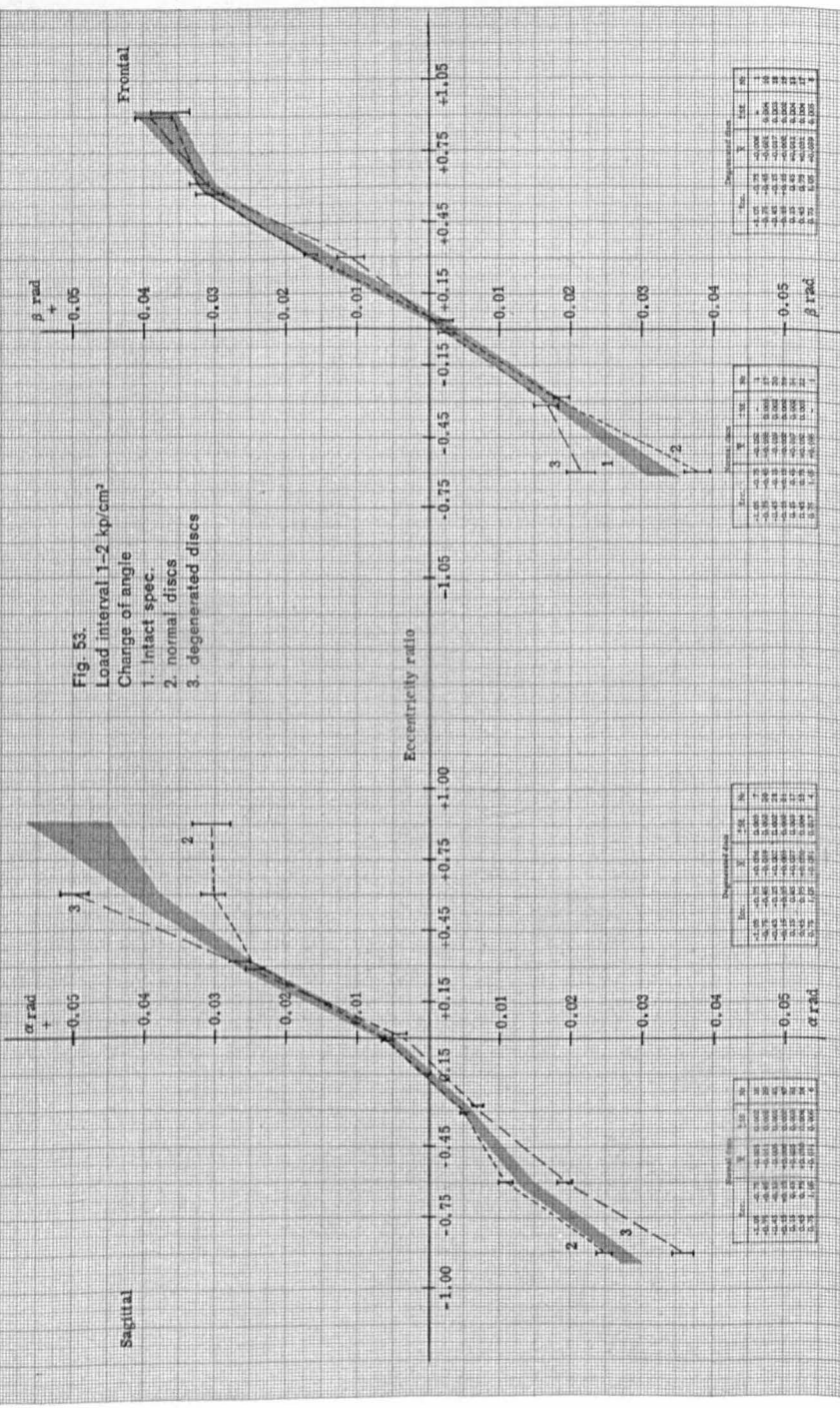


Fig. 52. Load interval 1-2 kp/cm<sup>2</sup>  
 Relative deformation in intact specimens.  
 1. All specimens  
 2. Degenerated discs  
 3. Normal discs



of  $0.5 \pm 0.04$  mm in absolute figures (cf. Fig. 51 a). For an increasing negative moment, the change in angle shows an almost linear regression line, with only a slightly larger change for degenerated than for healthy discs. For a positive moment the curve for healthy discs flattens out at about 0.05 radians, while that for degenerated discs again shows an almost linear increase in angle with a mean twice as large as that for healthy discs at the ultimate moment. The relative deformation shows a completely analogous course, that for healthy discs having the same tendency to level out at the maximum positive moment. The individual specimens contributing the measurements in the interval  $+0.75 - +1$  show, however, that an increased moment always gives increased deformation; thus, the aggregate curve exaggerates the position at the maximal moment (cf. p. 72). The pattern for deformation and change of angle is the same in principle for the loading intensity  $3 - 4$  kp/cm<sup>2</sup> and  $1 - 2$  kp/cm<sup>2</sup> (Figs. 52 and 53).

Rotation in the frontal plane (lateral flexion) is presented in the same way in Figs. 50 b and 49 b by the change of angle in the frontal plane ( $\beta$ ) and the relative displacement of the right-hand measuring point ( $\epsilon_2$ ). The change in angle gives a gently S-shaped curve with healthy discs tending to show a somewhat larger change than degenerated discs. The balanced position of the healthy discs is displaced slightly to the right of the centre (approx. 0.7 per cent), with a relative deformation of  $4.5 \pm 0.6$  per cent, that for the degenerated discs being  $5 \pm 0.6$  per cent. Loading at the eccentricity interval  $+0.45 - +0.75$  results in a compression of the disc at point 2 by approximately 13 per cent, while the stretch at the same point with the same negative moment is approximately 5 per cent, or in absolute figures  $-1.8$  mm and  $+0.5$  mm. The increase in the height of the disc on one side is thus only one-third of the decrease on the other. Fig. 54 illustrate the discal pressure at different eccentricity intervals in the sagittal plane. The data for pressure during lateral flexion are widely dispersed, with extreme values for individual specimens which upset the general picture. One would expect lateral flexion to give a symmetrically shaped curve. There does not seem to be any difference between healthy and degenerated discs, which is natural in view of the selective nature of the measurements. Nachemson (1960) has reported hydrostatic behaviour of the nucleus pulposus, which was not influenced by moderate degeneration (corresponding here to groups 0, 1 and 2) and states that the intradiscal pressures are on average 30 — 50 per cent higher than the applied load per unit area. The level of the disc in the lumbar spine did not influence these results. He has also demonstrated (Nachemson, 1963) that compression of the specimen between angled

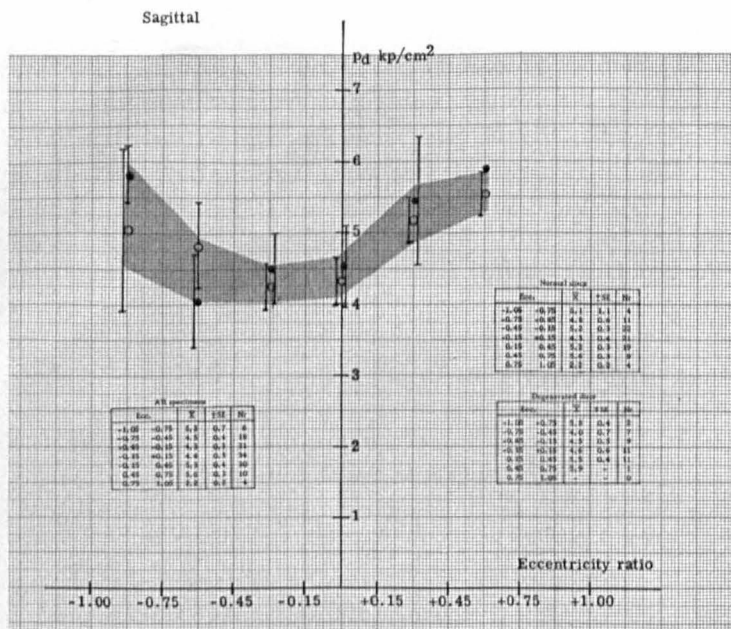


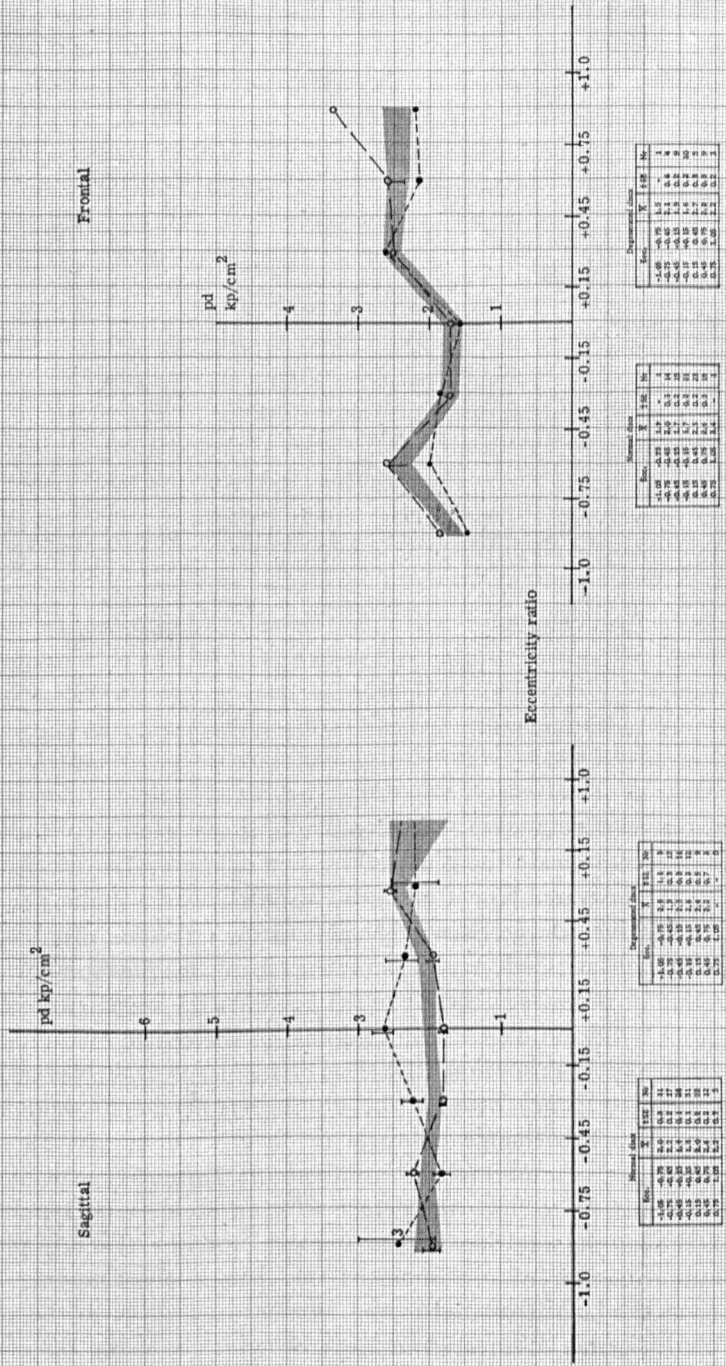
Fig. 54.  
Load interval 3-4 kP/cm<sup>2</sup>  
Intradiscal pressure in intact specimens

1. All specimens
2. ○ = normal discs
3. ● = degenerated discs.

jaws gives a higher intradiscal pressure than does compression between opposed plates. His explanation being that the nucleus tends to become more confined during angling of the disc. The increase was approx. 0.7 kP/cm<sup>2</sup> for a 5° angle. Specimens with the arches removed had no initial intradiscal pressure while those with the ligaments and arches retained had an initial pressure of 0.5 — 1 kP/cm<sup>2</sup> produced by the ligaments and capsules surrounding the posterior bony elements. He also concluded that the posterior bony elements have no weight-bearing capacity for loads up to 220 kp. The relation between intradiscal pressure and external load in the present specimens agrees with that of Nachemson. The pressure increases upon eccentric loading, being relatively lowest in the balanced position. However, a comparison with Figs. 55 a and b, which show the discal pressure at a loading intensity of 1 — 2 kP/cm<sup>2</sup>, shows that the rise in pressure appears to depend, not upon the change in angle but on the increase in moment. A specimen compressed between angled plates is subjected to a moment that increases with the load until the disc is at the same angle as the loading plates; after this the moment is constant, i.e. an increase in load does not further increase the moment.

Fig. 55. Intradiscal pressure in intact specimens with different degrees of degeneration.

- Load interval 1-2 kp/cm<sup>2</sup>
1. All specimens
  2. O = Normal discs (group) (0-1)
  3. ● = Degenerated discs (group) (2-3)



The motion of the segment (the disc's — and the vertebral body's — deformation) can be visualized in terms of a section along one main plane, with the forces acting in this (Figs. 56 and 57). Since the system is statically indeterminate, the distribution of forces in the section must be visualized in model form, with the arrows representing the tension in the annulus fibrosus' anterior and posterior circumference ( $p_1$  and  $p_3$ ), the nucleus on either side of the centre ( $pn_1$  and  $pn_2$ ) and the ligamentum flavum ( $p_6$ ) together with the external load on the disc ( $P$ ) and any additional load ( $P_5$ ). Every external load, centric or eccentric, elicits a thrust and a new position of equilibrium. Thrust is elicited, however, in

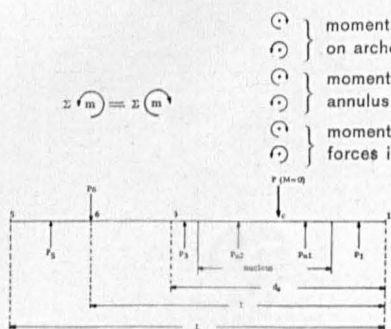


Fig. 56.  
Simplified vector analysis of intact specimen when loaded centrally.

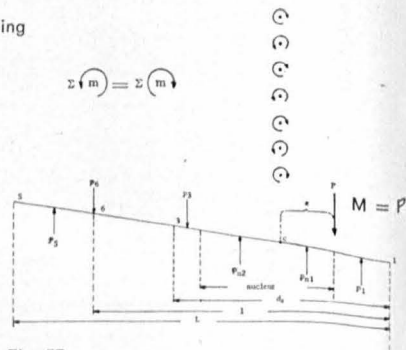
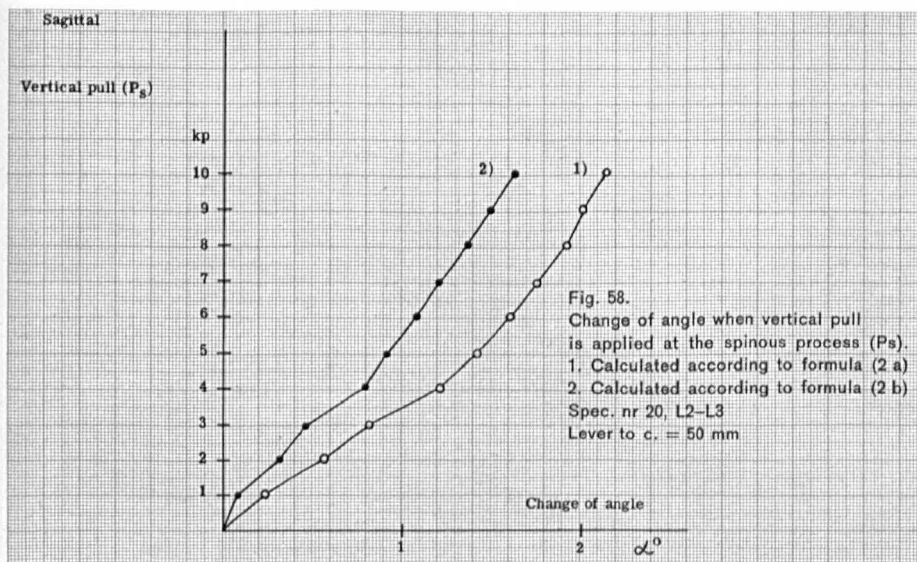


Fig. 57.  
Simplified vector analysis of intact specimen when loaded eccentricly

the vertebrae as well (cf. p. 62) and their geometry and composition further complicate the picture.

Fig. 38 illustrated how a small force applied to the spinous process resulted in a relatively large change in angle in the unloaded disc ( $+1.5^\circ$ ). In the specimen described in Fig. 58 the force in the spinous process was gradually increased from 0 to 10 kp.  $\alpha = 1.5$  was first recorded in this disc at a flexion moment of 45 kpcm in the centre of the disc, compared with 12 kpcm in specimen 17. This difference may, however, be attributed to the discrepancy between the dimensions of these specimens (see Table 4, p. 68). The change of angle ( $\alpha$ ) is plotted in Fig. 58 as calculated according to the normal method (formula 2b, p. 52) as well as according to formula 2a to show the deformation in the vertebral arch.

As shown the rotation in the sagittal (and the frontal) plane is not a linear function of the moment but has a characteristic S-shape, the curve of which is related to the moment as well as to the vertical force. This is further illustrated in Fig. 39, which is made up of such graphs for one specimen with several loads. It will be seen more clearly that the



discs resists extension more than flexion and that this resistance increases with the eccentricity of the load. This must be because the annulus fibrosus is compressed under increasing resistance, so that an increasing moment gives a tendency to the opposite direction of rotation. Since the disc is lower dorsally than ventrally, the moment acting in the direction of rotation increases more rapidly during dorsiflexion. The effect can also be reinforced by the horizontal displacement and by the annulus bulging on the compressed side and being stretched on the other, so that the disc's centre of gravity is displaced in the direction of rotation.

The stabilizing effect of the dorsal elements was studied by applying positive, eccentric loads and cutting the supraspinous and interspinous ligaments, the ligamentum flavum and the joint capsules one by one. Only the ligamentum flavum was found to have any restrictive effect within the range of movement tested. Removal of the intervertebral joints did not lead to any further increase in the range of movement. Nor did the asymmetric intervertebral joints appear to impede movement in either the sagittal or the frontal plane. The combined results for these specimens thus illustrates the effect of cutting the ligamentum flavum (Figs. 59 *a* and *b* and 60 *a* and *b*). The balanced position appears to have been displaced towards the centre. There is a tendency, not significant, to an increased change of angle for both positive and negative eccentricity and to the corresponding change in the ventral height of the disc. In the frontal plane, too, there is the same small tendency for the angle to increase.

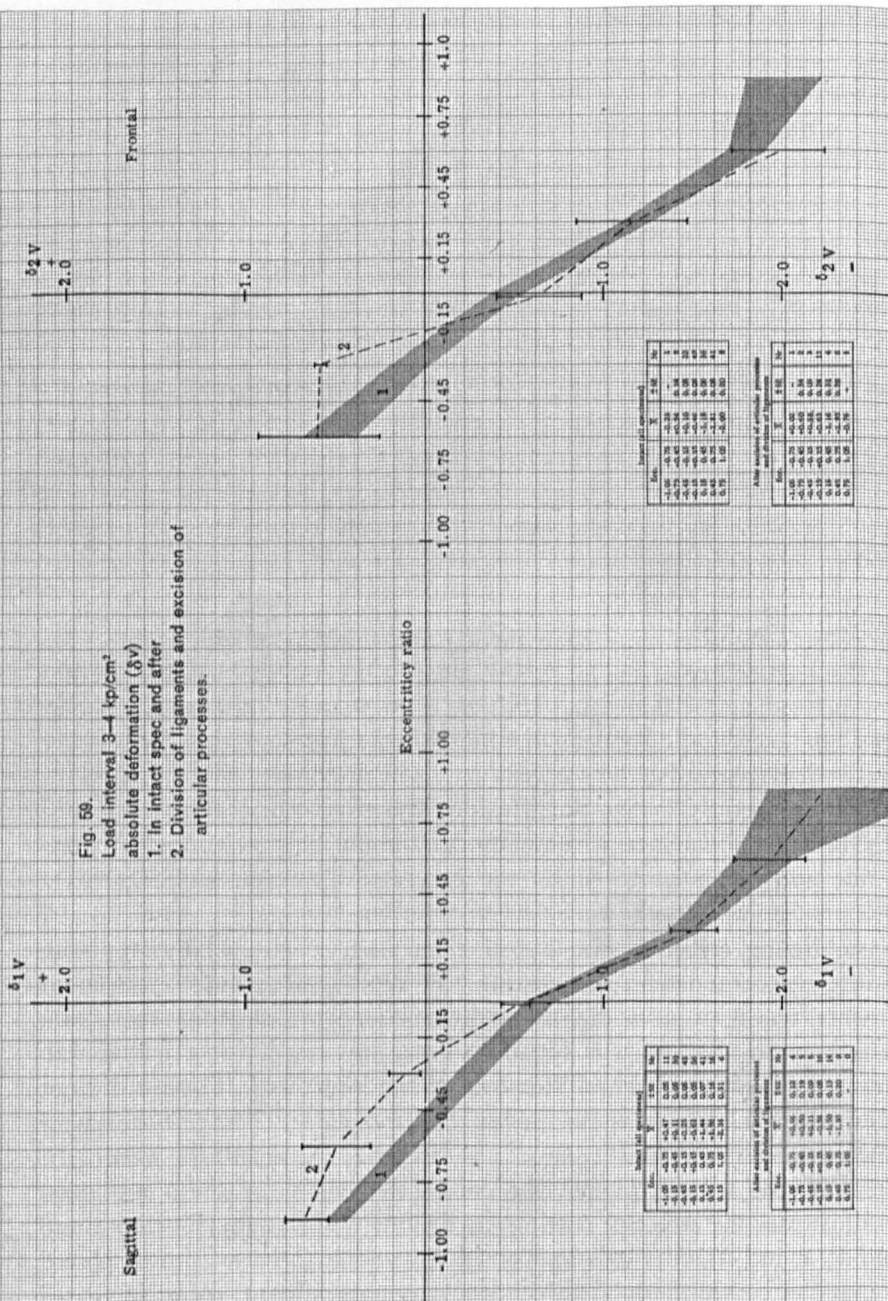
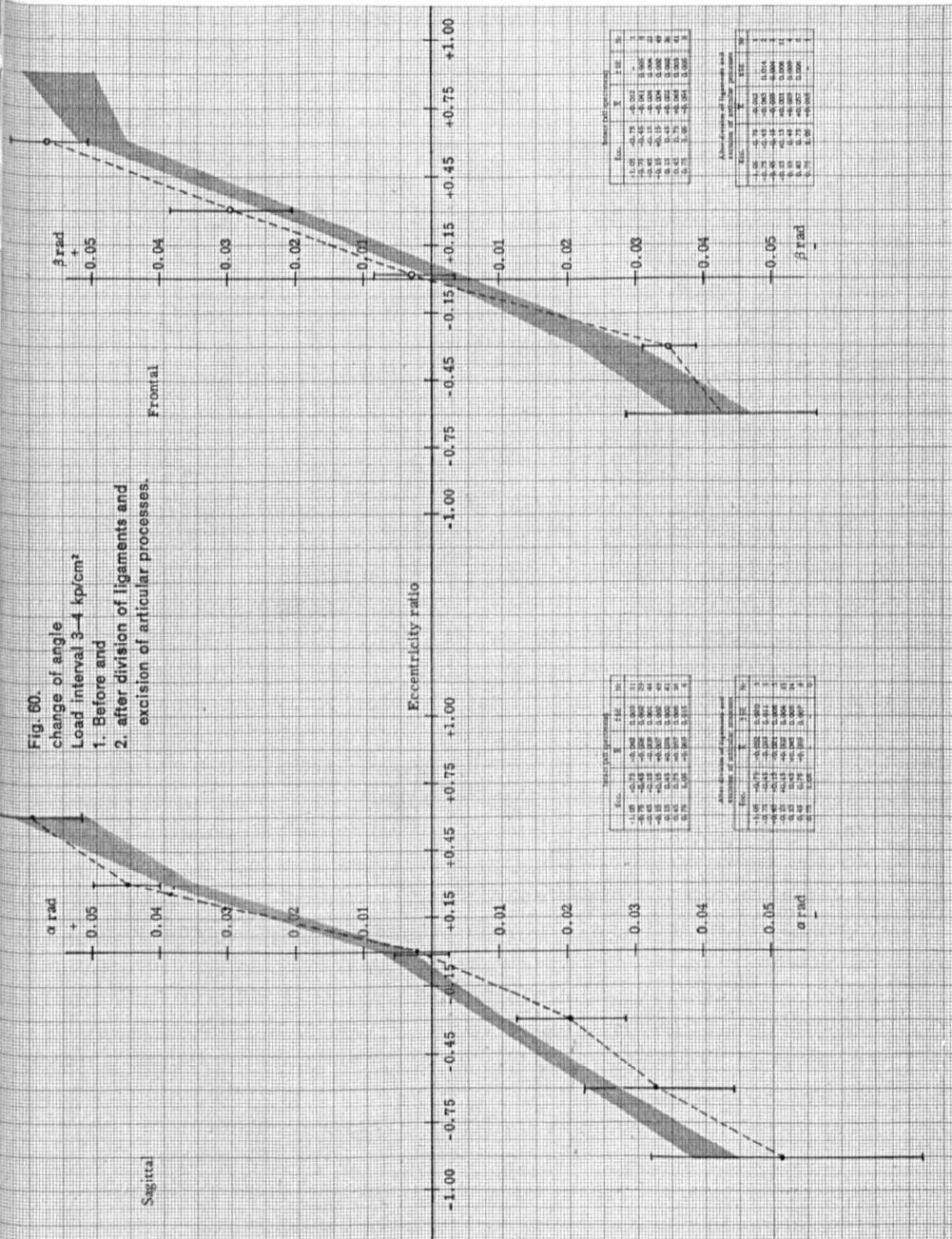


Fig. 60.

change of angle  
Load interval 3-4 kp/cm<sup>2</sup>  
1. Before and  
2. after division of ligaments and  
excision of articular processes.



Mean (rad. increments)

Ecc.	α	β
-1.00	-0.071	-0.070
-0.75	-0.060	-0.060
-0.45	-0.049	-0.049
-0.15	-0.038	-0.038
+0.15	-0.027	-0.027
+0.45	-0.016	-0.016
+0.75	-0.005	-0.005
+1.00	0.006	0.006

After division of ligaments and excision of articular processes

Ecc.	α	β
-1.00	-0.071	-0.070
-0.75	-0.071	-0.070
-0.45	-0.071	-0.070
-0.15	-0.071	-0.070
+0.15	-0.071	-0.070
+0.45	-0.071	-0.070
+0.75	-0.071	-0.070
+1.00	-0.071	-0.070

Inner part (increments)

Ecc.	α	β
-1.00	-0.071	-0.070
-0.75	-0.071	-0.070
-0.45	-0.071	-0.070
-0.15	-0.071	-0.070
+0.15	-0.071	-0.070
+0.45	-0.071	-0.070
+0.75	-0.071	-0.070
+1.00	-0.071	-0.070

Outer part (increments)

Ecc.	α	β
-1.00	-0.071	-0.070
-0.75	-0.071	-0.070
-0.45	-0.071	-0.070
-0.15	-0.071	-0.070
+0.15	-0.071	-0.070
+0.45	-0.071	-0.070
+0.75	-0.071	-0.070
+1.00	-0.071	-0.070

## The effect of fusion

Fusion was simulated with plastic casts as described above (p. 33). A total of 33 lumbar interspaces in 32 specimens were fused. Type 1 fusion (between the spinous processes) was performed on 9 specimens, type 2 (including the intervertebral joints) on 17 and type 3 (including the transverse processes) on 6 specimens. The results are reported along the same lines as for the intact specimens. The effect of fusion on the pattern of motion is of quite a different order than the relatively small differences between specimens with degenerated and normal discs. Consequently, the fused specimens have not been sub-divided according to the degree of disc degeneration. For the sake of comparison, the diagrams below thus include the corresponding curves (shaded areas) for all intact specimens.

### *Posterior fusion in general.*

Figs. 61*a* and *b* show the change of angle in the sagittal and frontal planes for different eccentricity intervals at loads of 3—4 kp/cm<sup>2</sup>. In the sagittal plane, the average change of angle is positive for both negative and positive eccentricity. There is a steady increase in a positive direction from the largest negative eccentricity. When loading over the geometric center of the disc, the change of angle is equally large for fused and intact specimens, but at the largest positive eccentricity the change of angle after fusion is only 20 per cent of that for intact specimens.

Measurements are lacking for the extreme eccentricities during lateral flexion. For central loading, however, there is no spread of the measurements, indicating that this interval of eccentricity falls within the width of the fusion so that loading in this region does not give rise to any rotating moment in the frontal plane. Increased eccentricity results in symmetrically increasing rotation in both a positive and a negative direction.

Figs. 62*a* and *b* and 63*a* and *b* show the relative ( $\epsilon$ ) and absolute ( $\delta_v$ ) deformation at points 1 and 2. As in the case of the change of angle,  $\epsilon_1$  displays only negative values which rise continuously as the load is moved in a ventral direction, i.e. as the moment in relation to the fusion increases. The eccentricity interval +0.75 to +1 has a preponderance of type 3 fusion, hence the misleading curve of the graph. Central loading gives almost the same deformation for both intact and fused specimens.

For lateral flexion and positive eccentricity the deformation at the right-hand measuring point after fusion is approximately half that with intact specimens. With negative eccentricity  $\epsilon_2$  (and  $\delta_2$ ) is positive but the total deformation in a positive direction is only one-third of that for intact

Fig. 61.  
 $\sigma = 3-4 \text{ kp/cm}^2$   
 Change of angle  
 1. before fusion  
 2. after fusion

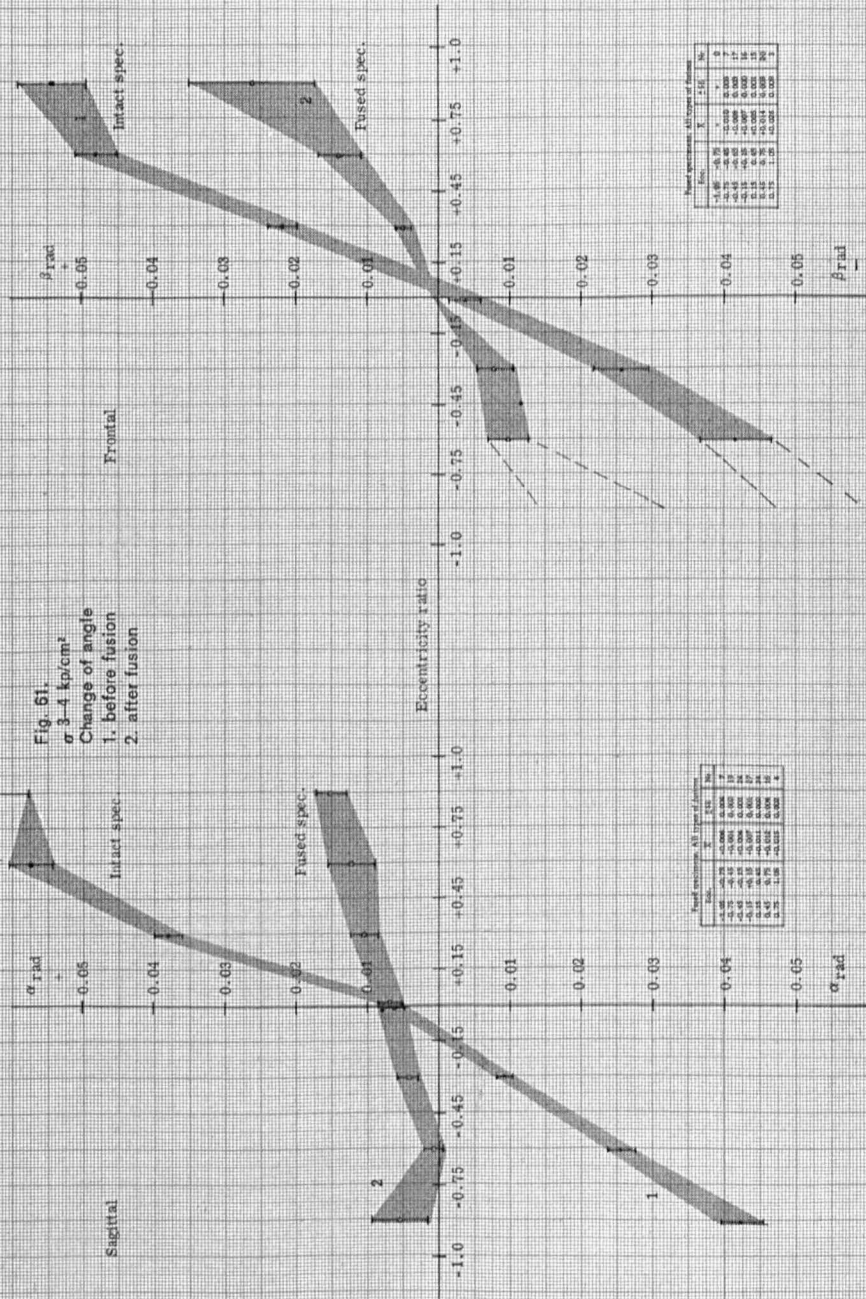
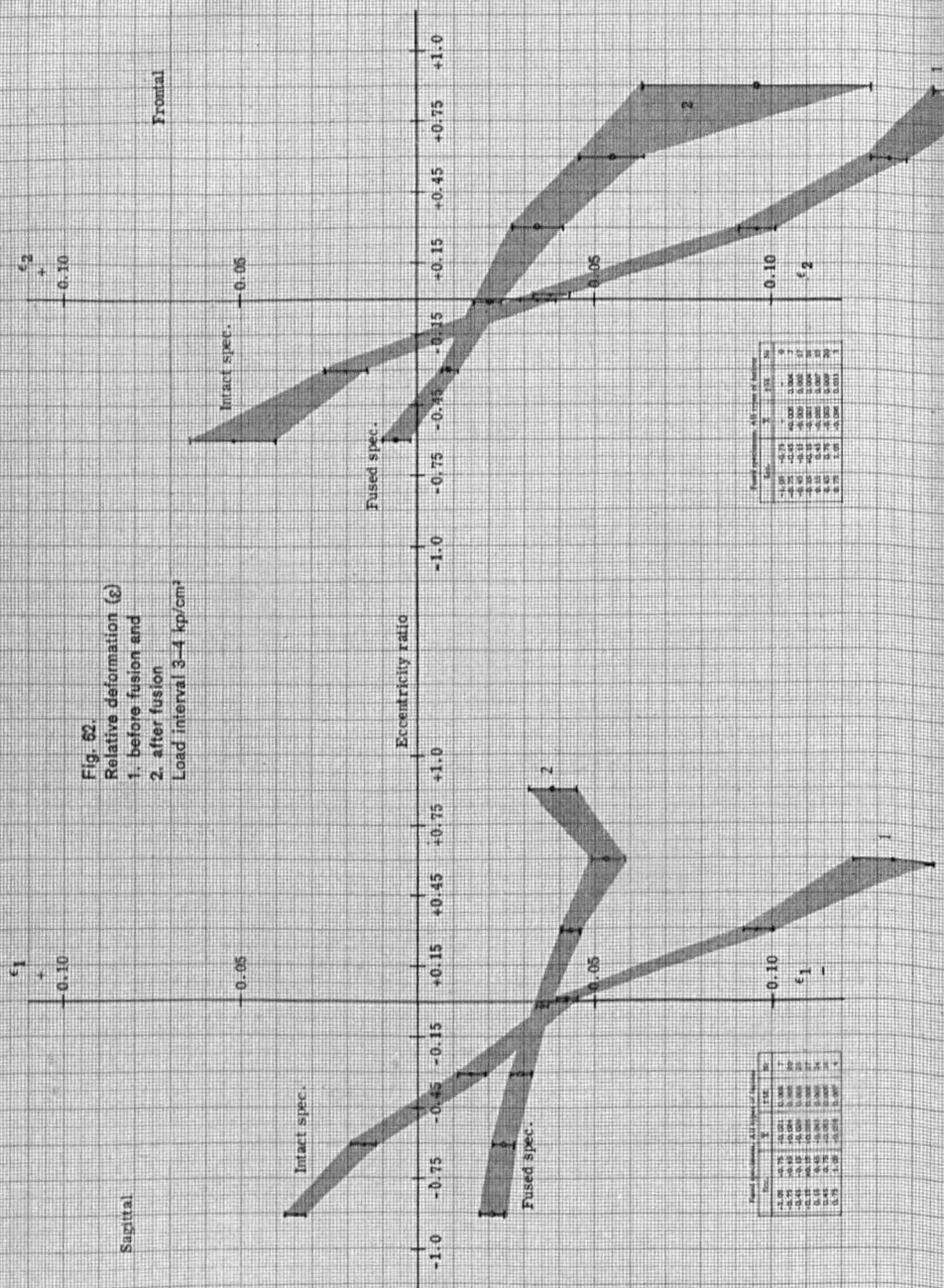


Fig. 52.  
Relative deformation ( $\epsilon$ )  
1. before fusion  
2. after fusion  
Load interval 3-4 kp/cm<sup>2</sup>



Mean Properties All Spec. of Material

Spec.	$\bar{\epsilon}$	15%	50%	85%
1	-0.07	-0.15	-0.02	0.06
2	-0.05	-0.13	-0.01	0.05
3	-0.04	-0.11	-0.00	0.04
4	-0.03	-0.09	0.00	0.03
5	-0.02	-0.07	0.00	0.02
6	-0.01	-0.05	0.00	0.01

Mean Properties All Spec. of Material

Spec.	$\bar{\epsilon}$	15%	50%	85%
1	-0.07	-0.15	-0.02	0.06
2	-0.05	-0.13	-0.01	0.05
3	-0.04	-0.11	-0.00	0.04
4	-0.03	-0.09	0.00	0.03
5	-0.02	-0.07	0.00	0.02
6	-0.01	-0.05	0.00	0.01

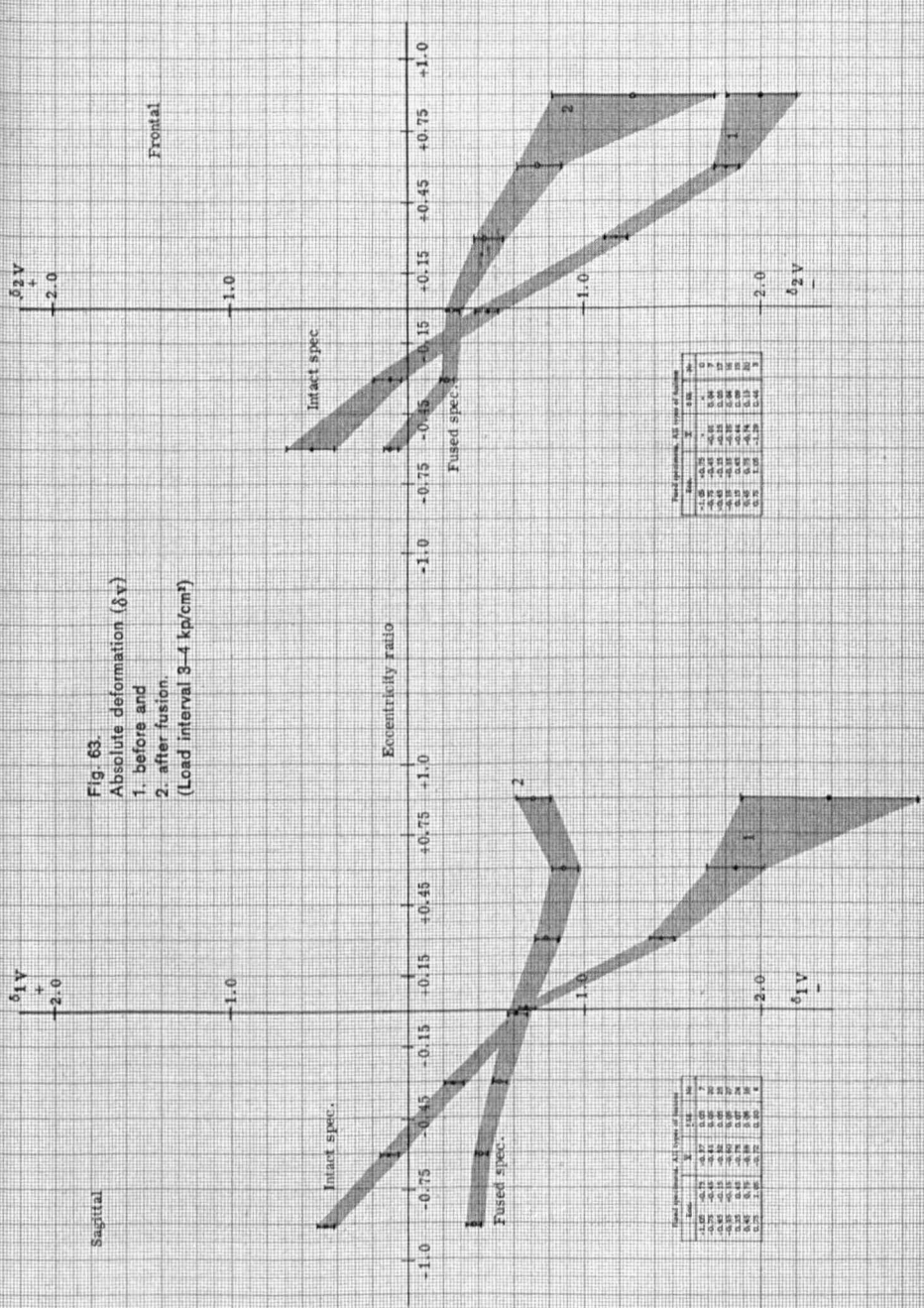


Fig. 63.  
Absolute deformation ( $\delta y$ )  
1. before and  
2. after fusion.  
(Load interval 3-4 kp/cm<sup>2</sup>)

specimens. At central loading the compression after fusion is considerably less than with intact specimens, unlike the finding for loading in the sagittal plane. This is because central loading after fusion always gives a positive value for the angle  $\alpha$ , so that the top-plate of the specimen angles forward against the sagittal, horizontally positioned loading edge. This means that the resultant of the loads in the frontal plane lies somewhat dorsal of the centre, reducing the sagittally rotating moment.

The effect of fusion on the intradiscal pressure is shown in Fig. 64. The pressure is considerably less after fusion with negative eccentricity, i.e. loading near the fusion, and increases gradually as the load is moved ventrally and the moment is thereby increased. For large positive moments the intradiscal pressure may be greater at the same load after fusion than for the corresponding intact specimen. Fig. 65 shows the quotients for the discal pressure after fusion divided by that in the same intact specimens at the same load. Thus, a quotient of 1 indicates that the pressure was the same before and after fusion, while quotients greater than 1 indicate that the fusion led to an increase in intradiscal pressure. On an average, there was a reduction by 50 per cent. In 21 comparable series of intact and fused specimens the intradiscal pressure remained unchanged or increased after fusion.

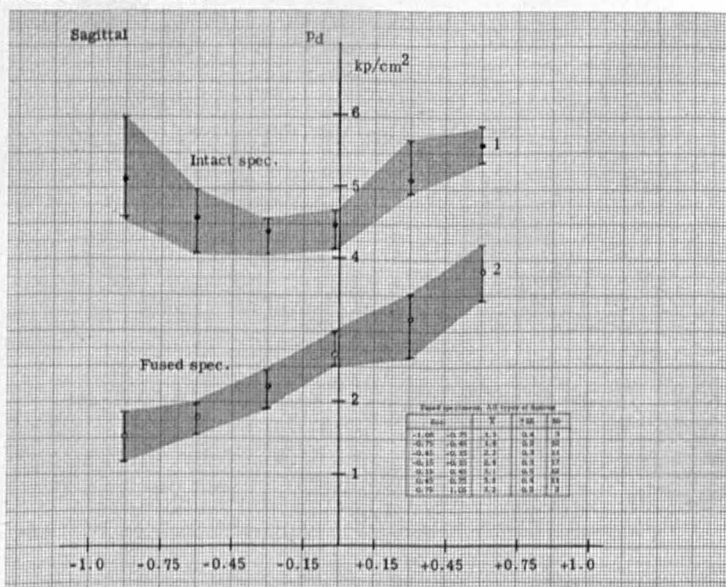
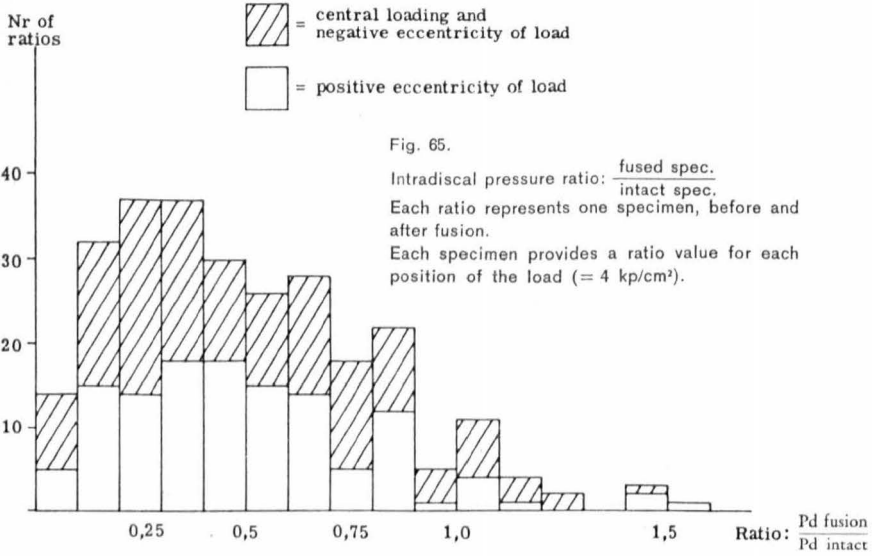


Fig. 64.  
Intradiscal pressure (Pd)  
1. before fusion  
2. after fusion  
Load interval 3-4 kp/cm<sup>2</sup>



*Posterior fusion according to method.*

The individual vertebra in a fused segment may be regarded as a beam clamped at one end (the arch) and with the other end (the vertebral body) resting on several deployed supports. As already mentioned, the system is statically indeterminate and consequently the distribution of forces cannot be calculated. As a working model, however, one can visualize the moment acting in the sagittal section (Fig. 66). The only difference in principle between the three types of experimental fusions is in the distance between the clamp and the support. In other words, a central load on the vertebral body results in the greatest bending moment in type 1

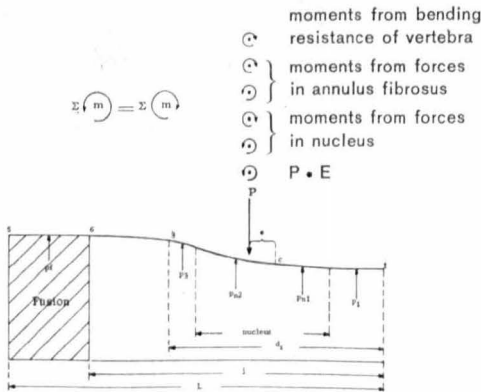


Fig. 66.  
Simplified vector analysis of fused specimen

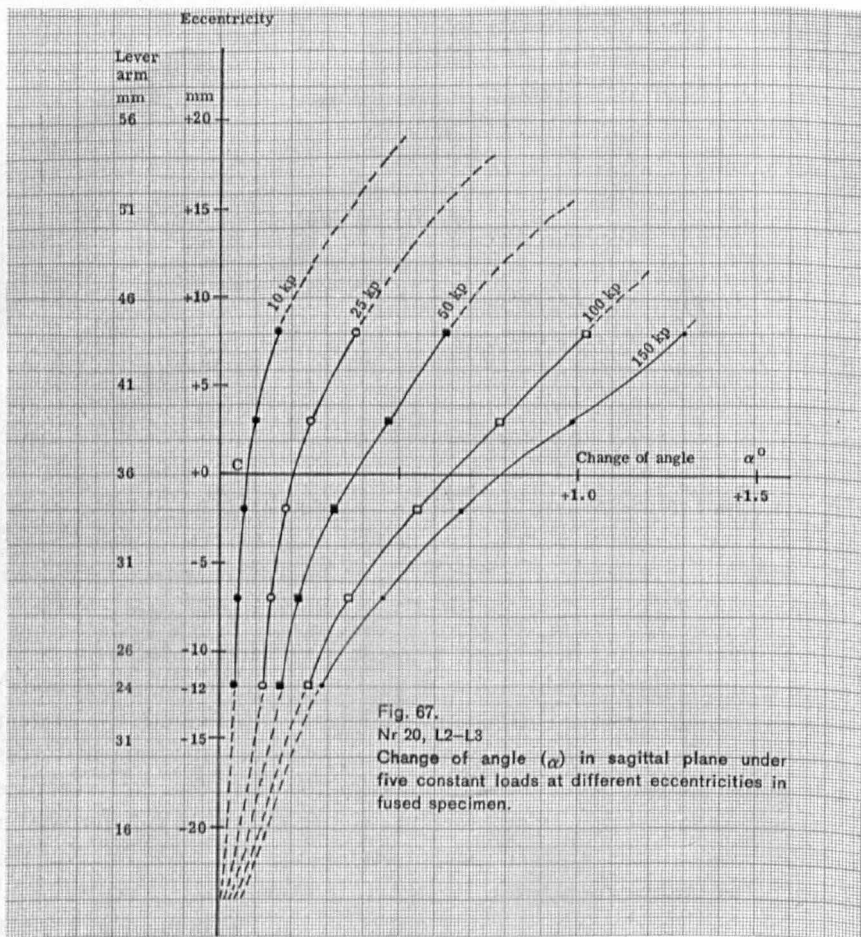


Fig. 67.  
Nr 20, L2-L3  
Change of angle ( $\alpha$ ) in sagittal plane under five constant loads at different eccentricities in fused specimen.

fusions and the least in type 3, type 2 lying somewhere between these two. Since it has been shown (Fig. 32 and 58) that a vertebra is quite deformable, it is clear that the relatively long, unsupported part of the "beam" in type one fusion permits a change of the angle in both a positive and a negative direction. The possibility of negative rotation diminishes the further the extension of the fusion in the ventral direction. The system is visualized in Fig. 66, showing arbitrary resultant forces and moments for the various supporting surfaces. The fixation in the fusion is accounted for by a force upwards (the thrust) and a (negative) clamping moment.

Fig. 67 shows the change of angle in the sagittal plane during constant loads on a fused specimen (type 2) at different eccentricities. Fig. 68 shows the results for loading after excision of the disc. Once the disc has been removed, the vertebra can obviously offer little resistance to bending.

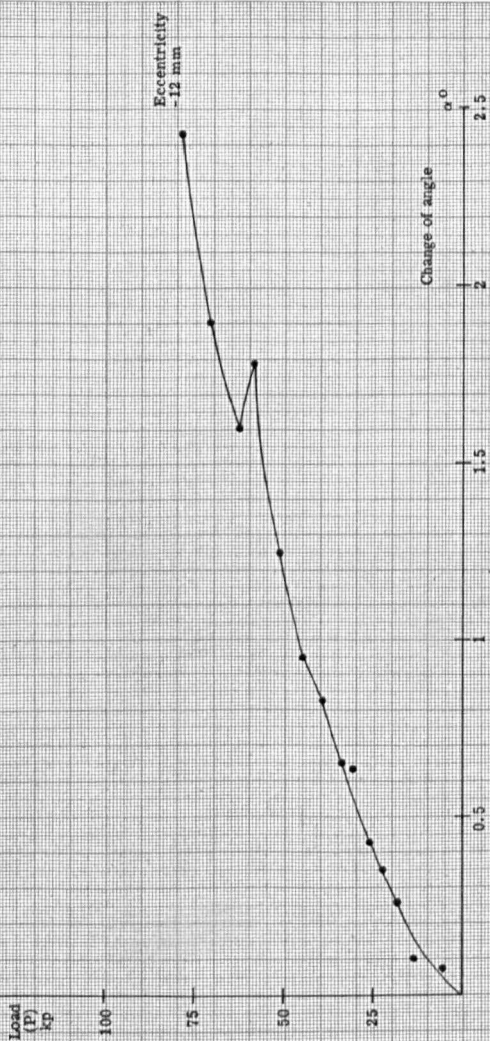


Fig. 68.  
Spec. nr. 20, L2-L3  
Change of angle ( $\alpha$ ) in sagittal plane of fused  
specimen (type 2) with the disc excised.  
Increasing load at constant eccentricity (-12  
mm).

The stability of a segment after fusion is thus still highly dependent upon the load-carrying capacity of the disc. Compared to the intact specimen (Fig. 39), the resistance to bending with negative eccentricity is extremely large at all loads, but diminishes gradually as the load is shifted ventrally. Within the range of loads applied, the regression is steeper throughout after fusion than for intact specimens. On the other hand, the change of angle with increasing load tends to diminish for intact specimens, but to accelerate after fusion. Thus, the intact specimen is characterised by the disc's increased rigidity with increasing loads while the fused specimen is characterised by the elastic change in the bone.

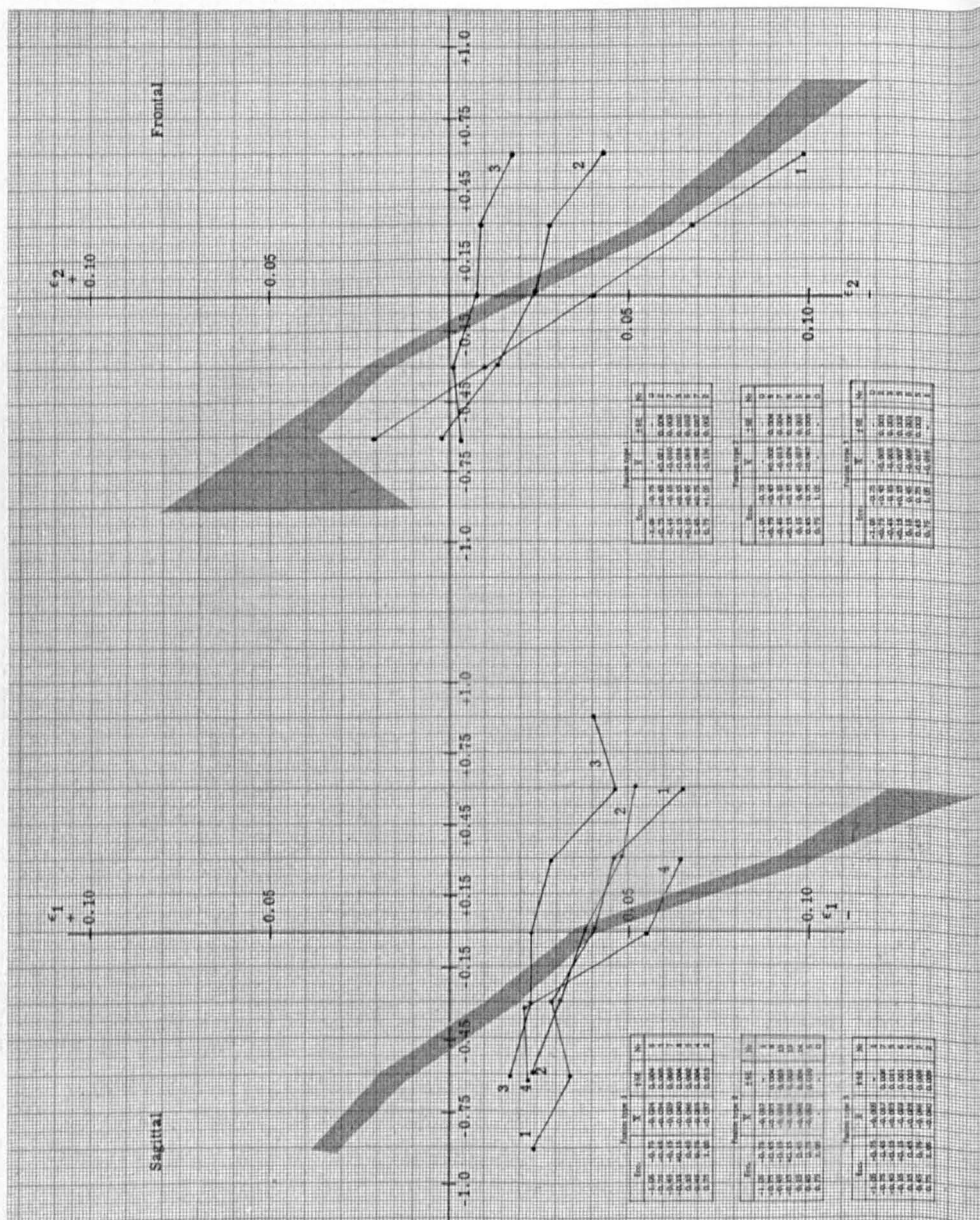


Fig. 69.  
Relative deformation ( $\epsilon$ )  
1. Fusion type 1  
2. " " 2  
3. " " 3  
4. Screws through intervertebral joints.  
Load interval 3-4 kp/cm<sup>2</sup>



This brings us to a consideration of the effect of different types of fusion. Figs. 69 and 70 show the relative displacement at point 1 and the change of angle in the sagittal plane. Type 1 fusion results in a considerable depression of the disc's ventral circumference for positive as well as negative eccentricity, but the deflexion accelerates towards the extremes. Accordingly, the angle changes only a little during loading around the central position and it is only at the extreme eccentricities the tendency to rotation increases rapidly in both a negative and a positive direction. Type 3 fusion displays a considerably greater stability with respect to both vertical displacement and change of angle, while positive rotation occurs even at maximum negative eccentricity. As already mentioned, type 2 fusion represents an intermediate condition.

For loading in the frontal plane, the compression with centric loading is considerably greater after type 1 fusion than in intact specimens, while during eccentric loading the depression and elevation of point 2 is almost as large as in intact specimens and the angle change is only slightly smaller.

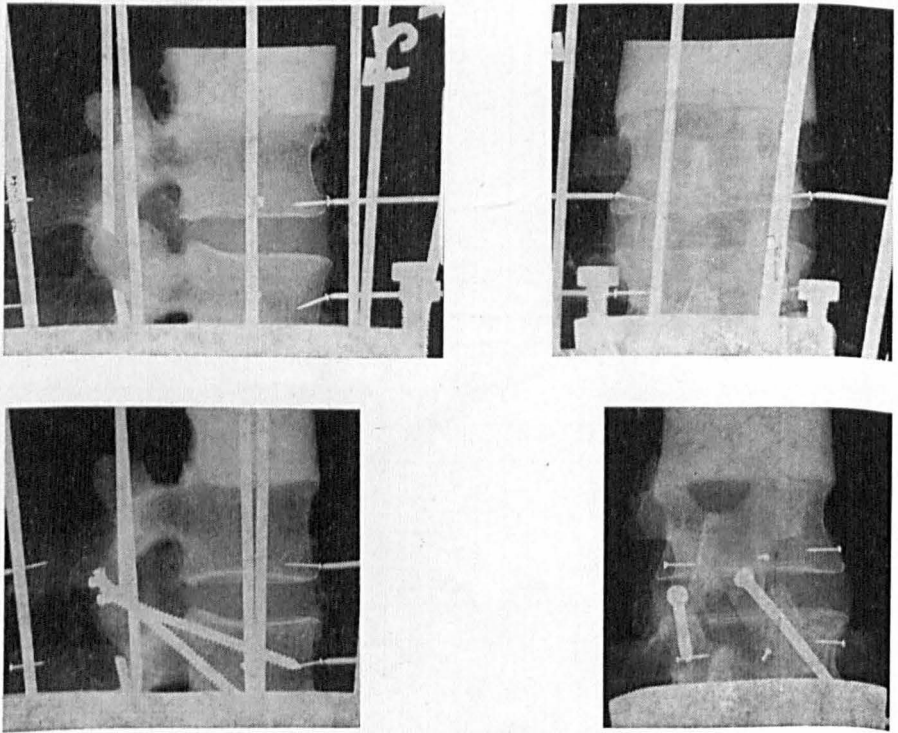
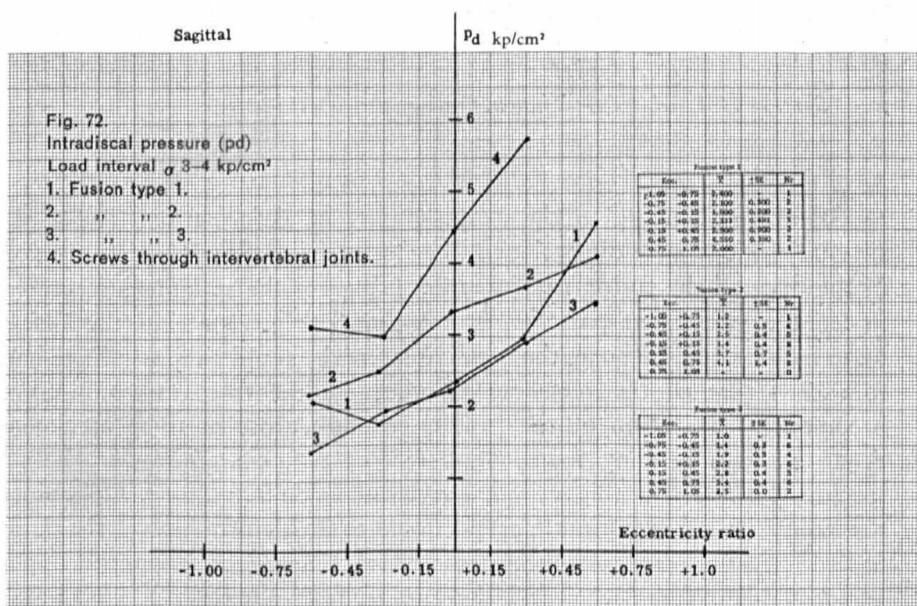


Fig. 71 (a—d).  
Roentgenograms of spec. nr 16 L2—L3 fixed in the loading apparatus, (a, b) intact specimen, (c, d) specimen with long screws through the intervertebral joints.

Type 3 fusion, on the other hand, shows very slight negative deformations for positive eccentricities — still negative at maximum negative eccentricity. The change in angle gives a symmetrical curve but the changes are small both positively and negatively.

In 8 specimens (including one comprising several segments) the intervertebral joints were fixed with screws instead of a plastic cast (Fig. 71). Technically, this results in an upward thrust but no (or a very small) clamping moment. The screws exert a certain stabilizing effect at negative eccentricities but at positive eccentricities the results rapidly approximate to those for the intact specimen. There is a considerable spread because the introduction of the screws resulted in a positive rotation that varied between the specimens; in other words, this spread does not indicate any major difference in behaviour.

The intradiscal pressure for different types of fusion and for specimens fixed with screws through the intervertebral joints is shown in Fig. 72. There is a tendency for the pressure to increase from negative to positive eccentricity. The curve for type 1 fusion is low initially because this relatively unstable fixation gives the disc a greater chance of balancing the forces produced. Both here and with screws through the intervertebral joints, however, the intradiscal pressure increases rapidly at maximum positive eccentricity and reaches or exceeds the level for the intact specimens.



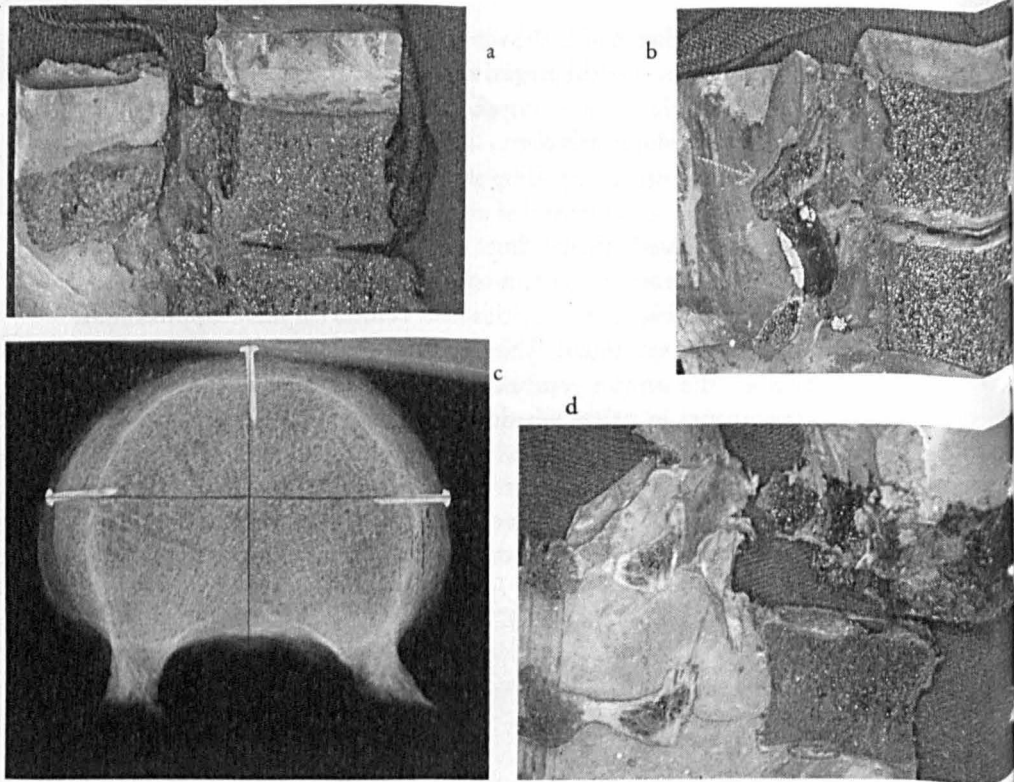


Fig. 73.

*Different types of fractures produced by loading fused specimens after excision of the discs. (a) Spec. nr 23 L<sub>2</sub>—L<sub>3</sub>. Type 1 fusion. Fracture through the base of the spinous process. (b) Spec. nr 30 L<sub>4</sub>—L<sub>5</sub>. Type 2 fusion. Fracture through the laminae and articular processes.*

*(c, d) Spec. nr 14. L<sub>2</sub>—L<sub>3</sub> Type 3 fusion. Fracture through the pedicles.*

#### *Fused specimens with excised disc.*

As discussed above, vertebrae in a fusion display very slight resistance to downward bending in the actual region of deformation. The experimental fusions were dimensioned to prevent any measurable deformation in the mass of the fusion itself and consequently the specimens fractured in front of the fused parts — at the clamp (Fig. 73). Had the fusion material consisted of bone, the bending strength would similarly have had to exceed that of the vertebrae as otherwise the fracture would have occurred in the region of the fusion. Fracture arose in these specimens at an average bending moment of  $185 \pm 18$  kpcm. Data for the 28 specimens included in this series are given in Table 8 and 9 (p. 113). Since the stress in fused specimens is proportional to the deformation at the point of loading, the stress is multiplied several times over when the upper vertebra in the fused segment lacks support from the disc.

Table 8.

Data aquired at point of fracture of fused specimens with excised discs.

Specimen identification nr #	Disc level	Fusion type	Leverarm mm	P max kp	$\sigma$ kp/cm <sup>2</sup>	$-\delta_{1V}$ mm	$\frac{\delta_{2V} + \delta_{4V}}{2}$ mm	$-\delta_{3V}$ mm	Eccentricity, measured to center of interspace mm	Bending moment at fracture kpcm
2	3	2	18.0	20	2.8	4.3	3.4	3.0	— 9	36
4	2	1	45.3	20	1.1	4.0	2.7	1.4	— 3	91
5	1	1	43.5	10	0.5	6.0	4.9	2.9	— 3	44
6	4	1	39.5	80	3.4	5.0	4.0	3.7	— 5	316
7	2	2	32.5	77	5.0	5.3	2.8	1.9	— 3	250
7	4	2	28.0	56	3.1	2.5	2.4	2.3	— 4	157
13	1	3	22.0	94	8.2	4.0	3.6	3.3	$\pm$ 0	207
14	2	3	26.5	118	6.0	3.7	2.7	1.8	$\pm$ 1	313
14	4	3	25.5	145	7.6	5.2	3.0	0.8	$\pm$ 0	370
15	1	3	28.0	59	3.8	5.2	3.2	1.7	— 3	165
15	3	3	28.8	104	5.8	2.4	1.3	0.3	$\pm$ 0	247
16	2	2	31.5	73	3.9	2.8	2.0	1.3	— 5	230
16	4	2	26.0	65	3.1	4.0	2.9	1.8	— 5	169
19	5	2	10.8	98	4.0	3.1	2.7	2.3	—22	105
20	2	2	23.8	78	4.2	3.5	2.6	1.8	—12	185
21	3	2	16.0	91	4.5	4.8	2.4	1.6	—14	146
22	2	2	30.8	35	1.8	2.0	1.7	1.3	— 6	108
22	4	1	37.0	20	0.9	2.8	2.1	1.5	— 8	74
23	2	1	35.3	42	2.4	4.8	3.2	1.6	— 5	148
25	4	1	21.4	45	2.5	6.0	4.8	3.0	—21	96
26	2	2	22.3	87	3.8	3.8	2.3	1.2	— 8	194
26	4	2	23.5	146	5.6	6.0	4.7	3.4	— 5	343
27	2	3	29.0	73	3.3	3.9	3.1	2.0	$\pm$ 0	212
27	4	2	36.8	37	1.6	5.5	3.3	1.1	$\pm$ 0	136
29	4	2	26.3	120	7.9	2.5	1.3	0.9	— 6	315
29	3	2	26.3	108	6.4	4.6	2.8	1.5	$\pm$ 4	284
30	4	2	30.0	69	3.8	5.1	5.1	5.1	$\pm$ 1	207
32	3	2	25.0	12	1.2	5.5	4.4	3.6	— 3	30
				$\bar{x}$ 3.6	$\bar{x}$ 4	$\bar{x}$ 3	$\bar{x}$ 2			$\bar{x}$ 185

Table 9.

Bending moment at fracture ( $\bar{x}$ ).

Fusion type	Nr of specimens tested	$\bar{x}$ kpcm	$\pm$ SE
1	6	128.2	36.6
2	16	180.9	21.8
3	6	252.3	28.3
1+2+3	28	184.9	17.7



L3, L4 and L5 with the two intermediate discs. The specimen was arranged and fastened in the loading apparatus in the usual way. It was loaded first as an intact specimen with the vertical load applied centrally and with positive and negative eccentricities. A plastic cast was then applied

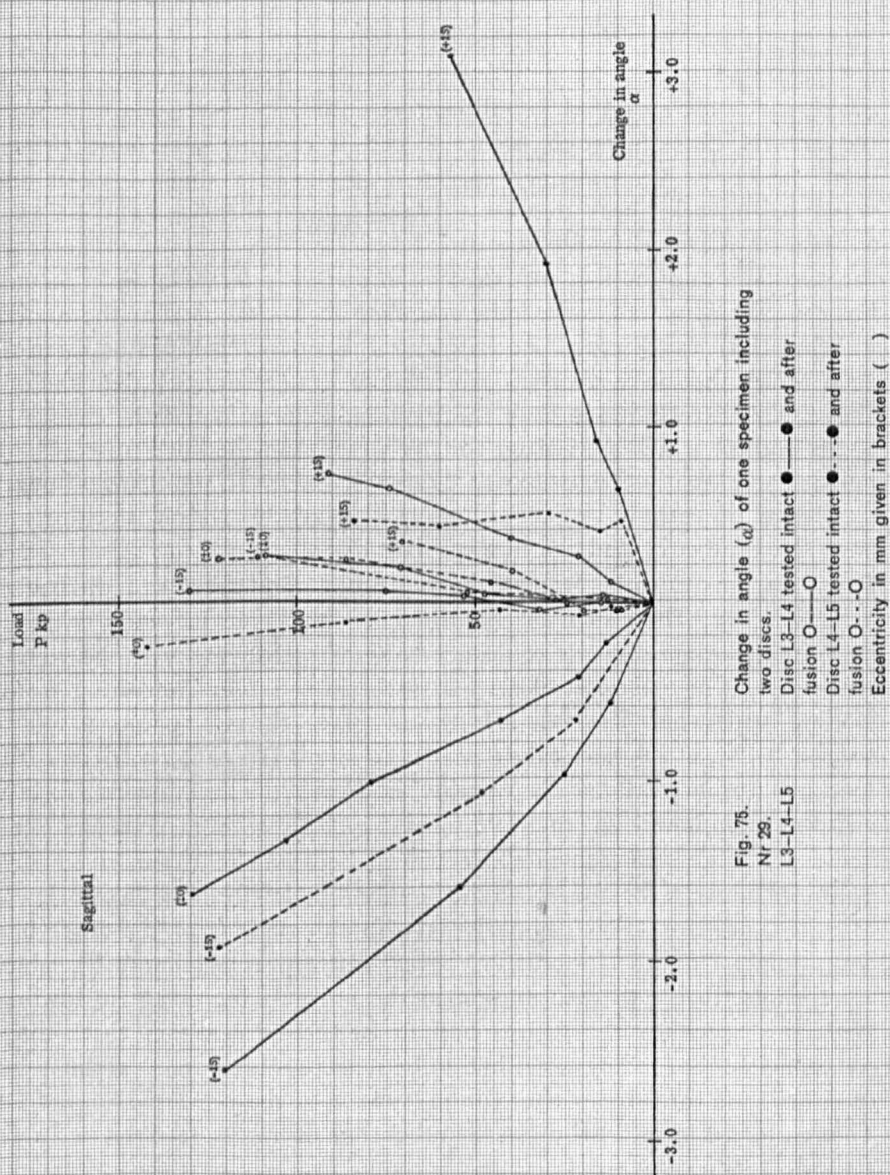


Fig. 76. Change in angle ( $\alpha$ ) of one specimen including two discs.

Nr 29.

L3-L4-L5

- Disc L3-L4 tested intact (●) and after fusion (○) ———
- Disc L4-L5 tested intact (●) and after fusion (○) - - -
- Eccentricity in mm given in brackets ( )

which fused the spinous processes, laminae and intervertebral joints of the three vertebrae in a single block. The loading series was then repeated as for the intact specimen. As a limited number of pressure and motion gauges were available, consequently the measurements were made first on the lower disc and then repeated with the gauges applied to the upper disc.

The results for intradiscal pressure in each disc before and after fusion are presented in Fig. 74 and for the change in angle in Fig. 75. The eccentricity was measured in millimeters positively and negatively from the frontal plane through points 2 and 4 on the lowermost (fused) vertebral body. The unloaded specimen displayed a slight lordosis and was fused in such a way that central loading over the disc L4 — L5 gave a negative eccentricity for the disc L3 — L4. The changes of angle in the two discs and the fact that the two uppermost vertebrae could become horizontally displaced caused the specimen to buckle so that the middle vertebra (L4) was displaced horizontally against the direction of rotation. As a result, the lower disc was subjected to less eccentricity than the one above. This is reflected in both the intradiscal pressure and the change of angle, both of which are greater for the upper than the lower disc at both positive and negative eccentricities. Otherwise, however, the changes in each interspace are entirely in line with those observed in specimens comprising two vertebrae only and the intermediate disc.

*Specimen no. 32* came from a five-year old child who had died after a skull injury. The specimen comprised the vertebrae L2 — L5 with the three intermediate discs. It could not be fixed satisfactorily to the sacrum alone so half of the body of L5 had to be included in the casting to the loading apparatus. The vertical frontal plane through points 2 and 4 on the body of L4 was taken as the zero plane for eccentricity. The specimen was so small and the vertebral bodies so low that only one serie of makers was placed in each vertebra. No direct measurements were made of the deformation in the vertebral bodies. The angles given were measured between the makers on the vertebral body (formula 2b). It should be noted, however, that comparisons with calculations of the angle between points 1 and 5 (formula 2a) reveal differences of almost  $1^\circ$ , which are thus ascribable to deformation in the bone during eccentric loading. With this specimen the gauges had to be moved between three discs; consequently the loading series had to be repeated three times on the intact specimen, and three times after fusion (type 2) of the vertebrae L3 and L4. The results for intradiscal pressure and change of angle are given in Tables 10 and 11. With this specimen, too, it should be noted that the eccentricity is not identical for all three discs during each loading series. Counter-

Table 10.

*Intradiscal pressure pd kp/cm<sup>2</sup> in a specimen including three discs; tested intact (figures in brackets) and after fusion of the intermediate segment.*

Load kp/ cm <sup>2</sup>	Disc- level	Eccentricity (mm) of the load						Mean
		-12	-8	-4	0	+2	+4	
1	L2—L3	(1.3)	(1.7)	(1.8)	(1.5)	(1.3)	(—)	(1.5)
		1.8	2.2	1.6	1.9	1.9	1.8	1.9
		(1.8)	(2.1)	(1.8)	(2.0)	(1.8)	(2.1)	(1.9)
L3—L4	1.3	1.3	1.4	1.1	1.2	1.3	1.3	
	(1.4)	(1.4)	(1.5)	(1.6)	(1.2)	(1.4)	(1.4)	
	1.4	1.5	1.5	1.5	1.5	1.7	1.5	
2	L2—L3	(2.9)	(3.6)	(3.7)	(3.1)	(2.9)	(—)	(3.3)
		3.6	4.2	3.1	3.8	3.7	2.7	3.5
		(3.8)	(4.1)	(3.7)	(3.9)	(3.7)	(3.9)	(3.9)
L3—L4	2.6	2.6	2.8	2.6	2.7	2.8	2.7	
	(2.8)	(2.9)	(3.0)	(2.9)	(2.7)	(2.9)	(2.9)	
	2.8	3.0	3.0	3.1	3.1	3.1	3.0	
3	L2—L3	(4.6)	(4.9)	(5.3)	(4.6)	(4.6)	(—)	(4.8)
		5.2	5.9	4.6	5.6	5.3	4.1	5.1
		(5.9)	(6.2)	(5.6)	(5.4)	(5.5)	(5.5)	(5.7)
L3—L4	4.0	3.8	4.2	4.2	4.5	4.3	4.2	
	(4.1)	(4.3)	(4.2)	(4.3)	(4.1)	(4.2)	(4.2)	
	4.2	4.5	4.5	4.6	4.7	4.5	4.5	
4	L2—L3	(6.3)	(6.2)	(6.7)	(6.2)	(6.1)	(—)	(6.3)
		6.6	7.5	6.0	7.2	7.0	6.9	6.9
		(7.7)	(7.7)	(7.1)	(6.3)	(7.0)	(6.9)	(7.1)
L3—L4	5.4	5.1	5.5	5.7	6.4	6.0	5.7	
	(5.4)	(5.6)	(5.5)	(5.6)	(5.4)	(—)	(5.5)	
	5.5	5.8	5.9	6.1	6.1	5.7	5.9	
5	L2—L3	(7.6)	(7.5)	(7.5)	(7.2)	(7.3)	(—)	(7.4)
		7.8	8.9	7.0	7.9	8.5	—	8.1
		(8.6)	(8.9)	(8.3)	(7.2)	(8.1)	(—)	(8.6)
L3—L4	6.7	6.7	7.0	7.2	7.7	—	7.1	
	(6.6)	(6.8)	(6.9)	(6.9)	(6.9)	(—)	(6.8)	
	6.9	7.1	7.3	7.4	7.3	—	7.2	
Mean	L2—L3	(4.5)	(4.8)	(5.0)	(4.5)	(4.4)	(—)	(4.7)
		5.0	5.7	4.5	5.3	5.3	3.9	5.1
		(5.6)	(5.8)	(5.3)	(5.0)	(5.2)	(4.6)	(5.4)
L3—L4	4.0	3.9	4.2	4.2	4.5	3.8	4.2	
	(4.1)	(4.2)	(4.2)	(4.3)	(4.1)	(2.8)	(4.2)	
	4.2	4.4	4.4	4.5	4.5	3.8	4.4	

Table 11.

Nr 32  
 L2—L3—L4—L5  
 Fusion Type 2  
 Sagittal

*Change of angle ( $\alpha^\circ$ ) in a specimen including three discs, tested intact (figures in brackets) and after fusion of the intermediate segment.*

Load kp/ cm <sup>2</sup>	Disc- level	Eccentricity (mm) of the load				
		—12	—8	—4	±0	+2
1	L2—L3	(—0.66)	(—0.50)	(—0.07)	(+0.45)	(+0.87)
		—0.72	—1.04	—0.84	—1.75	—2.40
	L3—L4	(—0.31)	(—1.45)	(—1.48)	(—1.60)	(—1.19)
		—0.17	—0.02	—0.05	+0.05	+0.02
L4—L5	(—0.71)	(—0.56)	(—1.18)	(—0.17)	(—0.10)	
	—0.19	—0.10	—0.13	—0.19	—0.20	
2	L2—L3	(—1.16)	(—0.98)	(—0.17)	(+0.89)	(+1.16)
		—1.43	—1.87	—1.68	—3.38	—3.40
	L3—L4	(—0.91)	(—2.52)	(—2.31)	(—2.21)	(—2.00)
		—0.27	—0.05	—0.05	+0.06	+0.07
L4—L5	(—1.43)	(—1.11)	(—1.64)	(—0.39)	(—0.13)	
	—0.39	—0.18	—0.23	—0.30	—0.40	
3	L2—L3	(—1.52)	(—1.20)	(—0.33)	(+1.28)	(+1.66)
		—2.04	—2.24	—2.25	—3.46	—3.26
	L3—L4	(—1.76)	(—2.89)	(—2.62)	(—2.35)	(—2.13)
		—0.28	—0.08	—0.06	+0.07	+0.14
L4—L5	(—1.59)	(—1.24)	(—1.59)	(—0.70)	(—0.37)	
	—0.62	—0.26	—0.28	—0.41	—0.57	
4	L2—L3	(—1.88)	(—1.42)	(—0.45)	(+1.68)	(+2.51)
		—2.52	—2.61	—2.51	—3.52	—2.82
	L3—L4	(—2.47)	(—3.21)	(—2.94)	(—2.59)	(—2.26)
		—0.29	—0.12	—0.08	+0.11	+0.14
L4—L5	(—0.71)	(—1.27)	(—1.62)	(—1.09)	(—0.67)	
	—0.85	—0.41	—0.29	—0.50	—0.67	
5	L2—L3	(—2.25)	(—1.64)	(—0.49)	(+2.10)	(+3.18)
		—2.80	—2.85	—2.97	—3.41	—2.37
	L3—L4	(—2.86)	(—3.49)	(—3.24)	(—2.73)	(—2.38)
		—0.36	—0.14	—0.14	+0.15	+0.23
L4—L5	(—1.83)	(—1.40)	(—1.66)	(—1.51)	(—1.22)	
	—1.00	—0.56	(—0.29)	—0.54	—0.79	

balancing in the discs by means of horizontal displacement is still more noticeable than in the previous specimen owing to the larger number of motion segments. The initial position of the specimen ("own shape" Fick, 1904) is shown in Fig. 76. The automatic balancing in the specimen is illustrated schematically for the intact specimen (Fig. 77 *a*) and after fusion (Fig. 77 *b*). It will be seen that although changes of angle do occur positively and negatively after fusion of the interspace L3—L4, they are very small. At zero and + 2 mm eccentricities the disc L3—L4 rotated in a negative direction before fusion but in a positive afterwards. This change of angle was accompanied in the disc above, by a relatively large positive change of angle, in the intact specimen, to a relatively large negative change after fusion of the middle segment. The lowermost disc displayed negative rotation throughout, but this was considerably smaller after fusion of the middle segment. Fusion thus resulted in a quite different balancing of the complete specimen owing to the fact that the scope for horizontal displacement was largely eliminated in the fused segment.

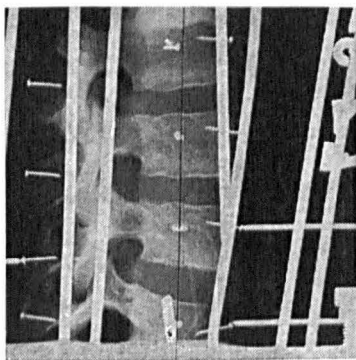


Fig. 76. *Lateral X-ray view of spec. nr 32 L2—L5 (c.f. Fig. 77).*

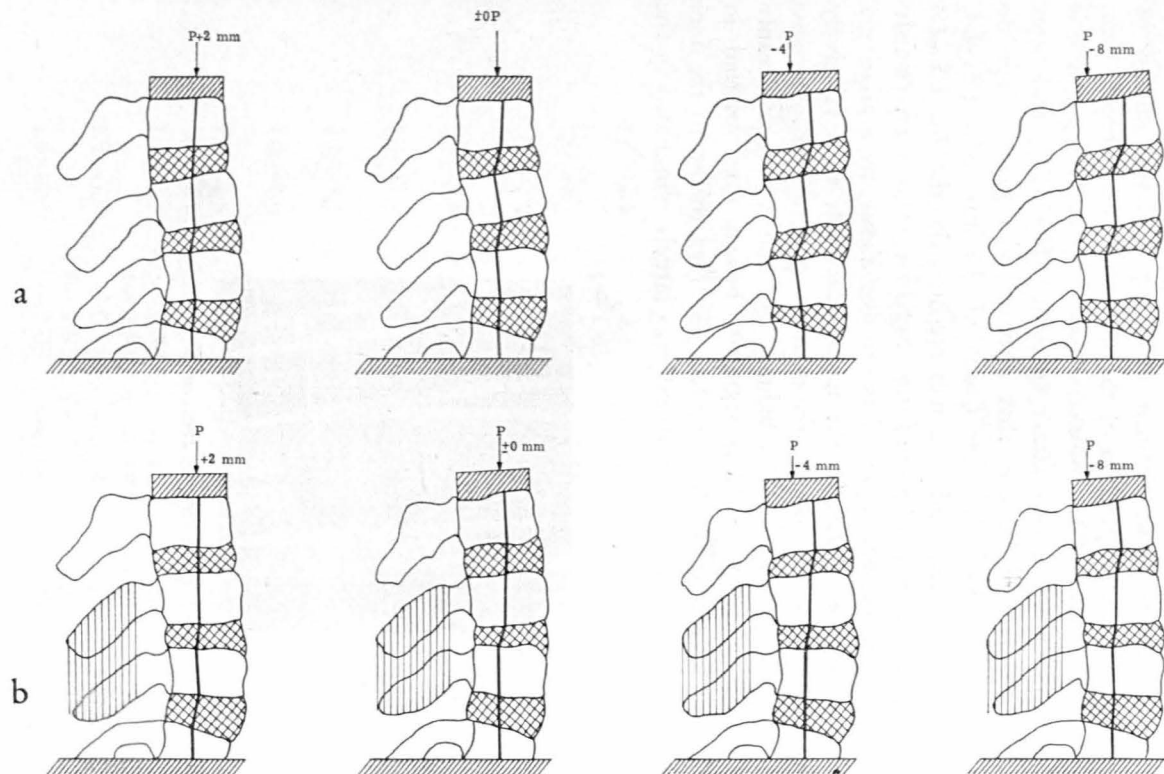


Fig. 77.

Scheme of horizontal shift (buckling) in a specimen (Nr 32) including three discs at various application of a constant load ( $5 \text{ kp/cm}^2$ ) tested (a) intact and with the intermediate disc fused (b).

## V Summary and conclusions

Low back pain has frequently been interpreted as a mechanical disturbance based on structural changes in one or several intervertebral discs. The selection of suitable cases for fusion on the basis of this assumption has failed, however, to give uniform results. In mechanical terms, the aim of fusion is to prevent motion and to relieve the load on the intervertebral disc. To achieve this, various surgical procedures have been developed, approaching different parts of the vertebrae.

In order to elucidate the mechanical efficiency of different types of posterior lumbar fusion, experiments were made in the present study on autopsy specimens. A method was developed for fusing the posterior elements of two vertebrae with plastics in such a way as to preclude both slipping at the junction between bone and plastics and any appreciable deformation in the plastic cast itself. Precautions were taken to avoid desiccation during the experiments as well as an excessive temperature during hardening of the cast. Three types of fusion were simulated. Type 1, involving only the spinous process, corresponds to Albee's graft. Type 2 includes the laminae and intervertebral joints (a combination of Albee's and Hibbs' fusion) while type 3 includes the transverse processes as well. Using a compression apparatus, the specimen was subjected to vertical loads corresponding to those incurred in the upright body posture and in bending forwards, backwards and to the sides. The load was applied in such a way that its position in relation to the centre of the disc could be measured and varied. The lower vertebral body was firmly fixed in the loading apparatus, while the upper part of the specimen was free to move horizontally and vertically in the plane being studied and thereby adjust its position to the load applied. Deformations and displacements, both vertical and horizontal, in the disc and vertebral body were measured with extensometers applied between markers on the specimen itself. This meant that no external reference points were necessary and separate measurements could be made of different parts of the vertebra and disc, giving greater accuracy than could be achieved with previous methods. Vertical deformations in the segment were measured between the spinous processes, along the anterior surface and both sides of the disc as well as

between two markers on the upper vertebral body. For investigations in the sagittal plane, horizontal displacement was measured on the upper spinous process and on the anterior margins of both vertebrae. The pressure in the centre of the disc was also measured at the same time. The vertical load was increased by stages and recorded, together with the corresponding deformations, via an electric monitor and recorder. The specimens were subjected to series of loading with varying eccentricity in the frontal and sagittal planes, both in an intact state and after fusion, as well as after excision of the disc from the fused specimen. A total of 71 specimens were studied, from 38 autopsies. Some 1500 loading sequences were carried out on these.

The tested discs were examined macroscopically and classified into 4 degrees of degeneration. Groups 0 and 1 were regarded as normal discs and groups 2 and 3 as discs with an increasing degree of degeneration. Fusion was performed on 33 specimens and the remainder were investigated for the stabilizing effect of ligaments and intervertebral joints or used for other special studies.

From the primary data, calculations were made of the load per unit area, the relative (percentage) deformation of the disc at each measuring point as well as the change of angle in the sagittal and frontal planes. Tables were compiled for each loading sequence, giving the primary data and calculated values, and graphs were drawn for each parameter.

The investigation was arranged so that each specimen served as its own control. There were considerable differences between the various specimens, particularly in their geometric properties (initial angle, height and surface of the disc). By using relative figures for the size and location of the load, for the deformations measured and for intradiscal pressure, it was nevertheless possible to combine the results and report them in diagram form, as means with their standard deviation. Special aspects could be illustrated with graphs from single specimens.

The geometric centre of the disc was defined as the mid-point of the sagittal diameter, measured between the tangents to the ventral and dorsal peripheries of the horizontal cross-section. If a vertical point-source load is moved along the sagittal diameter, a point — characteristic of each disc — will be reached at which the height of the disc is diminished equally all round its periphery. This point (termed the balanced position of the load) lies at an average 2.5 mm dorsal to the geometric centre of the disc, but is here equated with this for the sake of convenience. Central loading thus means that the disc is compressed without any change of angle in either the sagittal or the frontal plane. As the central load increases, the disc becomes gradually more rigid, indicating its viscous

nature. For all specimens the compression of the disc amounted to only 3 per cent with an external load of 5 kp/cm<sup>2</sup> disc area (a total load of about 100 kp). Measurable deformation of the vertebral body starts at about this load; as the rigidity of the disc increases so does the deformation of the vertebral body. Previous investigations with external reference points have in actual fact produced a combination of these two curves for disc specimens, plus a large initial deformation arising from adaptation of the specimen to the loading surfaces. The deformation curve for disc and vertebral body is indicative of an excellent balance between the two different materials comprising a segment. At relatively small loads, energy is absorbed in the disc, but, as the load increases, the energy is gradually taken up by the vertebral body until, ultimately, the end-plate fractures.

Degenerated discs show a larger vertical deformation than normal ones, at least up to loads of 100 — 120 kp. The difference is small in absolute figures, but statistically significant.

Eccentric loading involves a vertical force acting at the centre of the disc and a moment, both of which elicit counterforces until a new balance is set up through a change in the shape of the disc and in the angle between the vertebrae. For the same moment and the same vertical load, the disc's resistance to a change of angle is greatest in extension, less in lateral flexion and least in flexion. A load of 60—80 kp acting through its resultant at half the radius of the disc, gives extension of approximately 0.02 radians (1.1°) but flexion of approximately 0.04 radians (2.3°). The change of angle is not proportional to the moment but diminishes as this increases. Similarly for the same moment, an increasing vertical load component results in a diminishing tendency to change of angle. Conversely, this implies that the spinal musculature can straighten the spine from a posture of flexion with a smaller moment than that achieved by the superimposed body weight. In this respect the disc serves as an energy-saving device in the construction of the spine.

In keeping with the greater vertical deformation of degenerated discs, these also display less resistance than normal discs to flexion. On the other hand, no instability in the form of increased horizontal displacement was detected in the degenerated discs studied in this investigation. The horizontal component in ventrodorsal and lateral motion seldom exceeded  $\pm 1$  mm and was never more than  $\pm 2$  mm. The picture might differ if larger levers were used for the load.

On excision of the intervertebral joints and severance of the ligaments between the posterior elements, a slight increase in the dorsal height of the disc was observed when the ligamentum flavum (interarcuate ligament)

was cut, demonstrating that this ligament produces a small pre-load on the disc, the significance of which is eliminated upon vertical loading. The ligamentum flavum is probably not an essential factor in the mechanics of the spine, its function being rather to give the vertebral canal a smooth, dorsal covering in all positions of the spine. The intervertebral joints are so designed that they resist torsion in the segment, but, in the present study and for the range of movement tested, they did not impede either extension or lateral flexion.

Fusion of the posterior elements of the vertebrae gives rise to a force acting cranially in the segment and a moment directed dorsally. The size of this moment is conditioned by the physical properties and dimensions of the fusion material and by the leverage of the vertical load. In the experimental fusion, the plastic cast was dimensioned so as to give no appreciable deformation. In fused specimens with the disc excised — loaded as a cantilever — the posterior elements fractured, immediately in front of the fusion, i.e. for type 1 through the base of the spinous process, for type 2 through the laminae or articular processes and for type 3 through the pedicles. The bending moment at fracture was  $128 \pm 37$  kp for type 1 fusion,  $181 \pm 22$  kp for type 2 fusion, and  $252 \pm 28$  kp for type 3 fusion (mean  $185 \pm 18$  kp). The mean load at fracture was 70 kp applied 5 mm dorsal to the specimen's centre. It seems unlikely that even the strongest posterior fusion (combining Albee's Hibbs' and transverse fusion) *in vivo* would be able to resist the force of superimposed body weight without anterior support unless all forward bending is restricted. If the strength of the bone is impaired, even the erect posture should be deleterious.

The specimens fractured at a mean vertical displacement at the anterior border of the upper vertebra of 4 mm and at the posterior border of 2 mm. This displacement is much more than is possible with the intervening disc supporting the vertebral body. During loading of fused specimens with the disc excised, the greatest concentration of stress is immediately in front of the fusion and this is where the fracture occurs. The same load which fractures specimens from which the disc has been removed, produces a vertical displacement at the anterior border of less than 1 mm in specimens with the disc retained; this corresponds to a displacement at the posterior border of less than 0.4 mm. Thus, the strain in fused specimens supported by the discs is less than 25 per cent compared to fused specimens with the discs excised.

As the disc's resistance to deformation increases with the load, the percentage increase of strain in the fusion diminishes, at the same time as it grows in the disc. When maximal deformation of the disc has been reached,

the vertebra may be regarded as a beam supported at both ends and loaded at the anterior support. The strain in the fusion and the posterior elements will then increase only to the extent that the vertebral body is compressed. In intact specimens, a load applied in front of the centre of the disc produces compression in the anterior and tension in the posterior parts of this, and vice versa for loading dorsally of the centre. This tendency naturally persists even after fusion, but, for the loads used, the bone's resistance to bending was sufficient to entirely prevent tension forces in the anterior part of the disc; the posterior part of the annulus, however, was subjected to tension if the unsupported part of the vertebra was sufficiently long, i.e. in type 1 fusion. In theory, the same effect should be produced at a larger moment in type 3 fusion, but in practice, the vertebral body would probably fracture first.

With the disc retained, fusion thus results in a lifting force in the posterior elements and a dorsally directed moment; in this way, the angle of the segment is largely prevented from changing. The strain in the posterior elements and in the fusion is relatively small but this suggests that, in spite of the fusion, the stability of the system is largely determined by the ability of the disc to resist tensile and compressive forces. The poorer the support which the disc can offer, the greater the strain on the fusion and the weaker its stabilizing effect.

Further, this means that, to be mechanically efficient, a fusion requires good strength in both bone and disc. A spine weakened by infectious processes, tumors, osteoporosis or recent fractures seems hardly suitable mechanically for a posterior fusion. In theory, a degenerated disc supports fusion less well than a healthy one. The differences in behaviour observed in the present study between healthy and degenerated discs were relatively small. If the mass of the disc, however, is reduced through partial excision or through lesion of the endplates, there is less chance of achieving a stable posterior fusion.

Fusion has the effect of distributing the vertical load over the segment in such a way that changes of angle are considerably reduced. The pressure is thereby distributed evenly over the entire disc. The intradiscal pressure, measured at the centre of the disc, is appreciably reduced when loads are applied near the fusion. From there it rises steadily, however, and for positive moments (flexion) tends to increase more rapidly than at corresponding loads without fusion, suggesting that moments larger than those employed in the present study would tend to produce a greater strain in the centre of the disc after fusion than before.

In the case of specimens comprising several segments, the effect of the fusion is noticeable even in adjacent segments. These have to balance the

applied vertical loads in quite a different way after fusion. This can mean that a load which gave a change of angle in a negative direction before fusion produces a positive change in the free segments after fusion. Depending upon the application of the load — the moment — fusion can thus exert a stabilizing effect on the free segments or an increased strain as well.

Although the conclusions which can be drawn from the results are naturally limited by the nature of the material and the methods used, they may provide a basis for clinical interpretations.

These experimental results indicate that a posterior fusion obviously provides a stabilizing effect on the involved segment. It is not possible to obtain a complete obstruction of all motion between vertebrae, even if most parts of the posterior elements are fused. The effect is dependent on the forces involved. A posterior load resultant is counteracted by the fusion, whereas, a more anterior load will tend to put increasing strain on the disc. In the most extreme cases the strain on the disc may be even greater after than before a posterior fusion.

## VI References

- Abel, M. S. & Harmon, P. H.*: Oblique motion studies and other non-myelographic roentgenographic criteria for diagnosis of the traumatized or degenerated lumbar intervertebral discs. *Amer. J. Surg.* 99: 177, 1960.
- Adkins, E. W. O.*: Lumbo-sacral arthrodesis after laminectomy. *J. Bone Jt Surg.* 37B: 208—223, 1955.
- Albanese, A.*: Sulla resistenza meccanica della rachide. *Ricerche sperimentali. Arch. Ortop.* 38: 391—421, 1922.
- Albee, F. H.*: Transplantation of a portion of tibia into the spine for Pott's disease. *J. amer. med. Ass.* 57: 885, 1911.
- Albee, F. H.*: Spondylolisthesis. *J. Bone Jt Surg.* 9A: 427, 1927.
- Albert, E.*: Einige Fälle von künstlicher Ankylosenbildung an paralytischen Gliedmassen. *Wien. Med. Presse* 23, 1882.
- Allbrock, D.*: Movements of the lumbar spine column. *J. Bone Jt Surg.* 39B: 339, 1957.
- Alvik, I.*: Tuberculosis of the spine. I) An analysis and follow up study of 507 patients. II) The mobility of the lumbar spine after tuberculous spondylitis. *Acta chir. scand. suppl.* 144, 1949.
- Andersson, C. E.*: Spondylolisthesis following spine fusion. *J. Bone Jt Surg.* 38A: 1142, 1956.
- Andersson, N. & Ekström, T.*: Über die Beweglichkeit der Wirbelsäule. *Morph. Jb.* 85: 135—185, 1940.
- Andraé, R.*: Über Knorpelknötchen im hinteren Ende des Wirbelbandscheiben im Bereich des Spinalkanals. *Beitr. path. Anat.* 82: 468, 1929.
- Arima, S.*: Photoelastic study of the spondylolidesis procedure. *J. jap. orthop. Surg. Soc.* 32: 947—948, 1958.
- Arima, S.*: Photoelastic experimental study on the pathogenesis of spondylolysis. *Orthop. Surg. Tokyo* 10: 295—299, 1959.
- Armstrong, J. R.*: Lumbar disc lesions. Livingstone, Edinburgh & London, 1958.
- Asmussen, E. & Klausen, K.*: Form and function of the erect human spine. *Clin. Orthop.* 25: 55—63, 1962.
- Attenborough, C. G.*: Symposium on lumbo-sacral fusion and low back pain. *J. Bone Jt Surg.* 37B: 164, 1955.
- d'Aubigné, M.*: Arthrodèse par voie transpéritonéale pour le traitement des spondyloses et spondylolisthésis de la 5<sup>ème</sup> lombaire. *Mém. Acad. Chir.* 78: 210, 1952.
- Ayers, C. E.*: Further case studies of lumbo-sacral pathology with considerations of the involvement of the intervertebral discs and facets. *New Engl. J. Med.* 213: 716, 1935.
- Azéma, M. A.*: Le spondylolisthésis. Jouve & Cie, Paris 1932.

*Bachlechner, K.*: Zur operativen Versteifung der Wirbelsäule bei tuberkulöser Spondylitis. *Brun's Beitr.* 124: 655, 1921.

*von Baeyer, H.*: Paraspinoöse Schienung der Wirbelsäule. *Z. orthop. Chir.* 42: 366—370, 1922.

*Backe, S. N.*: Röntgenologische Beobachtungen über die Bewegungen der Wirbelsäule. *Acta radiol. suppl* 13, 1931.

*Barr, J. S., Mixer, W. J. & Jason, W.*: Posterior protrusion of the lumbar intervertebral discs. *J. Bone Jt Surg.* 23A: 444, 1941.

*Barr, J. S.*: "Sciatica" caused by intervertebral disc lesions. *J. Bone Jt Surg.* 19A: 323, 1937.

*Bartelink, D. L.*: The role of abdominal pressure in relieving the pressure on the lumbar intervertebral discs. *J. Bone Jt Surg.* 39B: 718, 1957.

*Biesalski, K.*: Zweck und Schicksahl des Albee-Spans im Spondylitischen Gibbus. *Arch. klin. Chir.* 127: 667—715, 1923.

*Blount, W. P.*: 1942. Quoted by *Breck & Basom* 1943.

*Blount, W. P.*: In discussion to *Moe*: Analysis of methods of fusion for scoliosis. *J. Bone Jt Surg.* 40A: 544, 1958.

*Blount, W. P., Schmidt, A., Keever, E. D. & Leonard, E. T.*: The Milwaukee brace in the operative treatment of scoliosis. *J. Bone Jt Surg.* 40A: 511, 1958.

*Bobeckho, W. P. & Hirsch, C.*: Auto-immune response to nucleus pulposus in the rabbit. *J. Bone Jt Surg.* 47B: 574—580, 1965.

*Bosworth, D. M.*: Clothespin or inclusion graft for spondylolisthesis or laminal defect of lumbar spine. *Surg. Gynec. Obstet.* 75: 593—598, 1942.

*Bosworth, D. M.*: Clothespin graft of the spine for spondylolisthesis and laminal defects. *Amer. J. Surg.* 67: 61—67, 1945.

*Bosworth, D. M.*: Technique of spinal fusion in the lumbosacral region by the double clothespin graft (distraction graft; H-graft) and results. *Amer. Acad. Orthop. Surg. instr. course lectures* 9: 44—52, 1952.

*Boucher, H. H. & Vancouver, B. C.*: A method of spinal fusion. *J. Bone Jt Surg.* 41B: 248, 1959.

*Brailsford, J. F.*: Deformities of the lumbosacral region of the spine. *Brit. J. Surg.* 16: 562, 1928—29.

*Braus, H.*: Anatomie des Menschen. Erstes Band. Bewegungsapparat. Verlag Julius Springer, Berlin 1921.

*Breck, L. W. & Basom W. C.*: The flexion treatment for low back pain, indications, outline of conservative managements and a new spine fusion procedure. *J. Bone Jt Surg.* 25A: 58, 1943.

*Briggs, H. & Milligan, P. R.*: Chip fusion of the low back following exploration of the spinal canal. *J. Bone Jt Surg.* 26A: 125—130, 1944.

*Brocher, J. E. W.*: Die Wirbelverschiebung in der Lendengegend. George Thieme Verlag, Stuttgart, 1958.

*Bröman, I. & Hjortsjö, C. H.*: Människans rörelseapparat. Gleerups förlag, Lund, 1952, p. 137—183.

- Brown, T., Hansen, R. J. & Yorra, A. J.*: Some mechanical tests on the lumbosacral spine with particular reference to the intervertebral discs. *J. Bone Jt Surg.* 39A: 1135, 1957.
- Burns, B. H.*: An operation for spondylolisthesis. *Lancet* 1: 1233, 1933.
- Bush, H. D., Horton, W. G., Smare, D. L. & Naylor, A.*: Fluid content of the nucleus pulposus as a factor in the disc syndroms. Further observations. *Brit. med. J.* 2: 81, 1956.
- Böhmig, R.*: Über Formanomalien des Nucleus pulposus der Wirbelsäule. *Virchows Arch.* 280: 873, 1931.
- Calandrucchio, R. A. & Benton, B. F.*: Anterior lumbar fusion. *Clin. Orthop.* 35: 63, 1965.
- Calot, E.*: Traitement des tumeurs blanches. Paris 1905.
- Calvé, J. & Lelièvre, H.*: Radiography of the vertebral column in profile in Pott's disease. *J. orthop. Surg.* 11: 193, 1913.
- Calvé, J. & Galland, M.*: De l'ostéo-synthèse dans le traitement du mal de Pott. *Rev. Chir.* 58: 340—378, 1920.
- Calvé, J. & Galland, M.*: The intervertebral nucleus pulposus, its anatomy, its physiology, its pathology. *J. Bone Jt Surg.* 12: 555, 1930.
- Calvé, J. & Galland, M.*: Osteosynthesis in spinal tuberculosis. *J. Bone Jt Surg.* 18: 46—48, 1936.
- Campbell, W. C.*: Operative measures in the treatment of affections of the lumbosacral and sacro-iliac articulation. *Surg. Gynec. Obstet.* 51: 381, 1930.
- Capener, N.*: Spondylolisthesis. *Brit. J. Surg.* 19: 374, 1931—1932.
- Carr, C. R. & Hyatt, G. W.*: Clinical evaluation of freeze-dried bone grafts. *J. Bone Jt Surg.* 37A: 549, 1955.
- Chaklin, V. D.*: 1937. Quoted by Friberg 1939.
- Chandler, F. A.*: Trisacral fusion. An operative technique facilitating the combined ankylosis of the lumbosacral joints of the spine and both sacro-iliac joints. *Surg. Gynec. Obstet.* 48: 501, 1929.
- Chandler, F. A.*: Spinal fusion operations in the treatment of low back and sciatic pain. *J. amer. med. Ass.* 93: 1447, 1929.
- Chandler, F. A.*: Lesions of the "isthmus" (pars interarticularis) of the laminae of the lower lumbar vertebrae and their relation to spondylolisthesis. *Surg. Gynec. Obstet.* 53: 273, 1931.
- Charnley, J.*: Orthopedic signs in the diagnosis of disc protrusions with special reference to the straight-leg-raising test. *Lancet* 1: 186—192, 1951.
- Charnley, J.*: The imbibition of fluid as a cause of herniation of the nucleus pulposus. *Lancet* 262: 124, 1952.
- Chase, S. W. & Herndon, C. H.*: The fate of autogenous and homogenous bone grafts. A historical review. *J. Bone Jt Surg.* 37A: 809—841, 1955.
- Chipault, A.*: Un cas de gibbosité avec paraplégie traité avec succès par les ligatures apophysaires. (A case of gibbosity with paraplegia treated with success by apophysial ligatures.) *Trav. neurol. chir.* 5: 20—26, 1900.
- Cleveland, M., Bosworth, D. M. & Thompson, F. R.*: Pseudarthrosis of the lumbosacral spine. *J. Bone Jt Surg.* 30A: 302, 1948.

- Cloward, R. B.*: The treatment of ruptured lumbar intervertebral disc by vertebral body fusion. *J. Neurosurg.* 10: 154, 1953.
- Cloward, R. B.*: Lesions of the intervertebral discs and their treatment by interbody fusion method. *Clin. Orthop.* 27: 51—75, 1963.
- Cobb, J. R.*: Technique, after-treatment and results of spine fusion for scoliosis. *Amer. Acad. Orthop. Surg. Instr. Course Lect.* 9: 65—70, 1952.
- Coventry, M. B., Ghormley, R. K. & Kernohan, J. W.*: The intervertebral disc: its microscopic anatomy and pathology. Part I. Anatomy, development and physiology. *J. Bone Jt Surg.* 27: 105, 1945 a.
- Coventry, M. B., Ghormley, R. K. & Kernohan, J. W.*: The intervertebral disc: Part II. Changes in the intervertebral disc concomitant with age. *J. Bone Jt Surg.* 27: 233, 1945 b.
- Coventry, M. B., Ghormley, R. K. & Kernohan, J. W.*: The intervertebral disc: Part III. Pathological changes in the intervertebral disc. *J. Bone Jt Surg.* 27: 460, 1945 c.
- Currey, J. D.*: Three analogies to explain the mechanical properties of bone. *Biorheology* 2: 1—10, 1964.
- Dandy, E. W.*: Concealed ruptured intervertebral discs. *J. amer. med. Ass.* 117: 821, 1941.
- Dandy, W. E.*: Treatment of recurring attacks of low back ache without sciatica. *J. amer. med. Ass.* 125: 1175, 1944.
- Danforth, M. S. & Wilson, P. D.*: The anatomy of the lumbo-sacral region in relation to sciatic pain. *J. Bone Jt Surg.* 7: 109, 1925.
- Davis, P. R.*: Variations of the human intraabdominal pressure during weight-lifting in different postures. *J. Anat., Lond.* 90: 601, 1956.
- Davis, P. R.*: Posture of the trunk during the lifting of weights. *Brit. med. J.* 1: 87—89, 1959 a.
- Davis, P. R.*: The causation of herniae by weight-lifting. *Lancet*: 155—157, aug. 1959 b.
- Davis, P. R., Troup, D. G. & Burnard, J. H.*: Movements of the thoracic and lumbar spine when lifting: a chrono-cyclophotographic study. *J. Anat., Lond.* 99: 18—26, 1965.
- Debrunner, H.*: Über den Wert der Albeeschen Operation bei tuberkulöser Spondylitis. *Arch. Orthop. Chir.* 19: 86, 1921.
- Decoulx, P. & Rieunau, G.*: Les fractures du rachis dorso-lombaire sans troubles nerveux. *Rev. chir. orthop.* 44: 254—322, 1958.
- Delaunay, A., Bazin, S., Henon, M. & Baggi, G.*: Etudes sur le collagène. *Rev. franc. Gerontologia* 91:50—59, 1956.
- Dempster, W. T. & Liddicoat, R. T.*: Compact bone as a non-isotropic material. *Amer. J. Anat.* 91: 331—362, 1952.
- Denecke, K.*: Reposition der luxierten Wirbelsäule bei Spondylolisthese. *Verhandl. dtsch. orthop. Ges.* 44 Kongr. sept. 1956. (*Z. Orthop.* 88: 404, 1957).
- Dick, I. L.*: Treatment of traumatic paraplegia in fractures, of lumbo-dorsal spine. *Edinb. med. J.* 60: 249—264, 1953.
- Dittmar, O.*: Beobachtungen an den Gelenkfortzätzen der Lendenwirbel bei sagittal- und lateralflektorische Bewegung. Zur Mechanologie der Wirbelsäule 2. Mitteilung. *Z. Anat. Entw. Gesch.* 93: 477—483, 1930.

- Dittmar, O.*: Die Vor- und Rückwärtsbeugung der normalen Wirbelsäule. Bemerkungen zu der gleichnamigen Arbeit von F. Heuer. *Z. orthop. Chir.* 53: 245—248, 1931 a.
- Dittmar, O.*: Röntgenstudien zur Mechanologie der Wirbelsäule. *Z. orthop. Chir.* 55: 321—336, 509—548, 1931 b.
- Domisse, G. F.*: Lumbo-sacral interbody spinal fusion. *J. Bone Jt Surg.* 41B: 87, 1959.
- Du Toit, J. G., Domisse, G. F. & Muller, L. H.*: Anterior inter-corporal spinal fusion. *J. Bone Jt Surg.* 38B: 593, 1956.
- Eckert, C. & Decker, A.*: Pathological study of intervertebral discs. *J. Bone Jt Surg.* 29: 447, 1947.
- Eie, N.*: Combined extirpation and spinal fusion in lumbar intervertebral disc herniations. *J. Oslo City Hosp.* 14: 149—174, 1964.
- Eie, N.*: Load capacity of the low back. *J. Oslo City Hosp.* 16: 75—98, 1966.
- Eie, N. & Wehn, P.*: Measurements of the intraabdominal pressure in relation to weight bearing of the lumbosacral spine. *J. Oslo City Hosp.* 12: 205, 1962.
- Elward, J. F.*: Motion in the vertebral column. *Amer. J. Roentgenol.* 42: 91, 1939.
- Erlacher, P. R.*: Nucleography. *J. Bone Jt Surg.* 34B: 204, 1952.
- Erlacher, P. R.*: In discussion to Denecke 1957.
- Evans, G. F.*: Stress and strain in bones. Charles Thomas, Publisher, Springfield Ill., 101, 1957.
- Evans, G. & Lebow, M.*: The strength of human compact bone as revealed by engineering technics. *Amer. J. Surg.* 83: 326—331, 1952.
- Evans, G. F. & Lissner, H. R.*: Biomechanical studies on the lumbar spine and pelvis. *J. Bone Jt Surg.* 41A: 278—290, 1959.
- Evans, G. F. & Lissner, H. R.*: Studies on the energy absorbing capacity of human lumbar intervertebral discs. The seventh stop car crash conference 1965. pp 1—17 Thomas, Puplicher, Springfield, Ill. 1965.
- Farrel, P. B. & McCracken, B. W.*: Spine fusion of intervertebral discs. *J. Bone. Jt Surg.* 23A: 457, 1941.
- Felländer, M.*: Radical operation in tuberculosis of the spine. *Acta orthop. scand. suppl.* 19, 1955.
- Felländer, M.*: Radical operation in tuberculosis of the spine. Paper read at the meeting of the swedish med. Ass in dec. 1965.
- Ferguson, A.*: The clinical and roentgenographic interpretation of lumbosacral anomalies. *Radiology* 22: 548, 1934.
- Fernström, U.*: A discographical study of ruptured lumbar intervertebral discs. *Acta chir. scand. suppl.* 258, 1960.
- Fick, R.*: Handbuch der Anatomie und Mechanik der Gelenke. Verlag Fischer, Jena 1904.
- Fletcher, C. H.*: Backward displacement of fifth lumbar vertebra in degenerated disc disease. *J. Bone Jt Surg.* 29: 1019, 1947.
- Floyd, W. F. & Silver, P. H. S.*: The function of the erectores spinae muscles in certain movements and postures in man. *J. Physiol.* 129: 184—203, 1955.
- Friberg, S.*: Studies on spondylolisthesis. *Acta chir. scand.* 82, suppl. 55, 1939.
- Friberg, S.*: Low back and sciatic pain caused by intervertebral disc herniation. *Acta chir. scand. suppl.* 64: 85, 1941.

- Friberg, S.*: Anatomical studies on lumbar disc degeneration. *Acta orthop. scand.* 17: 224, 1947.
- Friberg, S. & Hirsch, C.*: On late results of operative treatment for intervert. disc prolaps in the lumbar region. *Acta chir. scand.* 93: 161—168, 1946.
- Friberg, S. & Hirsch, C.*: Anatomical and clinical studies on lumbar disc degeneration *Acta orthop. scand.* 19: 222, 1950.
- Galante, J. & Hirsch, C.*: Laboratory conditions for tensile tests in the annulus fibrosus of the human intervertebral disc. *Acta orthop. scand.* In print, 1966.
- Ghormley, R. K.*: Low back pain, with special reference to the articular facets with presentation of an operative procedure. *J. amer. med. Ass.*, 1773, 1933.
- Ghormley, R. K.*: The problem of multiple operations on the back. *Amer. acad. orthop. surg. instr. course lect* 14: 56—63, 1957.
- Gianturco, C.*: A roentgen analysis of the motion of the lower lumbar vertebrae in normal individuals and in patients with low back pain. *Amer. J. Roentgenol.* 52: 261, 1944.
- Gibson, A.*: A modified technique for spinal fusion. *Surg. Gynec. Obstet.* 53: 365—369, 1931.
- Gjessing, M. H.*: Osteoplastic anterior fusion of the lower lumbar spine in spondylolisthesis, localized spondylosis, and tuberculous spondylitis. *Acta orthop. scand.* 20: 200, 1951.
- Goldthwaith, J. E.*: The lumbo-sacral articulation. An explanation of many cases of "lumbago, ischias and paraplegia". *Boston Med. Surg. J.* 164, 365, 1911.
- Gray, H.*: *Anatomy; Descriptive and applied.* Editor: D. V. and F. Davies, Longmans, London, 1962.
- Gruca, A.*: The pathogenesis and treatment of idiopathic scoliosis. *J. Bone Jt Surg.* 40A: 570, 1958.
- Gurdjian, E. S., Webster, J. E., Hardy, W. G., Ostrowsky, A. Z., Lindners, A. Z. & Thomas L. M.*: Herniated lumbar intervertebral discs — analysis of 1176 operated cases. *J. Trauma*, 1: 158, 1961.
- Guttman, L.*: Management of spinal cord injuries. *Modern Trend in diseases of the vertebral column.* Ed: Butterworth & Co, 245, 1959.
- Güntz, E.*: Die Erkrankungen der Zwischenwirbelgelenke. *Arch. orthop. Unfall-Chir.* 34: 333—355, 1934.
- Güntz, E.*: Schmerzen und Leistungsstörungen bei Erkrankungen der Wirbelsäule. Ferdinand Enke Verlag, Stuttgart, 1937.
- Göcke, C.*: Das Verhalten spongiösen Knochens im Druck- und Schlagversuch. *Verh. d. d. orthop. Ges.* 20: 116, 1926.
- Göcke, C.*: Traumatische Wirbelumformung im Versuch. *Hefte Unfallheilkunde*, 8: 136, 1931.
- Göcke, C.*: Das Verhalten der Bandscheiben bei Wirbelverletzungen. *Arch. orthop. Unfall-Chir.* 31: 42—80, 1932.
- Görres, H.*: Zur Frage der Spannbildung und Einpflanzung des Spanes nach Albee bei Spondylitis tuberculosa. *Zbl. Chir.* 49: 784, 1922.
- Haas, S. L.*: Study of fusion of the spine with particular reference to the articular facets. *J. Bone. Jt Surg.* 18A: 717, 1936.

- Haas, S. L.*: The prevention of deformity of the spine by vertebral fusion. *J. Bone Jt Surg.* 22A: 157—160, 1940.
- Haas, S. L.*: Fusion on vertebrae following resection of the intervertebral disc. *J. Bone Jt Surg.* 28A: 544, 1946.
- Hadra, B. E.*: Wiring the spinous processes in Pott's disease. *Trans. amer. Orthop. Ass.* 4: 206, 1891
- Hagelstam, L.*: Retroposition of lumbar vertebrae. *Acta chir. scand. suppl.* 143, 1949.
- Hallock, H. & Jones, J. B.*: Tuberculosis of the spine. (End result study of the effect of the spine fusion operation in a large number of patients). *J. Bone Jt Surg.* 36A: 219, 1954.
- Halstead, A. E.*: A new method of securing bony ankylosis of the spine in Pott's disease by means of a bone transplant. *Surg. Gynec. Obstet* 21: 18, 1915.
- Hanson, R.*: On the development of spinal vertebrae, as seen on skiagrams, from late foetal life to the age of fourteen. *Acta radiol.* 5: 112—126, 1926.
- Happey F., Mac Rae, T. P. & Naylor, A.*: X-ray chrystrallographic investigation on the change with age in the structure of the human intervertebral disk. *Nature and structure of collagen.* p. 65, Ed.; Randall J. T. Butterworths Scientific Publications London 1953.
- Hardy, W. G., Lissner, H. R., Webster J. E. & Gurdjian E. S.*: Repeated loading tests of the lumbar spine. *Surgical forum* 9: 690, 1958.
- Harmon, P. H.*: Operative technique and some ten years end results from abdominal, extraperitoneal disc excision and vertebral body fusions in the lower lumbar spine. *Amer. Acad. orthop. instr. course lectures.* 18: 24—29, 1959.
- Harmon, P. H.*: Anterior spinal fusion for lumbar disc lesions *J. Bone Jt Surg.* 43B: 174, 1961.
- Harmon, P. H.*: Saline injection test applied to lower lumbar disc degeneration: comparison to pantopaque myelography. *Ann. Surg.* 5: 767, 1962.
- Harmon, P. H.*: Anterior excision and vertebral body fusion operation for intervertebral disc syndromes of the lower lumbar spine. *Clin. Orthop.* 26: 107—127, 1963.
- Harmon, P. H.*: *Pers. com.* 1963.
- Harrington, P.*: Treatment of scoliosis. *J. Bone Jt Surg.* 44A: 591, 1962.
- Harris, R. I. & Wiley, J. J.*: Aquired spondylolysis as a sequel to spine fusion. *J. Bone Jt Surg.* 45A: 1159, 1963.
- Hellstadius, A.*: Experiences gained form spondylo-syndesis operations with H-shaped bone transplantations in cases of degeneration of discs in the lumbar back. *Acta orthop. scand.* 24: 207, 1955.
- Hendry, N. G. C.*: The hydration of the nucleus pulposus and its relation to intervertebral disc derangement. *J. Bone Jt Surg.* 40B: 132, 1958.
- Henle, A.*: Versteifung der Wirbelsäule durch Knochentransplantation. *Verh. dtsh. Ges. Chir.* T. I.: 118, 1911.
- Henle, A. & Huber E.*: Die operative Versteifung der erkrankten Wirbelsäule durch Kochentransplantation. *Ergebn. Chir. Orthop.* 19: 349, 1926.
- Henschen, C.*: Operation der Spondylolisthesis durch transabdominale lumbosacrale Verschraubung und zusätzliche transplantative Spanversteifung. *Helv. med. Acta* 9: 25, 1942.

- Hensell, V.*: Erfahrungen mit der ventralen extraperitonealen Wirbelblockierung. Arch. klin. Chir. 288: 209, 1958.
- Hibbs, R.*: An operation for progressive spinal deformities. New York Med. J. 93: 1013, 1911.
- Hibbs, R.*: Treatment of vertebral tuberculosis by fusion operation. Report on 210 cases. J. amer. med. Ass 71: 1372, 1918.
- Hibbs, R.*: Report on 59 cases of scoliosis treated by fusion operation. J. Bone Jt Surg. 22: 3, 1924.
- Hibbs, R. & Risser, J.*: Treatment of the spine by fusion J. Bone Jt Surg. 10: 805—815, 1928.
- Hibbs, R. A., Risser, J. C. & Ferguson, A. B.*: Scoliosis treated by the fusion operation. An end-result study of 360 cases. J. Bone Jt Surg. 13A: 91—104, 1931.
- Hibbs, R. & Swift, W.*: Development abnormalities at the lumbo-sacral juncture causing pain and disability (A report of 147 patients treated by the spine fusion operation). Surg. Gynec. Obstet. 48: 604, 1929.
- Hirsch, C.*: An attempt to diagnose the level of a disc lesion clinically by disc puncture. Acta orthop. scand. 18: 132, 1948.
- Hirsch, C.*: Studies on the mechanism of low back pain. Acta orthop. scand. 20: 261, 1951.
- Hirsch, C.*: Anterior grafting in spondylolisthesis. Arch. orthop. Unfall-chir. 60: 46, 1966.
- Hirsch, C., Ingelmark, B.-E. & Miller, M.*: The anatomical basis of low back pain. Acta orthop. scand. 33: 1—17, 1963.
- Hirsch, C. & Nachemson, A.*: New observations on the mechanical behaviour of lumbar discs Acta orthop. scand. 23: 254, 1954.
- Hirsch, C. & Nachemson, A.*: The reliability of lumbar disk surgery. Clinical Orthop. 29: 189, 1963.
- Hirsch, C., Paulson, S., Sylvén, B. & Snellman, O.*: Biophysical and physiological investigations on cartilage and other mesenchymal tissues. Acta orthop. scand. 22: 175—183, 1952.
- Hirsch, C. & Schajowicz, F.*: Studies on structural changes in the lumbar annulus fibrosus. Acta orthop. scand. 22: 184—231, 1952.
- Hitchcock, H. H.*: Spondylolisthesis. Observations on its development progression and genesis. J. Bone Jt Surg. 22A: 1—16, 1940.
- Hoag, J. M., Kosek, M. & Moser, J. R.*: Kinematic analysis and classification of vertebral motion. J. amer. osteopath. Ass. 59: part 1: 899—908, part 2: 982—986, 1960.
- Hoessly, H.*: Die osteoplastische Behandlung Wirbelsäulenerkrankungen speziell bei Verletzungen und bei der Spondylitis tuberculosa. Bruns' Beitr. 102: 153, 1916.
- Hoffmann, V.*: Die autoplastischen Knochentransplantationen vom Standpunkt der Biologie und Architektonik. Arch. klin. Chir. 135: 413, 1925.
- Holdsworth, F. W. & Hardy, A. C.*: Early treatment of paraplegia from fractures of the thoracic and lumbar spine. J. Bone Jt Surg. 35B: 540, 1953.
- Horton, W. G.*: Further observations on the elastic mechanism of the intervertebral disc. J. Bone Jt Surg. 40B: 552—557, 1958.
- Howorth, B. M.*: Management of problems of the lumbosacral spine. J. Bone Jt Surg. 45A: 1487—1508, 1963.

*Howorth, B. M.*: Low backache and sciatica: Results of surgical treatment. *J. Bone Jt Surg.* 46A: 1485—1519, 1964.

*Humphries, A. W., Hawk, W. A. & Berndt, A. L.*: Internal fixative device for anterior fusion of lumbar spine, preliminary experimental report. *Cleveland Clin. Quart.* 24: 210, 1957.

*Hult, L.*: Retroperitoneal disc fenestration in low-back pain and sciatica. *Acta orthop. scand.* 20: 342, 1951.

*Hult, L.*: The Munkfors investigation. *Acta orthop. scand. suppl.* 16, 1954.

*Ikata, T.*: Effects of overloading on the spine. *Pers. com.* 1966.

*Ingelmark, B.-E.*: De funktionellt anatomiska förhållandena i ryggraden med särskild hänsyn till dess småleder. *Acta Universitatis Gothoburgensis* 62: 1—48, 1956.

*Ingelmark, B.-E. & Ekholm, R.*: Über die Kompressibilität der Intervertebralscheiben. *Acta Soc. med. Upsaliensis* 57: 202, 1952.

*Inman, V. & Saunders, C. B.*: Anatomicophysiological aspects of injuries to the intervertebral disc. *J. Bone Jt Surg.* vol. 29/2: 461—467, 1947.

*Ito, H., Tsuchia, J. & Asami, G.*: A new radical operation for Pott's disease. *J. Bone Jt Surg.* 16A: 499, 1934.

*Jackson, H. C.*: Nerve endings in the human lumbar spine and its associated structures. Paper given at the meeting of the Orthop. Research Soc. in Chicago 1966.

*James, A. & Nisbeth, N. W.*, Posterior intervertebral fusion of the lumbosacral spine. Preliminary report of a new operation. *J. Bone Jt Surg.* 35B: 181, 1953.

*Jaslow, I.*: Intercorporal bone graft in spinal fusion after disc removal. *Surg. Gynec. Obstet* 82: 215—218, 1946.

*Jenkins, J. A.*: Spondylolisthesis. *Brit. J. Surg.* 24: 80, 1936.

*Johanson, N. A.*: A surgical operation for lumbago and sciatic rheumatism. *Northwest am. J. Med.* 19: 195, 1920.

*Johnson, W. R.*: Posterior luxation of the lumbosacral joint *J. Bone Jt Surg.* 16A: 867, 1934.

*Jónsson, B.*: Studies on Hibb's spine fusion in the treatment of scoliosis. *Acta orthop. scand. suppl.* 14, 1953.

*Joisten, C.*: Zur operativen Behandlung der Spondylitis tuberculosa nach Albee. *Arch. orthop. Unfall-Chir.* 27: 50—60, 1929.

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

*Joseph, J.*: Electromyographic studies of man's posture. (*Guy's Hosp. Rep.*) *Clin. Orthop.* 25: 92—97, 1962.

*Junghanns, H.*: Die Zwischenwirbelscheiben in Röntgenbild. *Fortschr. Röntgenstr.* 43: 275, 1931.

*Junghanns, H.*: Die funktionelle Pathologie der Zwischenwirbelscheiben als Grundlage für klinische Betrachtungen. *Langenbecks Arch. Dtch. Z. Chir.* 267: 393, 1951.

*Karlebo handbok*: Wezäta, Göteborg 1957.

*Keegan, J. J.*: Alterations of the lumbar curve related to posture and seating. *J. Bone Jt Surg.* 35A: 589—603, 1953.

- Kelly, M.*: Physical changes in the prolapsed disc. (Letter to editor) *Lancet* 11: 584, 1958.
- Key, A. J. & Ford, L. T.*: Experimental intervertebral disc lesions. *J. Bone Jt Surg.* 30A: 621, 1948.
- Keyes, D. C. & Compere, E. L.*: The normal and pathological physiology of the nucleus pulposus of the intervertebral disc. *J. Bone Jt Surg.* 14: 897—938, 1932.
- Kimberley, A. G.*: Low back pain and sciatica. *Surg. Gynec. Obstet* 65: 195, 1937.
- King, D.*: Internal fixation for lumbo-sacral fusion. *J. Bone Jt Surg.* 30A: 560, 1948.
- Klausen, K.*: The form and function of the loaded human spine. *Acta physiol. scand.* 65: 176—190, 1965.
- Knese, K. H.*: Knochenstruktur als Verbundbau. Versuch einer technischen Deutung der Materialstruktur des Knochens. George Thime Verlag, Stuttgart 1958.
- Knutsson, F.*: Om röntgendiagnosen av diskdegeneration i ländryggraden. *Nord. Med.* 7: 1367, 1940.
- Knutsson, F.*: The instability associated with disk degeneration in the lumbar spine. *Acta radiol.* vol. 25, fasc. 5—6, 21: 11, 1944.
- Knutsson F.*: Die anatomischen Grundlagen für die Erkennung der Chondrosis und Osteochondrosis Intervertebralis im Röntgenbild. *Acta radiol. suppl.* 116: 276, 1954.
- Knutsson, F.*: Clinical roentgenology of the vertebral body. A review. *Acta orthop. scand.* 26: 191, 1957.
- Krafka*: Quoted by Nunley 1958.
- Kurtz, A. D. & Horwitz, M. T.*: An investigation into wiring of spinous processes. *Arch. Surg.* 33: 630, 1936.
- Lance M. et Aourousseau*: Quoted by Azéma, M. A. 1932.
- Lane, J. D. & Moore, E. S.*: Transperitoneal approach to the intervertebral disc in the lumbar area. *Ann. Surg.* 127: 537, 1948.
- Lange, C.*: Untersuchungen über Elasticitätsverhältnisse in den menschlichen Rückenwirbeln mit Bemerkungen über die Pathogenese der Deformitäten. *Z. orthop. Chir.* 10: 47, 1902.
- Lange, C.*: Über Elasticitätswerte in Rückenwirbeln und über osteomalacia traumatica. *Verh. dtsh. orthop. Ges.* (15. Congress 1920) p. 589, 1921.
- Lange, F.*: Support for the spondylitic spine by means of buried steel bars, attached to the vertebrae. *J. Orthop. Surg.* 8: 344, 1910—11.
- Lange, M.*: Die Spondylolisthesis, ihre Ursache, ihre Behandlung und gutachtliche Beurteilung. *Z. Orthop. Beil. heft* 91: 152, 1959.
- Laurent, L. E.*: Spondylolisthesis. A study of 53 cases treated by spine fusion and 32 cases treated by laminectomy. *Acta orthop. scand. suppl.* 35, 1958.
- Leger, W.*: Röntgenologische Bewegungsstudien an der Lendenwirbelsäule. *Verh. dtsh. orthop. Ges.* (Beilageheft *Z. Orthop.* 87: 211, 1956).
- Leger, W.*: Die Form der Wirbelsäule mit Untersuchungen über ihre Beziehung zum Becken und die Statik der aufrechten Haltung. *Z. orthop. Beil.* 91: 1—108, 1959.
- Lewin, T.*: Osteoarthritis in lumbar synovial joints. A morphological study. *Acta orthop. scand. suppl.* 1964.
- Lewin, T.*: Anatomiska variationer i lumbosacralsegmentens synovialleder, in press. 1966.

- Lindabl, O. & Rexed, B.:* Histologic changes in spinal nerve roots of operated cases of sciatica. *Acta orthop. scand.* 20: 215, 1951.
- Lindblom, K.:* Protrusions of discs and nerve compression in the lumbar region. *Acta radiol.* 25: 195, 1944.
- Lindblom, K.:* Diagnostic puncture of intervertebral discs in sciatica. *Acta orthop. scand.* 17: 231, 1948.
- Lindblom, K.:* Technique and results of diagnostic disc puncture and injection (discography) in the lumbar region. *Acta orthop. scand.* 20: 315, 1951.
- Love, J. G.:* The disc factor in low-back pain with or without sciatica. *J. Bone Jt Surg.* 29A: 438—447, 1947.
- Lucas, D. B. & Bresler, B.:* Stability of the ligamentous spine. Technical report ser. 11, nr 40, Biomechanics Laboratory, University of California, Berkley and San Francisco, 1961.
- Lukas, R.:* Beitrag zur Bestimmung von Rotationsgraden an Wirbelkörpern mittels Winkelmesser. *Z. orthop.* 91: 287—296, 1959.
- Lundberg, T.:* Hållfasthetslära för tekniska gymnasiet. Akademiförlaget — Gumperts, Göteborg. Ed. 7, 1963.
- von Luschka, H.:* Die Altersveränderungen der Intervertebralscheiben. *Arch. pathol. Anat. Phys. klin. Med. Virchow*, 9: 311—327, 1856.
- von Luschka, H.:* Die Halbgelenke des menschlichen Körpers. Georg Reimer Verlag, Berlin 1858.
- Mc Bride, E. D.:* A mortised transfacet bone block for lumbosacral fusion. *J. Bone Jt Surg.* 31A: 385, 1949.
- Mc Bride, E. D. & Shorbe, H. B.:* Lumbosacral fusion: The mortised transfacet method by use of the vibrating saw for circular bone blocks. *Clin. Orthop.* 12: 268, 1958.
- Mc Elhaney, J. H.:* Strain rate sensitivity of certain biological materials. Diss. Univers. of West Virginia, Morgantown, 1965.
- Mc Master:* Tendon and muscle ruptures. Clinical and experimental studies on the causes and location of subcutaneous ruptures. *J. Bone Jt Surg.* 15: 705, 1933.
- Mac Nab, I.:* Spondylolisthesis with an intact neural arch the so called pseudospondylolisthesis. *J. Bone Jt Surg.* 32B: 325, 1950.
- Mack, R.:* Bone a natural two-phase material. Biomechanics Lab. Univ. California, San Francisco—Berkeley. Technical Memorandum, okt 1964.
- Magnusson, W.:* Über die Bedingungen des Hervortretens der wirklichen Gelenkspalte auf dem Röntgenbilde. *Acta radiolog.* 18: 733—741, 1937.
- Malmros, R.:* Den lumbale discusprolaps og ligamentaere rodcompression. Einar Munksgaard, København 1942.
- Mandarino, M.:* Chemical osteosynthesis in orthopaedic Surgery. Charles T Thomas, Springfield, USA 1960.
- Marble, H. C. & Bishop, W. A.:* Intervertebral disc injury. *J. Indust. Hyg. and Toxicol.* 27: 103—109, 1945.
- Matthiasb. H. H.:* Arbeitshaltung und Bandscheibenbelastung. *Arch. orthop. Unfall-Chir.* 48: 147, 1956.
- Mathieau, P. & Demirleau:* Traitement chirurgical du spondylolisthésis douloureux. *Rev. Orthop.* 23: 352, 1936.

- Melamed, A. & Ansfield, D. J.*: Posterior displacement of lumbar vertebrae. (Classification and criteria for diagnosis of true retrodisplacement of lumbar vertebrae) Amer. J. Roentgenol. 58: 307—328, 1947.
- Mercer, W.*: Spondylolisthesis. With a description of a new method of operative treatment and notes of ten cases. Edinburgh med. J. 43: 545, 1936.
- Messerer, O.*: Über Elasticität und Festigkeit der menschlichen Knochen. 1880.
- Milgram, J. E. & Robinson, R. A.*: Nerves in the haversian system of cortical bone. Paper given at the meeting in Chicago 1966 in the Orthopaedic Research Society.
- Millikan, C. H.*: The problem of evaluating treatment of protruded lumbar intervertebral discs. Observations of results of conservative and surgical treatment. J. amer. med. Ass. 155: 1141—1143, 1954.
- Mineiro, J. D.*: Coluna vertebral humana alguns aspectos da sua estrutura a vascularização. Lisboa 1965.
- Mitchell, P. E. G., Hendry, N. G. C. & Billewicz, W. Z.*: The chemical background of intervertebral disc prolapse. J. Bone Jt Surg. 43B: 141, 1961.
- Mixter, W. J. & Barr, J. S.*: Rupture of the intervertebral disc with involvement of the spinal canal. New Engl. J. Med. 211: 210, 1934.
- Moe, J. H.*: A critical analysis of methods of fusion for scoliosis. J. Bone Jt Surg. 40A: 529, 1958.
- Monticelli, G. & Maresca, A.*: The surgical treatment of spondylolisthesis. The Marino-Zuco technique. Orthop. traumat. app. motore, 25: 857, 1957.
- Morgan, P. & King, T.*: Primary instability of lumbar vertebrae as a common cause of low back pain. J. Bone Jt Surg. 39B: 6, 1957.
- Morris, L. M., Benner, G. & Lucas, D. G.*: An electromyographic study of the intrinsic muscles of the back in man. J. Anat. Lond. 96: 509—520, 1962.
- Morris, J. M., Lucas, D. B. & Bresler, B.*: Role of the trunk in stability of the spine. J. Bone Jt Surg. 43A: 327, 1961.
- Mouchet, A. & Roederer, C.*: Le spondylolisthésis. Rev. Orthop. 14: 461, 1927.
- Mulligan, J. H.*: The innervation of the ligaments attached to the bodies of the vertebrae. J. Anat. 91: 455—463, 1957.
- Müller, W.*: Weitere Beobachtungen über das Drehgleiten an skoliotischen Lendenwirbelsäulen älterer Leute und seine Bedeutung für die Unfallbegutachtung. Arch. orthop. Unfall-Chir. 33: 1, 1933.
- Nachemson, A.*: Lumbar intradiscal pressure. Acta orthop. scand. suppl. 43, 1960.
- Nachemson, A.*: Some mechanical properties of the lumbar intervertebral discs. Bull. Hosp. Joint Diseases, 23: 130, 1962.
- Nachemson, A.*: The influence of spinal movements on the lumbar intradiscal pressure and on the tensile stresses in the annulus fibrosus. Acta orthop. scand. 33: 183, 1963.
- Nachemson A.*: In vivo discometry in lumbar discs with irregular nucleograms. Acta orthop. scand. 36: 418—434, 1965.
- Nachemson, A.*: Electromyographic studies on the vertebral portions of the psoas muscle, Acta orthop. scand. 37: 177, 1966.
- Nachlas, W.*: End-result study of the treatment of herniated nucleus pulposus by excision with fusion and without fusion. J. Bone Jt Surg. 34A: 981—988, 1952.

- Naylor A. & Smare D.L.*: Fluid content of the nucleus pulposus as a factor in the disk syndrome. Prel.report. Brit. med. J. 2: 975, 1951.
- Naylor, A.*: The biophysical and biochemical aspects of intervertebral disc herniation and degeneration. Royal College Surgeons England 31: 91—114, 1962.
- Newman, P. H.*: Symposium on lumbo-sacral fusion and low back pain. J. Bone Jt Surg. 37B: 164, 1955.
- Newman, P. H.*: Modern trends in diseases of the vertebral column. (Low back pain). Butterherworth & Co Ltd, London 263, 1959.
- Nicoll, E. A.*: Fractures of the dorso-lumbar spine. J. Bone Jt Surg. 31B: 376, 1949.
- Nordlander, S., Salén, E. F. & Unander-Scharin, L.*: Discography in low back pain and sciatica. Acta orthop. scand. 28: 90, 1958.
- Nunley, R. L.*: The ligamenta flava of the dog. A study of tensile and physical properties. Amer. J. phys. Med. 37: 256, 1958.
- Odelberg-Johnson, G.*: On defects in the bone graft after Albee's operation for tuberculous spondylitis. Acta orthop. scand. suppl. 1, 1934.
- Overton, L.*: Lumbosacral arthrodesis: an evaluation of its present status. Amer. Surg. 25: 771, 1959.
- Owens, J. M. & Williams, H. G.*: Intervertebral spine fusion with removal of the herniated intervertebral disk. Amer. J. Surg. 70: 24, 1945.
- Pedersen, H. E., Blunck, C. F. J. & Gardner, E.*: The anatomy of lumbosacral posterior rami and meningeal branches of spinal nerves (sinusvertebral nerves). J. Bone Jt Surg. 38: 377, 1956.
- Pennal, G. F., Mc Donald, G. A. & Dale, G. A.*: Stress studies of the lumbo-sacral spine. J. Bone Jt Surg. 46B: 786, 1964.
- Pennybacker, J. B.*: The treatment of traumatic paraplegia (Editorial) J. Bone Jt Surg. 35B: 517—518, 1953.
- Perey, O.*: Contrast medium examination of the intervertebral discs of the lower lumbar spine. Acta orthop. scand. 20: 327, 1951.
- Perey, O.*: Fracture of the vertebral end-plate in the lumbar spine. An experimental biomechanical investigation. Acta orthop. scand. suppl. 25, 1957.
- Petter, C. K.*: Methods of measuring the pressure of the intervertebral disc. J. Bone Jt Surg. 15: 365, 1933.
- Platt, H.*: The backache-sciatica syndrome and the intervertebral disc. J. Bone Jt Surg. 30B: 394, 1948.
- Ponseti, I. V. & Friedman, B.*: Changes in the scoliotic spine after fusion. J. Bone Jt Surg. 32A: 751, 1950.
- Ponseti, I. V.*: pers. com. 1966.
- Poppem, J.*: The herniated intervertebral disc. (An analysis of 400 verified cases. New Engl. J. Med. 232: 211-215, 1945.
- Pouyanne, M. L.*: Lombo-Sciatalgie. Societé internationale chir. orthop. Traumat. V:me Congrès, Stockholm 1951.
- Puig Guri, J.*: The formation and significance of vertebral ankylosis in tuberculous spine. J. Bone Jt Surg. 29A: 136, 1947.
- Putti, V.*: New conceptions in the pathogenesis of sciatic pain. Lancet 2: 53—60, 1927.

*Putti, V.*: Aspetti clinici della degenerazioni del disco intervertebrale, Chir. Organ i Mov. 18, 1, 1933.

*Püschel, J.*: Der Wassergehalt normaler und degenerierter Zwischenwirbelscheiben. Beitr. path. Anat. 84: 123—130, 1930.

*de Quervain, F.*: Zur Behandlung veralteter Wirbelluxationen mittelst Osteoplastik. Bruns' Beitr. klin. Chir. 79: 155, 1912.

*de Quervain, F. & Hoessly, H.*: Operative immobilization of the spine. Surg. Gynec. Obstet 24: 428, 1917.

*Ramser, R.*: Transabdominelle Operation der nichttraumatischen Spondylolisthesis mit einem speziellen Dreilamellennagel und Ersatz der Zwischenwirbelscheibe durch Spongiosa nach reponierender Extensionsvorbehandlung. Helv. med. Acta 10: 365, 1943.

*Raney, F. & Adams, E. J.*: Anterior lumbar disc excision and interbody fusion used as a salvage procedure. University of California medical center, San Francisco 22: 1—16, 1962.

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

*Rauber & Kopsch*: Lehrbuch der Anatomie des Menschen Ed. 19 G. Thieme Verl. 1955.

*Rayerson, E. W.*: Surgical treatment of low back disabilities. J. Bone Jt Surg. 14: 154, 1932.

*Rietz, K.-A.*: Polymer osteosynthesis. Experimental studies with an epoxyresin (Araldite AW 120). Acta chir. scand. 128: 387—401, 1964.

*Riga, I. T. & Robacki, R.*: Beitrag zur entwicklungsgeschichtlichen und betriebsgestaltenden Mechanik der Wirbelsäulenkrümmungen beim Menschen. Anat. Anz. 116: 452—459, 1965.

*Rigby, B. J., Hirai, N., Spikes, J. D. & Eyring, H.*: The mechanical properties of rat tail tendon. J. gen. Physiol. 43: 265—283, 1959.

*Risser J. & Ferguson, A. B.*: Scoliosis. J. Bone Jt Surg. 18: 667, 1936.

*Roaf, R.*: Rotation movements of the spine with special reference to scoliosis. J. Bone Jt Surg. 40B: 312—332, 1958.

*Roaf, R.*: A study of the mechanics of spinal injuries. J. Bone Jt Surg. 42B: 810, 1960.

*Roeren, L.*: Span oder Korsett. Arch. orthop. Unfall-Chir. 22: 126—139, 1924.

*Rolander, S.*: Den mekaniska effektiviteten av lumbala osteosynteser. Paper given at the meeting of the Swedish Med. Soc. dec. 2. 1961.

*Rolander, S.*: Technical problems in lumbar fusions. Acta orthop. scand. 33: 361—362, 1963.

*Rolander, S.*: Reopererade lumbala osteosynteser. Nord. Med. 71: 160, 1964.

*Romanus, R. & Ydén, S.*: Diskography in ankylosing spondylitis. Acta radiol. scand. 38: 431, 1952.

*Roofe, P. G.*: Innervation of annulus fibrosus and posterior longitudinal ligament. Arch. Neurol. Psych., 44: 100, 1940.

*Roux, W.*: Gesammelte Abhandlungen über Entwicklungsmechanik der Organismen. W. Engelmann, Leipzig 1895.

*Rove, G. G. & Roche, M. B.*: The etiology of separate neural arch. J. Bone Jt Surg. 35A: 102—111, 1953.

- Ruff, S.*: Brief acceleration, less than one second. German Aviation Medicine, World War II. U.S. Government Printing Office, Washington 25, D. C. 1: 584, 1950.
- Rådberg, C.*: Diskografi med rörelsestudier i nedre ländryggen. Nord. Med. 52: 1740, 1954.
- Rövig, G.*: Rupture of lumbar discs with intraspinal protrusion of the nucleus pulposus. Acta chir. scand. suppl. 144, 1949.
- Sacks, S.*: Intervertebral disc excision and lumbar spine fusion by a transperitoneal abdominal approach. Pers. com. 1962.
- Sacks, S.*: Anterior interbody fusion of the lumbar spine. J. Bone Jt Surg. 47B: 211—223, 1965.
- Salmon, M. et Contiadès, K. J.*: Traitement Chirurgical du Spondylolisthésis. Rev. Orthop. 20: 193, 1933.
- Schalintzek, M.*: Roentgenological examination of the function of the lumbar spine. Universitetsforlaget Aarhus 1958.
- Schamburov, D.*: Zur operativen Behandlung der Lumbo-ischialgien, die mit Veränderungen der Wirbelsäule verbunden ist. Russkaja klinika. 6: 210, 1926.
- Schantz, A.*: Zur Kenntnis der Spondylitis deformans. Z. orthop. Chir. 53: 42—52, 1931.
- Schmieden, V.*: Chirurgie der Wirbelsäule. Arch. klin. Chir. 162: 388, 1930.
- Schmorl, G.*: Über die an den Wirbelbandscheiben vorkommenden Ausdehnungs- und Zerreißungsvorgänge und die dadurch an ihnen und der Wirbelspongiosa hervorgerufenen Veränderungen. Verh. dtsh. path. Ges. 22. Tag. 250, 1927.
- Schmorl, G. & Junghanns, H.*: Die gesunde und Kranke Wirbelsäule in Röntgenbild und Klinik. Georg Thieme Verlag, Stuttgart 1951.
- Sedlin, E. D.*: A rheologic model for cortical bone. (A study of the physical properties of human femoral samples). Acta orthop. scand. 36 suppl. 83, 1965.
- Sedlin, E. D. & Hirsch, C.*: Factors affecting the determination of the physical properties of femoral cortical bone. Acta orthop. scand. 37: 29—48, 1966.
- Severin, E.*: Degeneration of the intervertebral discs in the lumbar region. Acta chir. scand. 89: 355—378, 1943.
- Shaw, E. G.*: Symposium on lumbo-sacral fusion and low back pain. J. Bone Jt Surg. 37B: 164, 1955.
- Shaw, E. G. & Taylor, J. G.*: The results of lumbo-sacral fusion for low back pain. J. Bone Jt Surg. 38B: 485, 1956.
- Shore, L.*: On osteo-arthritis in the dorsal intervertebral joints. A study in morbid anatomy. Brit. J. Surg. 22: 833, 1935.
- Sicard, A.*: In discussion. Ref. d'Aubigné, M 1952.
- Smith, A. de F.*: A study of autopsy specimens of fused spines and cases subjected to secondary operation. J. Bone Jt Surg. 5A: 507, 1923.
- Smith, A. de F.*: Posterior displacement of the fifth lumbar vertebra. J. Bone Jt Surg. 16A: 877, 1934.
- Smith, A. de F.*: Lumbosacral fusion by the Hibb's technique. Amer. acad. orthop. Surg. instr. course lectures, 9: 41—43, 1952.
- Smith, J. W. & Walmsley, R.*: Factors affecting the elasticity of bone. J. Anat. 93: 503—523, 1959.

- Smith-Petersen, M. N.*: Routine examination of low back cases with particular reference to differential points between lumbo-sacral and sacro—iliac regions. *J. Bone Jt Surg.* 6A: 819, 1924.
- Speed, K.*: Spondylolisthesis. *Surg. Gynec. Obstet* 67: 123, 1938.
- Steindler, A.*: Kinesiology of the human body. Charles C. Thomas, Publ. Springfield, Ill. USA 1955.
- Stock, F. E.*: Anterior spinal fusion. A revue of five years work. *Austr. N. Z. J. Surg.* 31/3: 161—170, 1962.
- Strait, L. A., Inman, V. T. & Ralstone, J. H.*: Sample illustrations of physical principles selected from physiology and medicine. *Amer. J. Physics.* 15: 375, 1947.
- Strasser, H.*: Lehrbuch der Muskel und Gelenkmechanik. Vol. II Verlag Springer, Berlin 1913.
- Street, D. M.*: Foraminotomi and fusion following disc surgery. *J. Bone Jt Surg.* 39A: 223, 1957.
- Straub, L. R.*: Lumbo-sacral fusion by metallic fixation and grafts. *J. Bone Jt Surg.* 31B: 478, 1949.
- Sullivan, C. R. & Bickel, W. H.*: The problem of traumatic spondylolisthesis. A report of three cases. *Amer. J. Surg.* 100: 698—708, 1960.
- Swift, W. E.*: End result study of the spine-fusion operation for tuberculosis of the spine. *J. Bone Jt Surg.* 22A: 815, 1940.
- Sylvén B., Paulson, S., Hirsch, C. & Snellman, O.*: Biophysical and physiological investigations on cartilage and other mesenchymal tissues. II. The ultrastructure of bovine and human nuclei pulposi. *J. Bone Jt Surg.* 33A: 333—340, 1951.
- Söderberg, L.*: Prognosis in conservatively treated sciatica. *Acta orthop. scand. suppl.* 21, 1956.
- Taillard, W.*: Le spondylolisthesis chez l'enfant et l'adolescent. *Acta orthop. scand.* 24: 115, 1955.
- Tanz, S. S.*: Motion of the lumbar spine. A roentgenologic study. *Amer. J. Roentgenol.* 69: 399—412, 1953.
- Tavernier, L.*: Traitement operatoire des scoliozes. *Arch. franco-belges chir.* 34: 1, 1934.
- Teichert, G.*: Zur Morphologie und Funktion des Nucleus Pulposus. *Z. Orthop.* 95: 330, 1962 a.
- Teichert, G.*: Das Vakuum-Phenomen in der Zwischenwirbelscheibe, die Spontandarstellung des Nucleus- (Spalt) Raumes. *Z. Orthop.* 96: 148, 1962 b.
- Thompson, W. A. L. & Ralston, E. L.*: Pseudarthrosis following spine fusion. *J. Bone Jt Surg.* 400A: 31, 1949.
- Thompson, H. C.*: Effect of drilling into bone. *J. oral Surg.* 16: 22—30, 1958.
- Tideström, F.*: Rygggradens vridningsmekanism. *Nord. Med.* 59: 736, 1958.
- Todd, T. W. & Pyle, I. S.*: A quantitative study of the vertebral column by direct and roentgenologic methods. *Amer. J. Phys. Anthr.* 12: 321, 1928.
- Truchly, G. & Thompson, W. A. L.*: Posterolateral fusion of the lumbosacral spine. *J. Bone Jt Surg.* 44A, 1962.
- Tsukada, K.*: Histologische Studien über die Zwischenwirbelscheiben Befunde des Foetus. *Mitt. Akad. Kioto* 24: 1172, 1938.

- Töndury, G.*: Zur Anatomie und Entwicklungsgeschichte der Wirbelsäule mit besonderer Berücksichtigung der Altersveränderungen der Bandscheiben. Schweiz. med. Wschr. 85: 825, 1955.
- Turner, H. & Markellow, N. S.*: Die Röntgendiagnostik der Spondylolysis im Lichte experimenteller Forschung am Kadaver. Acta chir. scand. 57: 914, 1930.
- Tylman, D. & Ramotovsky, W.*: Study of strength of particular elements of the spine. Chir. Narzadow Ruchu Orthopedia polska 26, 21, 1961.
- Unander-Scharin, L.*: A case of spondylolisthesis lumbalis acquisita. Acta orthop. scand. 19: 536, 1950 a.
- Unander-Scharin, L.*: On low-back pain with special reference to the value of operative treatment with fusion. Acta orthop. scand. suppl. 5, 1950 b.
- Unander-Scharin, L.*: Spinal fusion in low back pain. Acta orthop. scand. 20: 335, 1951.
- Urist, M. R.*: Bone: Transplants, implants, derivatives, and substitutes — a survey of research of the past decade. Amer. acad. Orthop. Surg. instr. course lecture 17: 184—195, 1960.
- Verzár, F.*: The ageing of connective tissue. Gerontologia 1: 363—378, 1957.
- Verzár, F.*: The ageing of collagen. Scientific American 208: 104, 1963.
- Viidik, A. & Lewin, T.*: Changes in tensile strength characteristics and histology of rabbit ligaments induced by different modes of postmortal storage. Acta orthop. scand. 37: 141—155, 1966.
- Viidik, A., Sandqvist, L. & Mägi, M.*: Influence of postmortal storage on tensile strength characteristics and histology of rabbit ligaments. Acta orthop. scand. suppl. 79, 1965.
- Virchow, H.*: Einzelbeiträge bei der sagittalen Biegung der menschlichen Wirbelsäule. Anat. Anz. 38: 180, 1911.
- Virchow, H.*: Die sagittale flexorische Bewegung der menschlichen Halswirbelsäule. Arch. orthop. Unfall-Chir. 26: 1—42, 1928.
- Virgin, W. J.*: Experimental investigations into the physical properties of the intervertebral disc. J. Bone Jt Surg. 33B: 607, 1951.
- Virgin, W. J.*: Anatomical and pathological aspects of the intervertebral disc. Indian J. Surg. 20: 113, 1958.
- Wagner, L. C.*: Congenital defects of the lumbosacral joints with associated nerve symptoms. Am. J. Surg. 27: 311—327, 1935.
- Waldenström, H.*: Die Behandlung des Tuberkulösen Gibbus mit Osteosynthese nach allmählichem Redressment. Z. orthop. Chir. 45: 595, 1924.
- Walker L. B. Jr, Harris, E. H. & Benedict, J. V.*: Stress-strain relationship in human cadaveric plantaris tendon: A preliminary study. Med. electron. Biol. Eng. 2: 31, 1964.
- Watkins, M. B.*: Posteriolateral fusion of the lumbar and lumbosacral spine. J. Bone Jt Surg. 35A: 1014, 1953.
- Watkins, M. B.*: Posteriolateral bone-grafting for fusion of the lumbar and lumbo-sacral spine. J. Bone Jt Surg. 41A: 388, 1959.
- Watson-Jones, R.*: 1938. Quoted by Friberg 1939.
- Watson-Jones, R.*: Fractures and joint injuries. Livingstone Ltd, 2: 951—967, London 1955.

- Waugh, T.*: Strength of vertebral arches. Pers. com. 1966.
- Waygiel, E.*: Zur Technik der operativen Versteifung der Wirbelsäule. Zbl. Chir. 49: 1216—1217, 1922.
- Whitman, R.*: The operative treatment of deformity of Pott's disease. Ann. Surg. 54, 1911.
- Wiberg, G.*: Back pain in relation to the nerve supply of the intervertebral disc. Acta orthop. scand. 19: 211, 1949.
- Wiles, P.*: Movements of lumbar vertebra during flexion and extension. Proc. roy. Soc. Med. 28: 647, 1935.
- Wiley, A. M. & Trueta, J.*: The vascular anatomy of the spine and its relation to pyogenic vertebral osteomyelitis. J. Bone Jt Surg. 41B: 796, 1959.
- Wilkins, W. F.*: 1886. Quoted by Henle A. 1926.
- Wilkins, W. F.*: Separation of the vertebrae with Protrusion of Hernia Between the same. S:t Louis med. surg. J. 54: 340, 1888.
- Williams, M.*: "Operative surgery", vol. 5, Butterworth & Co (Publishers) Ltd. 1950.
- Williams, P. C. & Yglesias, L.*: Lumbosacral facetectomy for post-fusion persistent sciatica. J. Bone Jt Surg. 15: 579, 1933.
- Williams, P. C.*: Lesions of the lumbosacral spine. Part I. Acute traumatic destruction of the lumbosacral intervertebral disc. J. Bone Jt Surg. 19: 343, 1937.
- Willis, T. A.*: Backache from vertebral anomaly. Surg. Gynec Obstet 38: 112, 1924.
- Willis, T. A.*: Backward displacement of the fifth lumbar vertebra: an optical illusion. J. Bone Jt Surg. 17: 347—352, 1935.
- Willis, T. A.*: Anatomical variations and roentgenographic appearance of the low back in relation to sciatic pain. J. Bone Jt Surg. 23A: 410, 1941.
- Wilson, P. D. & Straub, L.*: Lumbosacral fusion with metallic-plate fixation. Amer. acad. Orthop. Surg. instr. course lect. 9: 53, 1952.
- Wiltberger, B. R.*: Surgical treatment of degenerative disease of the back. J. Bone Jt Surg. 45A: 1509—1516, 1963.
- Wiltse, L. L.*: Transverse process fusion. Spectator 1964.
- Witt, A. N., Cotta, H. & Hohmann, D.*: Experimentelle Untersuchungen der metallischen Osteosynthese der Wirbelsäule unter Bezugnahme auf die praktische Anwendung. Arch. orthop. Unfall-Chir. 51: 410—421, 1959.
- Young, R. H. & Burns, B. H.*: Results of surgery in sciatica and low back pain. Lancet i: 245, 1951.
- Young, H. H. & Love, J. G.*: End results of removal of protruded lumbar discs with and without fusion. Amer. acad. Orthop. Surg. instr. course lectures 16: 213, 1959.
- Zarek, J.*: pers. com. 1966.
- Übermuth, H.*: Die Bedeutung der Altersveränderungen der menschlichen Bandscheiben für die Pathologie der Wirbelsäule. Arch. klin. Chir. 156: 567, 1930.
- Åkerblom, B.*: Standing and sitting posture. AB Nordiska Bokhandeln, Stockholm 1948.