Photo-elastic Study on Lumbosacral Spine Fusion

by

KIYOSHI OHTANI

From the Department of Orthopaedic Surgery, School of Medicine, Keio University
(Director : Prof. Dr. TORAI IWAHARA)
Received for Publication Jan. 20, 1965

INTRODUCTION

The indications for spine fusion are considerably different now, many more fusions are performed for congenital, traumatic, and degenerative lesions and fewer for infective processes. Currently, spine fusion is performed chiefly for pathology in the lumbar or lumbosacral region. The indications and technics of spine fusion have being varied from year to year.

Fixation of the unstable spine by spine fusion is a prefered method of treatment in spondylolysis and spondylolisthesis at the present. Successful fusion strengthens the back, relieves symptoms, and enables the patient to be tolerable in hard work.

The operations for fusion of the spine are generally of two groups, viz. the anterior spine fusion and the posterior spine fusion. The posterior spine fusion was based upon the principles originated by ALBEE and HIBBS in 1911, the anterior spine fusion was conceived for the first time by CAPENER in 1923. In 1942, the anterior spine fusion by extraperitoneal approach was performed by Prof. TORAI IWAHARA at KEIO University Hospital. Since then, this method has been employed as the routine procedure we use for spondylolysis and spondylolisthesis.

From 1942 through 1961, the anterior spine fusion on 58 cases and the posterior spine fusion on 37 cases were performed at KEIO University Hospital. Follow up studies were presented in 1962, and the results were proven more satisfactory in the anterior spine fusion.

In order to analyze the dynamic characteristics of the lumbosacral spine fusion, the author investigated the photo-elastic experiments on the lumbosacral spine fusion under the cooperation of the photo-elastic department of RIKAGAKU KENKYUSHO in Tokyo.

PHOTO-ELASTIC STUDIES OF TWO DIMENSIONS

(1) The artificial models of the experimental planes : The measurements of the artificial models were referred to the postmortal vertebral body and intervertebral disc and to the transverse roentgenographical films showing the fourth and the fifth lumbar vertebrae of the Japanese adult.

For the construction of the models, the fourth lumbar vertebra (L_4), the fifth lumbar vertebra (L_5), the first sacral vertebra (S_1), and the intervertebral discs between those

vertebrae were prepared. The fusion of spinous processes and fusion of vertebral archs are firmly fused at the regions of spinous processes and vertebral archs of L_4, L_5, and S_1 one another. And the anterior spine fusion is fused at the anterior part of the vertebral bodies of L_5 and S_1 each other.

The YOUNG's ratio of the postmortal vertebral column of the Japanese adult is approximately 265.50 kgm/cm² in vertebral body and 107.23 kgm/cm² in intervertebral disc according to ARIGA's reports (1953). The experimental planes of vertebral bodies and intervertebral discs are optically fused each other.

σ max. means maximal stress and σ min. means minimal stress, and the following expression is concluded dynamically, $\sigma \max. = c\frac{l}{\rho}$ (c : constant l : distance between the point at stress measurement and the point bearing weight ρ : the radius of curvature). Therefore, it is natural that every experimental plane should be precisely made to be the same size and same radius of curvature. In these photo-elastic experiments, the planes having almost as large in size as life and the radius of curvature of corner of the experimental planes with 3 mm in diameter were made.

(2) The material of the experimental plane : The material is D. A. P. (Diallyl Phthalate), which is gradually heated at about 80 degrees of Celsius for two or three hours in a small bath-tub under the catalysis of benzoic peroxide. The heated D. A. P. is carefully poured into the space between two glass plates which have been heated at about 60 degrees of Celsius previously, and then it is cooled down slowly to a normal temperature. The YOUNG's ratio of D. A. P. resin plate is refered to the heat and cooling procedure of D. A. P., thus, the procedure of making plane has to be carefully done.

EXPERIMENTAL METHODS

The photo-elastic experiments are as follows,

I. The normal lumbosacral vertebral column, the fusion of spinous processes, the fusion of vertebral archs, and the anterior spine fusion of the one third in A–P diameter of the vertebra (the 1/3 anterior spine fusion).

II. The 1/3 anterior spine fusion, the 1/2 anterior spine fusion, the 2/3 anterior spine fusion, and the whole fusion of the intervertebral space.

The photo-elastic apparatuses were used of the photo-elastic department of RIKAGAKU KENKYUSHO. The every load of the photo-elastic experiments was exactly determined 60 kgm in weight.

MEASUREMENTS OF THE PHOTO-ELASTIC EXPERIMENTS

(1) The fringe photograph :

The dark-field photograph shows the fringes which are get from the two polarizers with right angle position, and also the light-field photograph shows the fringes which are get from the two polarizers with parallel position.

There is optically a difference of one fourth wave length between the dark and light field photographs. It is always necessary to get the dark and light field photographs in the photo-elastic study in order to analyze the stress distribution.

(2) The stress analysis:

The stress is closely analyzed from the dark and light field photographs. The fringe orders are an expression of the quantitative distribution of stress: that is, they are lines connecting points under equal stress.

In this experiment, a fringe order deserves 0.2087 kgm/mm^2 in the vertebral body plane and 0.1083 kgm/mm^2 in the intervertebral disc plane as a sequel to calculation of stress analysis. Therefore it is not so difficult to measure the stresses in all parts of the vertebral body and disc planes. There are no differences between the compression and traction stress in fringe order, but it is fairly necessary to differentiate these stresses in order to know the shearing stress distribution as mention below. The compression stress is usually marked positive and traction stress is marked negative in the signature.

(3) The isoclinic lines:

As the direction of principal stress changes usually in every part of the experimental plane, a curved line is described on the plane by connecting the points on the experimental plane where the direction of the principal stress is equal. It is called an isoclinic line.

On the change of direction of the principal stress, a chart which shows as inclination of the principal stresses is described on the experimental plane.

There is the point or line which is made by collecting together the isoclinic lines, and it is called the singular point or line. The existence of singular point or line means the shearing stress distribution.

(4) The line of principal stress:

The directions of two principal stresses on every part of the experimental plane are just described as the meshlike curves with a right angle position each other. These curves are called the lines of principal stress which are easily analyzed from the isoclinic lines.

In the photo-elastic study, it is most important to analyze the isoclinic lines and the lines of principal stress.

RESULTS OF THE EXPERIMENTS

I. The normal lumbosacral vertebral column, the fusion of spinous processes, the fusion of vertebral archs, and the 1/3 anterior spine fusion.

The normal lumbosacral vertebral column:

The σ max. of L_4, L_5, and S_1 is located on the posterior edge of these vertebral bodies. The concentration of these σ max. is 0.4171 kgm/mm^2 of L_4, 0.6261 kgm/mm^2 of L_5, and 0.6261 kgm/mm^2 of S_1. The σ min. of L_4, L_5, and S_1 is located on the anterior edge of these vertebral bodies. The concentration of these σ min. is 0.1043 kgm/mm^2.

Of the stress distribution of the intervertebral disc, the σ max. is located on the posterior edge of the intervertebral discs L_4–L_5 and L_5–S_1. The concentration of these σ max. is 0.7581 kgm/mm^2 of the disc between L_4 and L_5, and 0.6498 kgm/mm^2 of the disc between L_5 and S_1. The σ min. is located on the anterior edge of the intervertebral discs. The concentration of these σ min. is 0.1083 kgm/mm^2 of the disc between L_4 and L_5, and 0.0541 kgm/mm^2 of the disc between L_5 and S_1 (Fig. 1-A, 1-B, 2-A, and 2-B).

The lines of principal stress of the vertebral bodies and intervertebral discs tend to be

Fig. 1-A The light-field photograph of the normal lumbosacral vertebral column shows the distibution of many fring-orders of the posterior parts of the vertebral bodies and intervertebral discs.

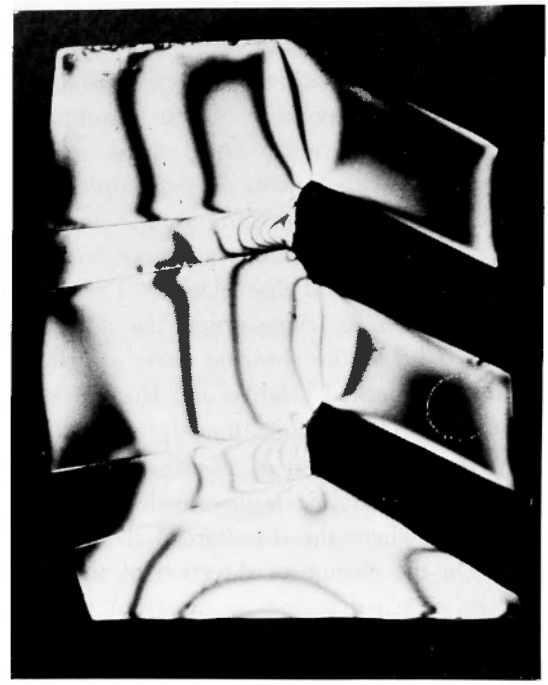


Fig. 1-B The dark-field photograph of the normal lumbosacral vertebral column which differentiates one-fourth wave length to the light-field photograph shows the same distribution of the fringe-orders to the light-field photograph.

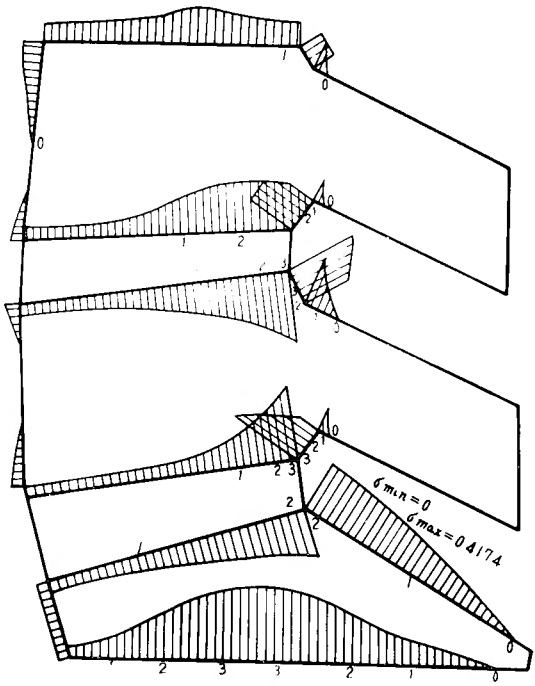


Fig. 2-A The surface stress distribution of the normal lumbosacral vertebral bodies. It's σ max. is located on the posterior edge of the vertebral bodies and it's σ min. is located on the anterior edge of the vertebral bodies.

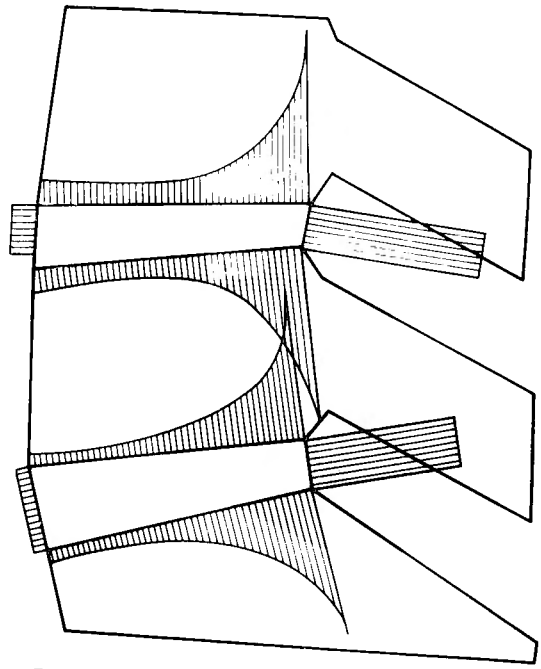


Fig. 2-B The surface stress distribution of the normal lumbosacral intervertebral discs. It's σ max. is located on the posterior edge of the intervertebral discs and it's σ min. is located on the anterior edge of the intervertebral discs.

localized upon the posterior part of the vertebral bodies and intervertebral discs (Fig. 3-A and 3-B).

The fusion of spinous processes:

The concentrated stresses are distributed on the anterior edge of the grafted site. The σ max. of L_4 and S_1 is 1.8723 kgm/mm^2, and it is located on the grafted site of spinous processes. The σ max. of L_5 is 1.6706 kgm/mm^2, and it is also located on the grafted site of spinous processes. The σ min. of the vertebral bodies is located on the posterior edge.

The σ max. of intervertebral discs is 0.6498 kgm/mm^2, and it is located on the anterior edge. The σ min. of intervertebral discs is located on the posterior edge (Fig. 4-A, 4-B, 5-A, and 5-B).

The isoclinic lines produce two singular points in the grafted site (Fig. 6-A).

The lines of principal stress are considerably concentrated at the grafted site of spinous processes (Fig. 6-B).

The fusion of vertebral archs:

There are the concentrated stresses at the anterior edge of the grafted site. The σ max. distributes at the grafted site of the vertebral archs, of which concentration is 1.6706 kgm/mm^2. The σ min. is distributed at the posterior edge of the vertebral bodies.

In the intervertebral discs, a concentration of stress distribution is increased on the anterior edge, it is 0.6498 kgm/mm^2, and it is decreased to 0.0541 kgm/mm^2 in the posterior edge (Fig. 7-A, 7-B, 8-A, and 8-B).

Four singular points of isoclinic lines appear in the grafted site of vertebral archs (Fig. 9-A).

The distribution of lines of principal stress is considerably concentrated in the grafted site of vertebral archs (Fig. 9-B).

The 1/3 anterior spine fusion:

The σ max. of L_4 is located on the posterior edge of vertebral body, it is 0.4174 kgm/mm^2, and the σ min. of L_4 is located on the anterior edge of vertebral body, it is 0.1043 kgm/mm^2. But in the L_5 and S_1, the concentration of stress distribution is transferred to the posterior edge of grafted site, of which σ max. is 1.2522 kgm/mm^2.

The stress distribution of intervertebral disc between L_4 and L_5 is concentrated in the posterior edge, of which σ max. is 0.5414 kgm/mm^2. And also the stress distribution of intervertebral disc between L_5 and S_1 is concentrated in the posterior edge. The σ min is located on the anterior edge of intervertebral discs (Fig. 10-A, 10-B, 11-A, and 11-B).

The isoclinic lines produce the singular line in the grafted site of the vertebral bodies (Fig. 12-A).

The lines of principal stress tend to be localizd upon the grafted site of the vertebral bodies (Fig. 12-B).

II. The 1/3 anterior spine fusion, the 1/2 anterior spine fusion, the 2/3 anterior spine fusion, and the whole fusion of the intervertebral space.

The 1/3 anterior spine fusion;

As mentioned above.

The 1/2 anterior spine fusion:

The concentration of stress distribution of L_4 increases in the posterior edge and

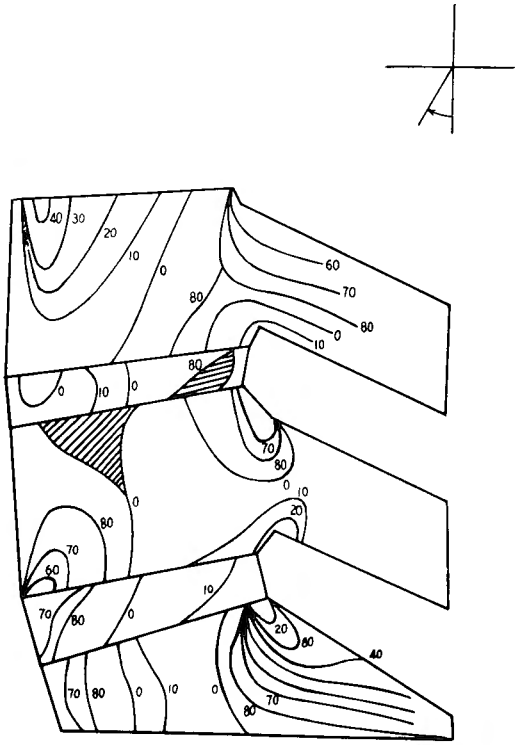


Fig. 3-A The isoclinic lines of the normal lumbosacral vertebral column.

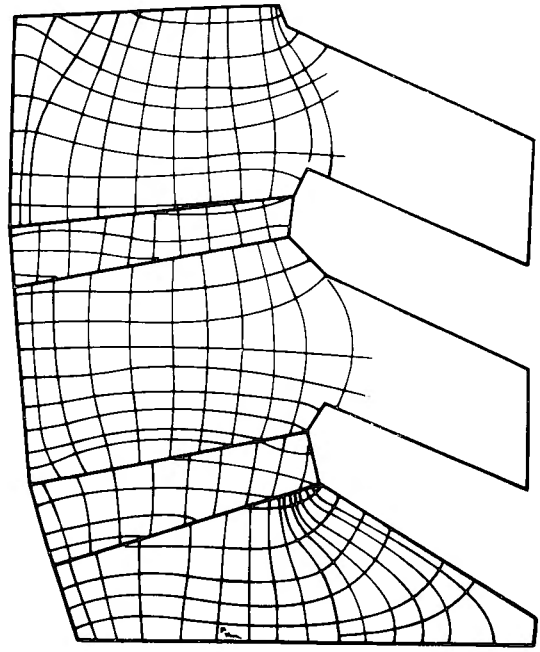


Fig. 3-B The lines of principal stress of the normal lumbosacral vertebral column, which are apt to be localizd upon the posterior parts of the vertebral bodies and intervertebral discs.

Fig. 4-A The light-field photograph of the fusion of spinous processes shows the distribution of many fringe-orders on the anterior part of the grafed site.

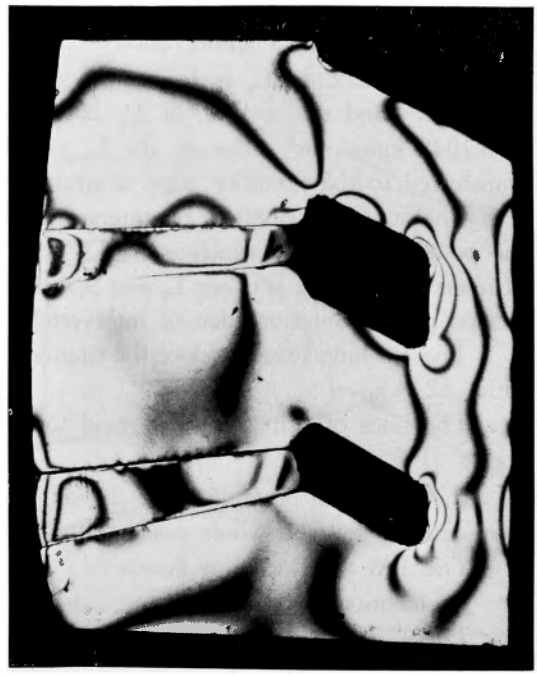


Fig. 4-B The dark-field photograph of the fusion of spinous processes.

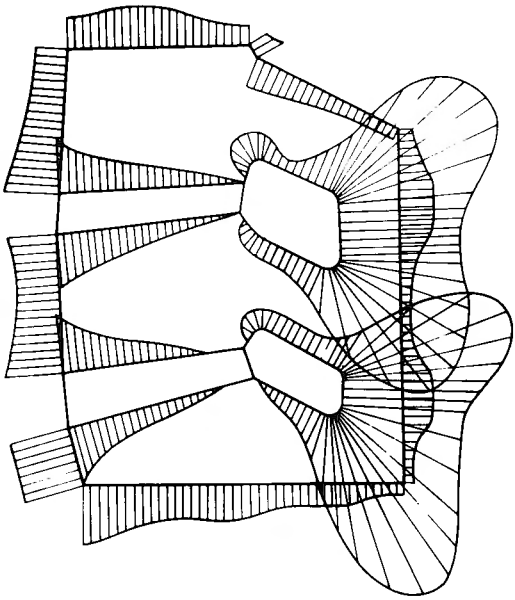


Fig. 5-A The surface stress distribution of the vertebral bodies of the fusion of spinous processes. It's σ max. is located on the anterior edge of the grafted site and it's σ min. is located on the posterior port of the vertebral bodies.

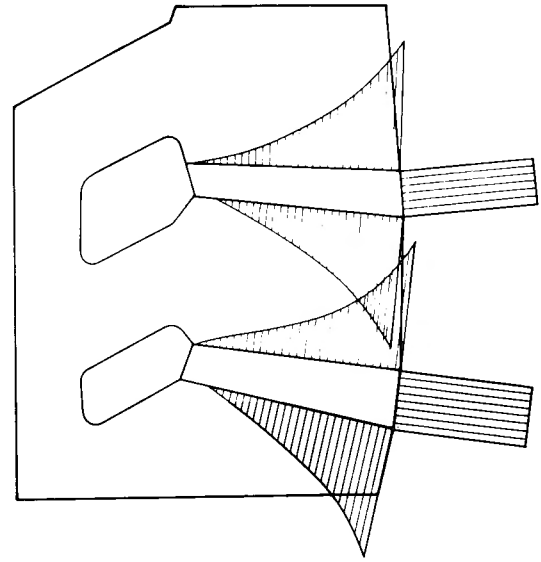


Fig. 5-B The surface stress distribution of the intervertebral discs of the fusion of spinous processes. It's σ max. is located on the anterior edge of the intervertebral discs and it's σ min. is located on the posterior part of the intervertebral discs.

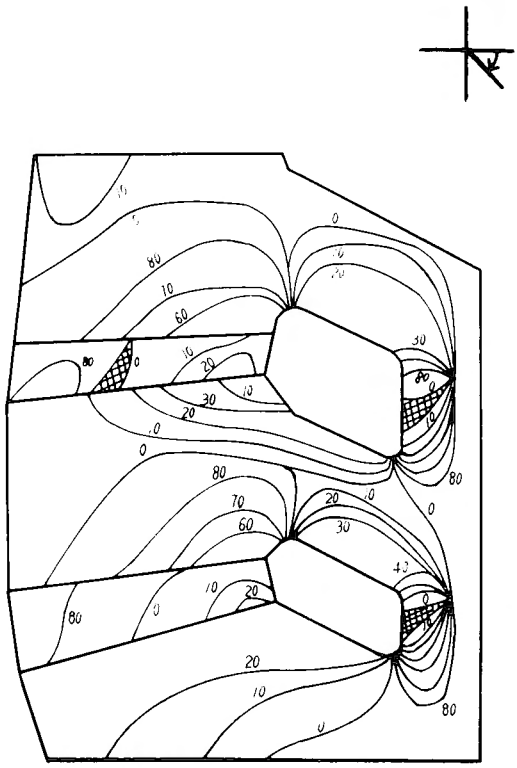


Fig. 6-A The isoclinic lines of the fusion of spinous processes, which is produced two singular points in the graft.

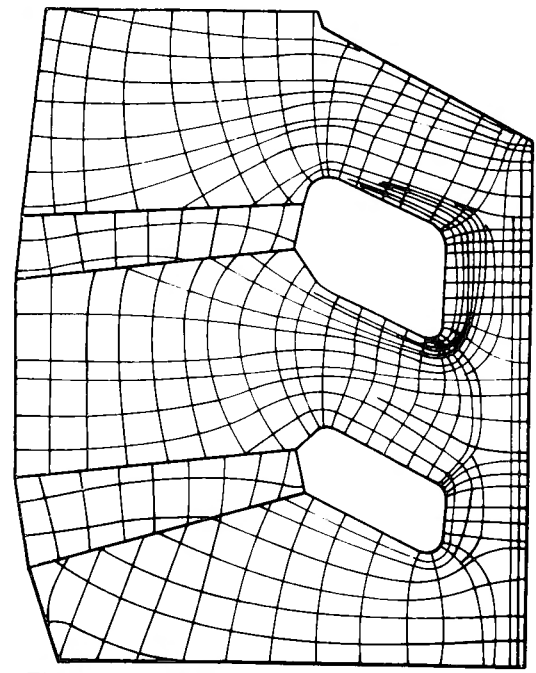


Fig. 6-B The lines of principal stress of the fusion of spinous processes is localized upon the anterior part of the grafted site.

Fig. 7-A The light-field photograph of the fusion of vertebral archs shows the distribution of many fringe-orders on the anterior part of the grafted site.

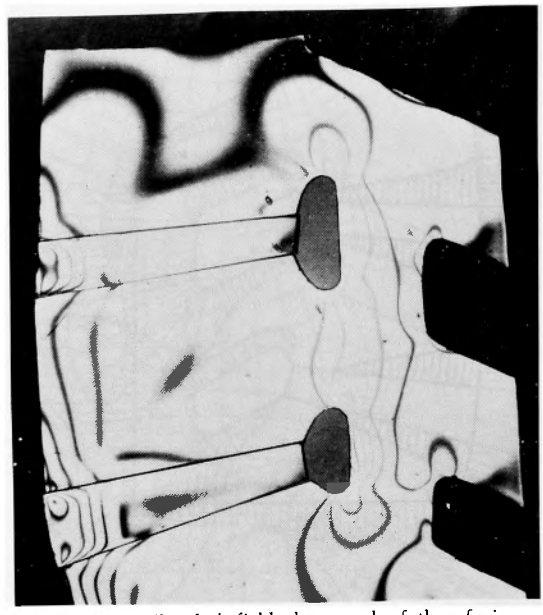


Fig. 7-B The dark-field photograph of the fusion of vertebral archs.

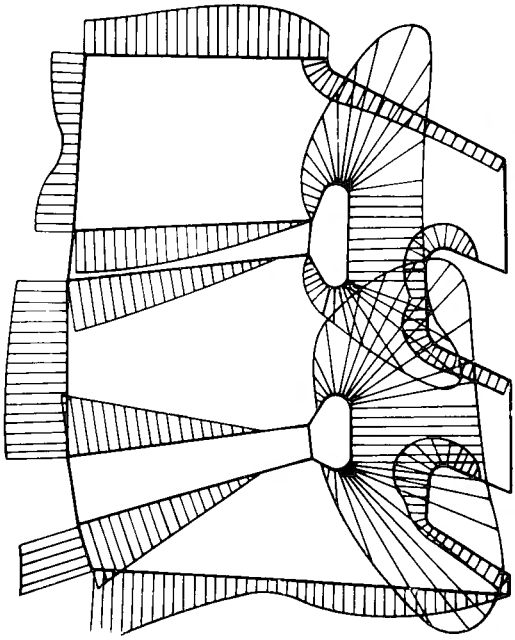


Fig. 8-A The surface stress distribution of the vertebral bodies of the fusion of vertebral archs. It's σ max. is located on the anterior edge of the grafted site and it's σ min. is located on the posterior part of the vertebral bodies.

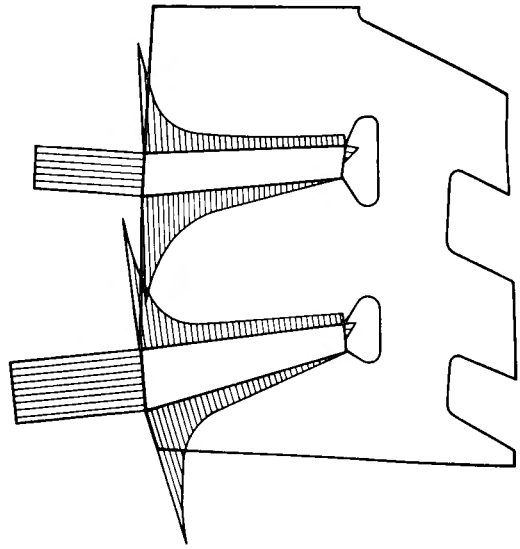


Fig. 8-B The surface stress distribution of the intervertebral discs of the fusion of vertebral archs. It's σ max. is located on the anterior edge of the intervertebral discs and it's σ min. is located on the posterior edge of the intervertebral discs.

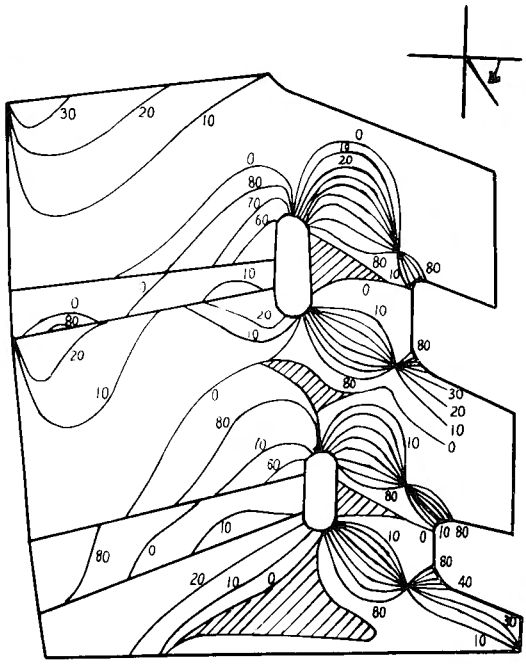


Fig. 9-A The isoclinic lines of the fusion of vertebral archs produce four singular points in the grafted site.

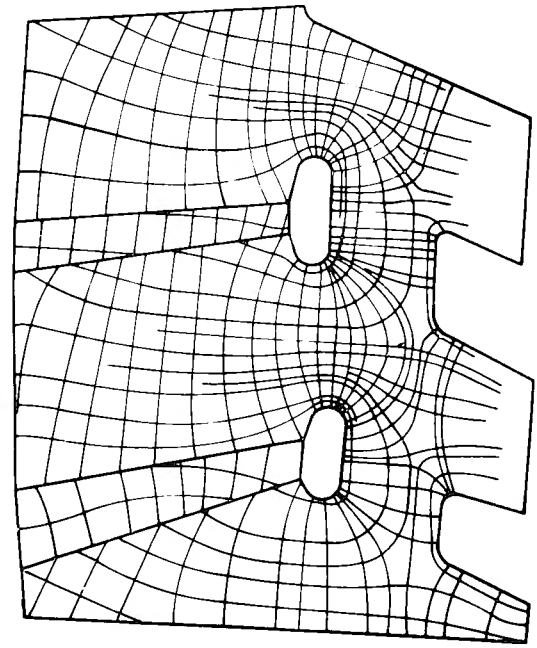


Fig. 9-B The distribution of the line of principal stress of the fusion of vertebral archs is localized upon the grafted site especially the anterior part.

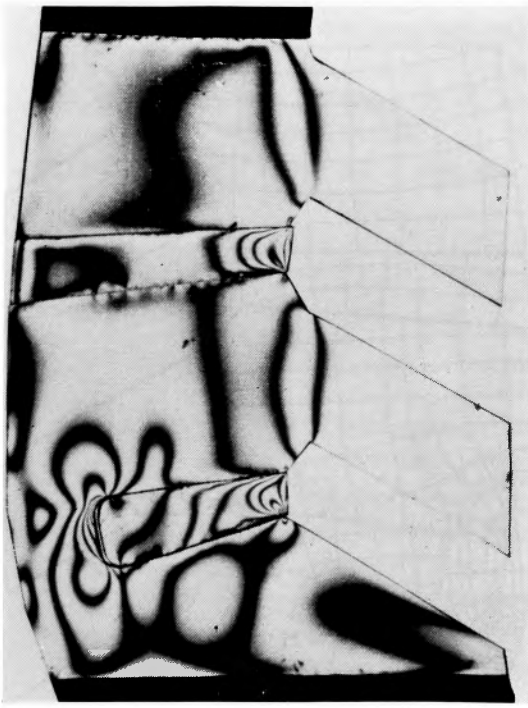


Fig. 10-A The light-field photograph of the 1/3 anterior spine fusion shows the distribution of many fringe-orders on the posterior part of the grafted site.

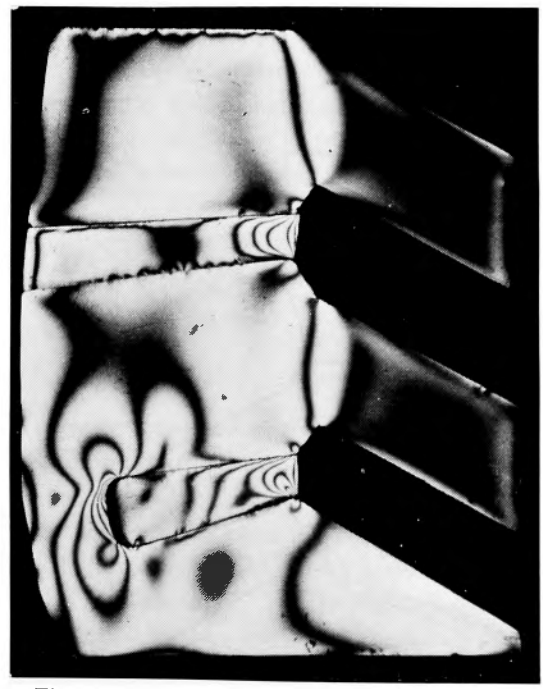


Fig. 10-B The dark-field photograph of the 1/3 anterior spine fusion.

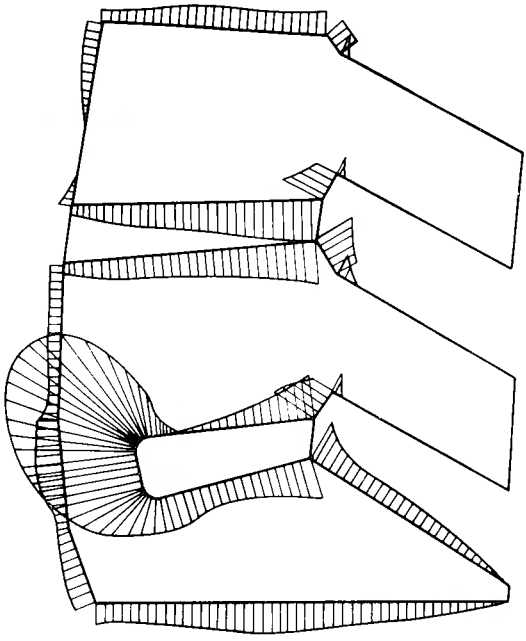


Fig. 11-A The surface stress distribution of the vertebral bodies of the 1/3 anterior spine fusion. It's σ max. is located on the posterior edge of the grafted site and it's σ min. is located on the anterior edge of the vertebral bodies.

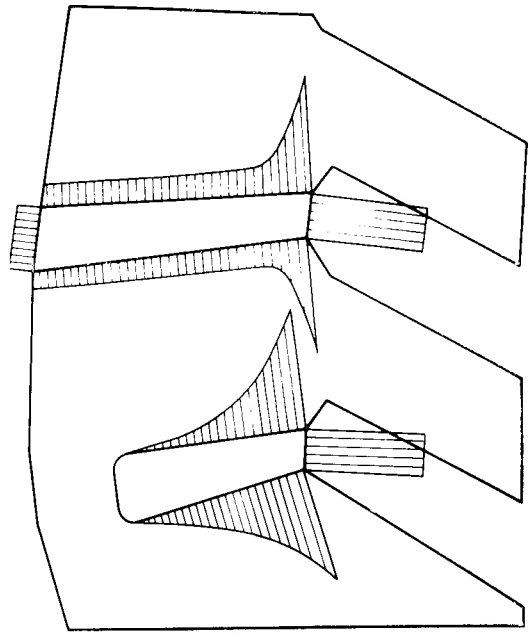


Fig. 11-B The surface stress distribution of the intervertebral discs of the 1/3 anterior spine fusion. It's σ max. is located on the posterior edge of the intervertebral discs and it's σ min. is located on the anterior part of the intervertebral discs.

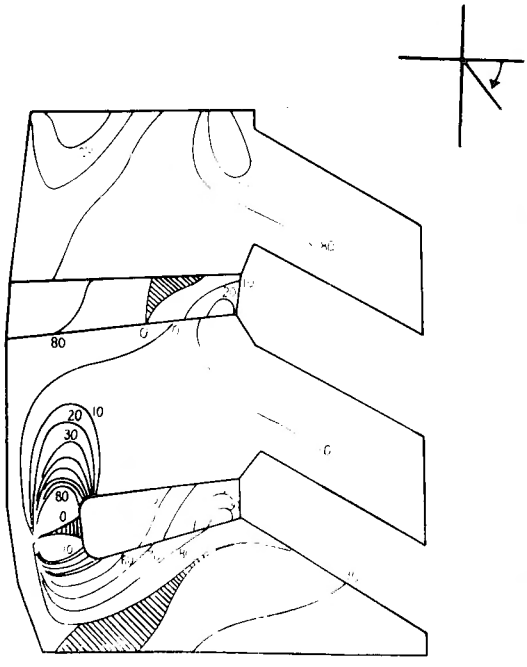


Fig. 12-A The isoclinic lines of the 1/3 anterior spine fusion produce the singular line in the grafted site.

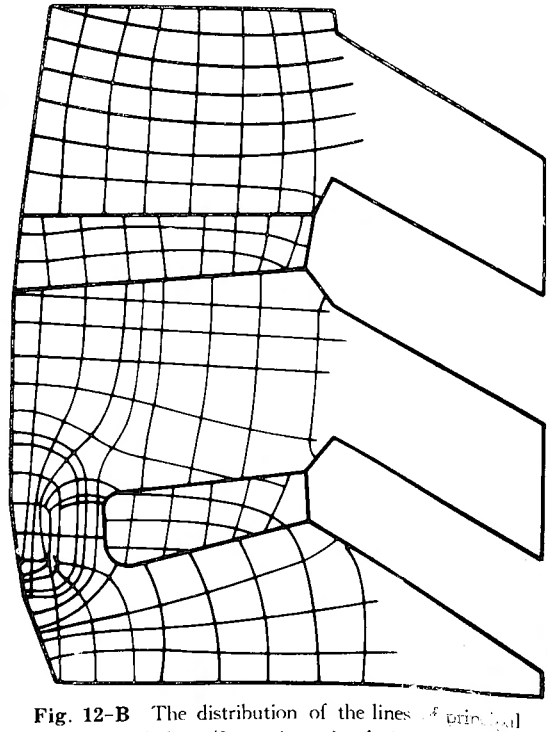


Fig. 12-B The distribution of the lines of principal stress of the 1/3 anterior spine fusion is localized considerably upon the grafted site.

decreases in the anterior edge, the σ max. is 0.3130 kgm/mm^2, the σ min. is 0.1043 kgm/mm^2. On the other hand, in the L_5 and S_1, the concentration of stress distribution is transferred to the posterior edge of grafted site, of which σ max. is 0.8348 kgm/mm^2.

The stress of intervertebral disc between L_4 and L_5 being accompanied with the σ max. of 0.4332 kgm/mm^2, is distributed in the posterior edge, the σ min. of 0.0541 kgm/mm^2 is in the anterior edge of the intervertebral disc. And also the stress distribution of intervertebral disc between L_5 and S_1 is concentrated in the posterior edge, of which σ max. is 0.3249 kgm/mm^2 (Fig. 13-A, 13-B, 14-A, and 14-B).

There is no singular point or line of the isoclinic lines in the grafted site. But the distribution of lines of principal stress tends to be concentrated in the posterior parts of vertebral bodies and grafted site (Fig. 15-A and 15-B).

The 2/3 anterior spine fusion:

There is still the tendency with a concentrated stress distribution. And 0.4171 kgm/mm^2 of the σ max. of vertebral bodies is located on the posterior edge, 0.1043 kgm/mm^2 of the σ min. of vertebral bodies is located on the anterior edge.

And also the stress distribution of the intervertebral discs is concentrated in the posterior edge, the σ max. of the intervertebral disc between L_4 and L_5 is 0.4510 kgm/mm^2, and the σ max. of the intervertebral disc between L_5 and S_1 is 0.3249 kgm/mm^2 (Fig. 16, 17-A, and 17-B).

There is no singular point or line, and the lines of principal stress distribute almost without discrimination in the vertebral bodies and intervertebral discs (Fig. 18-A and 18-B).

The whole fusion of the intervertebral space:

The stress distribution tends to be localized upon the posterior edge of vertebral bodies, the σ max. is 0.4171 kgm/mm^2, and the σ min. is 0.0541 kgm/mm^2.

And also in the intervertebral disc, the σ max. is located on the posterior edge, it is 0.3249 kgm/mm^2. And the σ min. is located on the anterior edge, it is 0.0541 kgm/mm^2 (Fig. 19 and 20).

As in the 2/3 anterior spine fusion, there is no singular point or line, and the lines of principal stress distribute almost equally in the vertebral bodies and intervertebral disc (Fig. 21-A and 21-B).

SUMMARY

If compared the stress distribution of the 1/3 anterior spine fusion, the fusion of spinous processes, and the fusion of vertebral archs, the concentration of stress distribution is located on the inferior edge of the grafted site of these fusions, but the maximum of those localized stresses is located on the grafted site of the fusion of spinous processes, it's concentration is 1.8723 kgm/mm^2. The minimum of those localized stresses is located on the grafted site of the 1/3 anterior spine fusion, it's concentration is 1.2522 kgm/mm^2. In the stress distribution of intervertebral discs, the maximum of stresses is located on the anterior edge of the fusion of spinous processes and fusion of vertebral archs, it's concentration is 0.6498 kgm/mm^2. On the other hand, the minimum of stresses in the intervetebral discs of the 1/3 anterior spine fusion is located on the posterior edge, it's concentration is 0.5414 kgm/mm^2

Fig. 13-A The light-field photograph of the 1/2 anterior spine fusion shows the distribution of many fringe-orders in the posterior part of the grafted site.

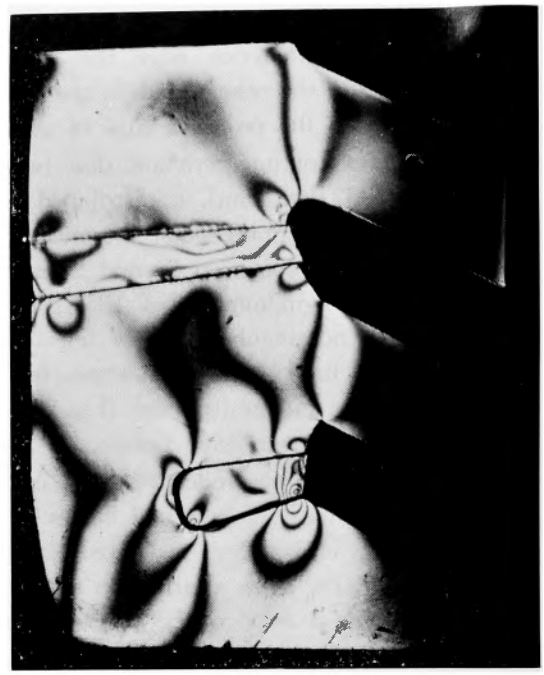


Fig. 13-B The dark-field photograph of the 1/2 anterior spine fusion.

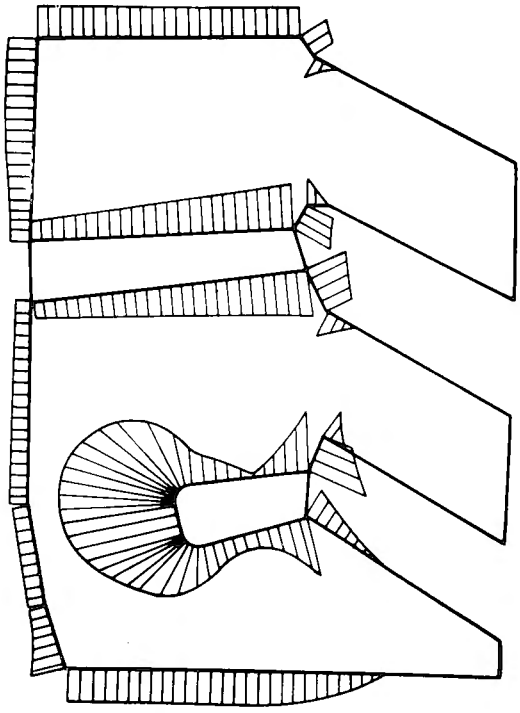


Fig. 14-A The surface stress distribution of the vertebral bodies of the 1/2 anterior spine fusion. It's σ max. is located on the posterior edge of the grafted site and it's σ min. is located on the anterior parts of the vertebral bodies.

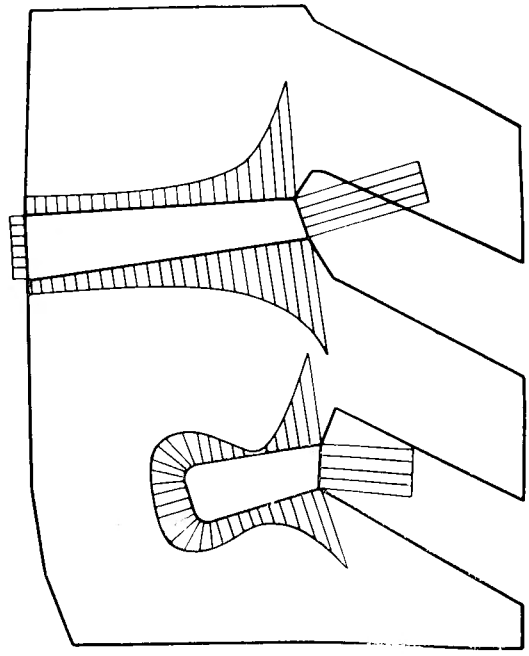


Fig. 14-B The surface stress distrib tion of the intervertebral discs of the 1/2 ante r spine fusion. It's σ max. is located on the po lge of the intervertebral discs and it's σ m ted on the anterior pars of the interver s

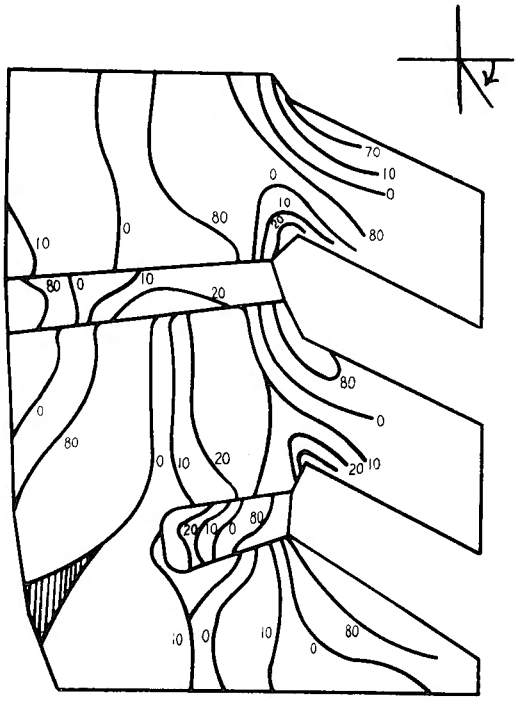


Fig. 15-A The isoclinic lines of the 1/2 anterior spine fusion. There is no singular point or line in the grafted site.

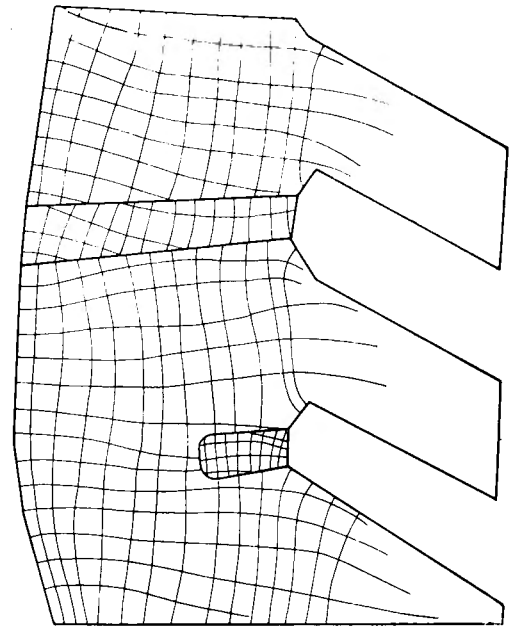


Fig. 15-B The lines of principal stress of the 1/2 anterior spine fusion, of which distribution is not apt to is localized in the vertebral bodies and intervertebral discs.

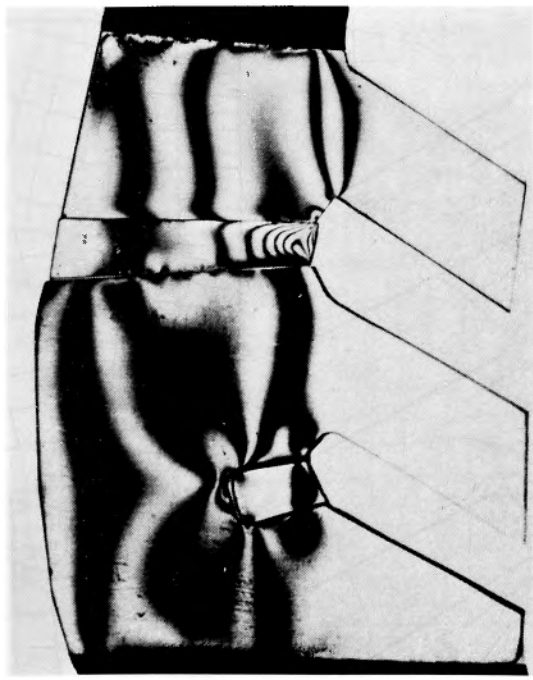


Fig. 16 The light-field photograph of the 2/3 anterior spine fusion shows the distribution of the fringe-orders tended to be localized upon the posterior parts of the vertebral bodies and intervetebral discs.

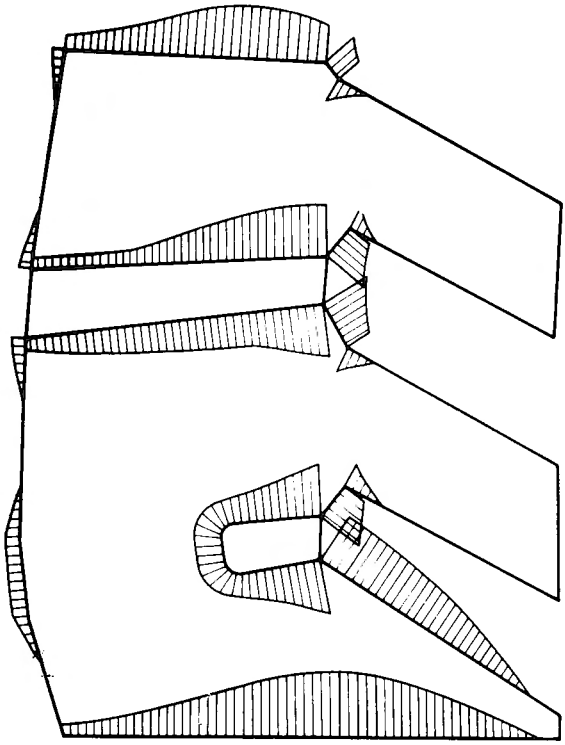


Fig. 17-A The surface stress distribution of the vertebral bodies of the 2/3 anterior spine fusion. It's σ max. is located on the posterior edge of the vertebral bodies and it's σ min. is located on the anterior edge of the vertebral bodies.

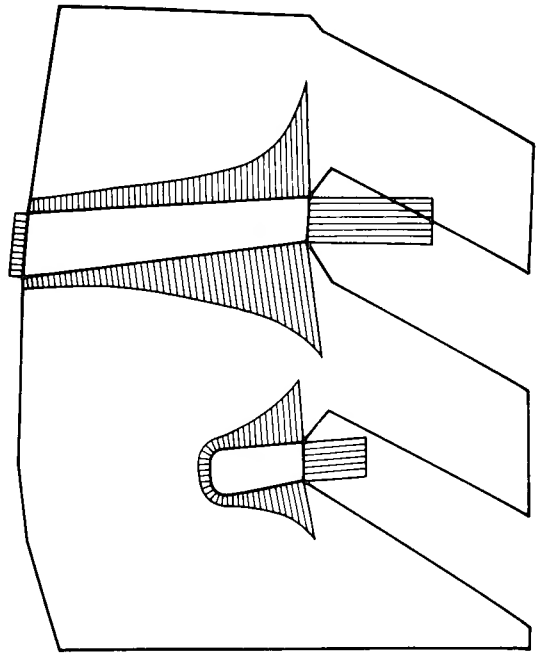


Fig. 17-B The surface stress distribution of the intervertebral discs of the 2/3 anterior spine fusion. It's σ max. is located on the posterior edge of the intervertebral discs and it's σ min. locates on the anterior edge of the intervertebral discs.

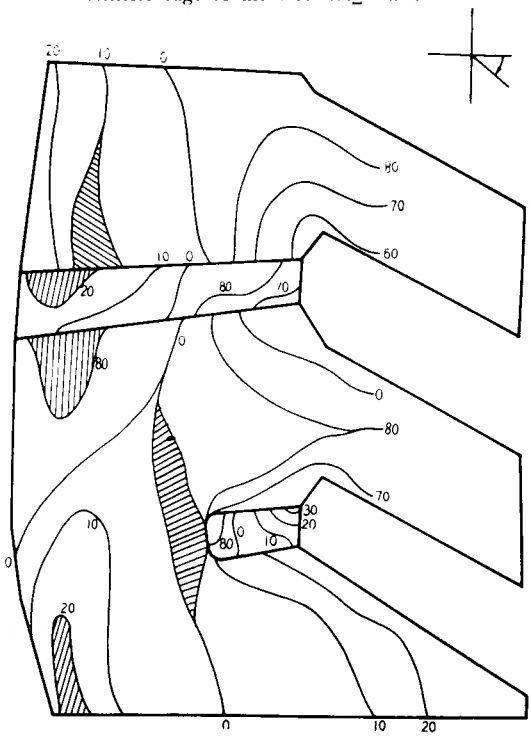


Fig. 18-A The isoclinic lines of the 2/3 anterior spine fusion do not produce the singlar point or line in the intervertebral discs and vertebral bodies.

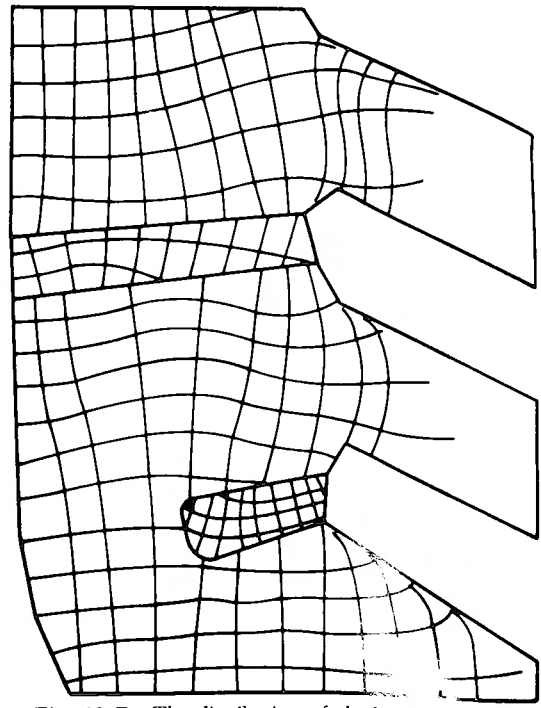


Fig. 18-B The distribution of the li[illegible] principal stress of the 2/3 anterior spine fu[illegible] [illegible]ated almost equally on the vertebral bo[illegible] [illegible]nter-vertebral discs.

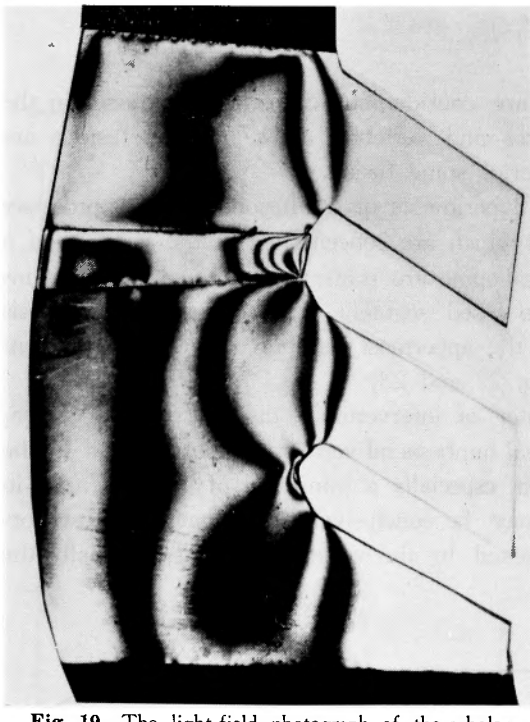


Fig. 19 The light-field photograph of the whole fusion of the intervertebral space shows the distribution of the fringe-order tended to be localized upon the posterior part of the vertebral bodies and intervertebral disc.

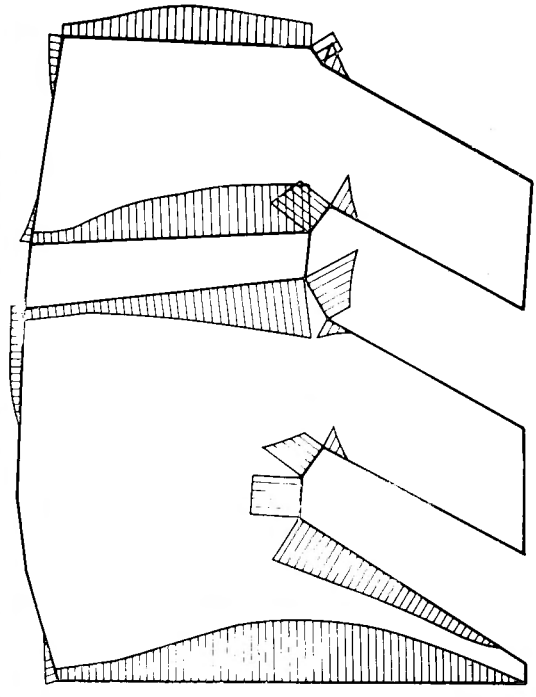


Fig. 20 The surface stress distribution of the vertebral bodies of the whole fusion of the intervertebral space. It's σ max. is located on the posterior edge of the vertebral bodies and it's σ min. is located on the anterior edge of the vertebral bodies.

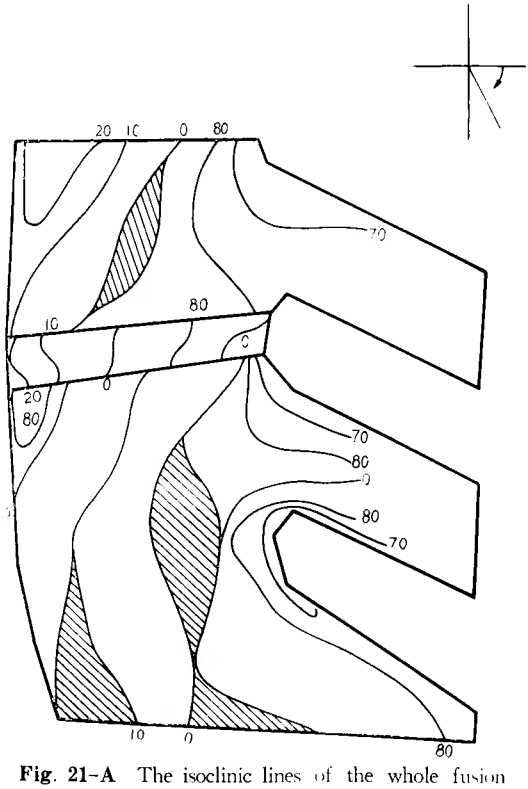


Fig. 21-A The isoclinic lines of the whole fusion of the intervertebral space do not produce the singular point or line.

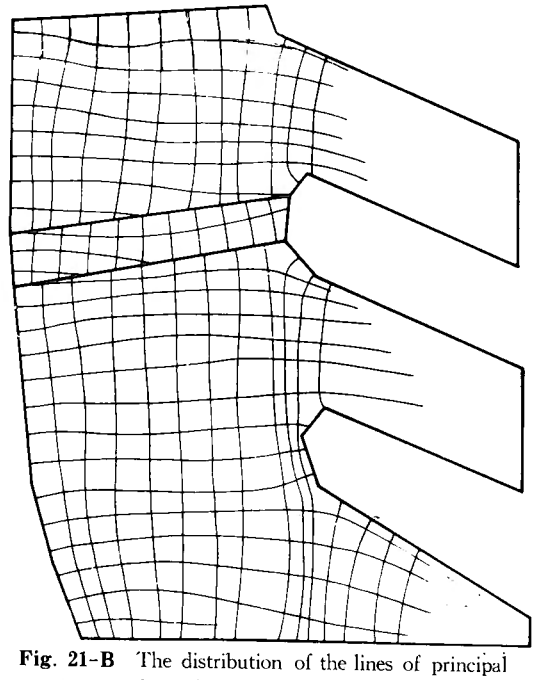


Fig. 21-B The distribution of the lines of principal stress is located almost equally on the vertebral bodies and intervertebral disc.

which is smaller than other fusions. There are considerably concentrated stresses in the grafted site of the fusion of spinous processes and vertebral archs. These fusions are dynamically more unstable than the 1/3 anterior spine fusion.

And also, according to the photo-elastic experiments of the fusion of spinous processes and vertebral archs, the stresses of movement which are concentrated at the junction of a fused and a mobile segment of the lumbosacral spine are transmitted through the pars interarticularis of the uppermost vertebra of the fused segment that acquired spondylolysis rarely develops at the pars interarticularis of the uppermost vertebra of the fused segment as a sequel to the posterior spine fusion (Fig. 22 and 23).

The posterior-directed stress at the center of intervertebral disc between L_5 and S_1 is a maximum of 62.70 gm/mm² in the normal lumbosacral vertebral column, small in the posterior fusion and 1/3 anterior spine fusion, especially a minimum of 4.32 gm/mm² in the 1/3 anterior spine fusion. That is, it may be conclusively said that the posterior-directed stress of the nucleus pulposus is lessened by the vertebral fusions, especially the anterior spine fusion (Fig. 24).

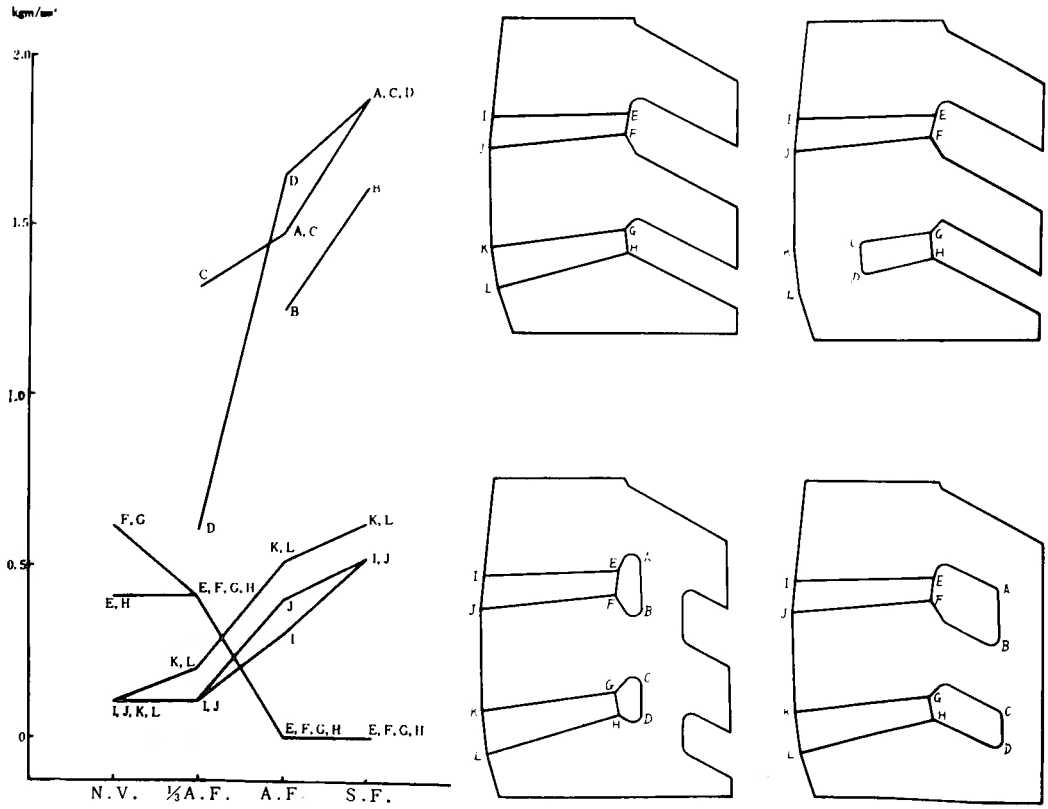


Fig. 22 The stress distribution in the parts of the vertebral bodies of the normal lumbosacral vertebral column, the posterior spine fusions, and the 1/3 anterior spine fusions. The fusion of spinous processes and the fusion of vertebral archs has considerably localized stress distribution in the parts of A, B, C and D of these fusions.

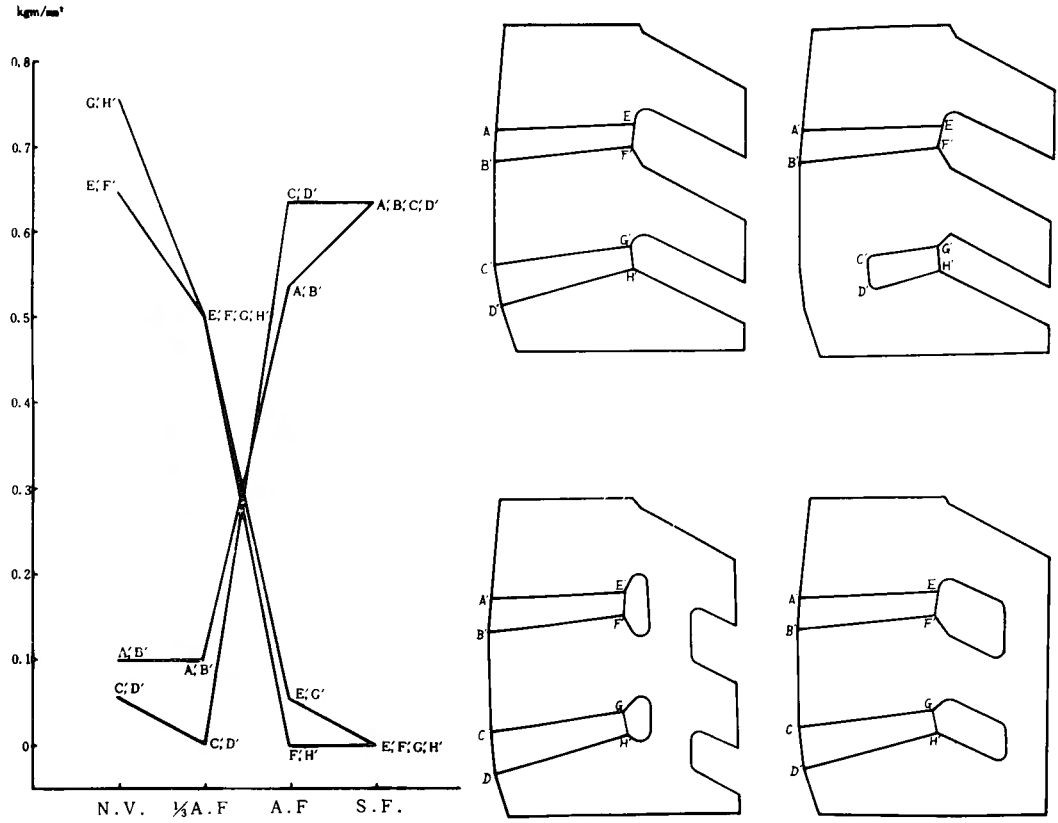


Fig. 23 The stress distribution in the parts of the intervertebral discs of the normal lumbosacral vertebral column, the posterior spine fusions, and the 1/3 anterior spine fusions. There is considerably localized stress distribution in the parts of A′, B′, C′ and D′ of the fusions of vertebral archs and spinous processes, and also in the parts of E′, F′, G′ and H′ of the 1/3 anterior spine fusion.
(N.V. : The normal lumbosacral vertebral column S.F. : The fusion of spinous processes A.F. : The fusion of vertebral archs 1/3 A. F. : The 1/3 anterior spine fusion W. F. : The whole fusion)

If compared the stress distribution of the 1/3 anterior spine fusion, the 1/2 anterior spine fusion, the 2/3 anterior spine fusion, and the whole fusion of the intervertebral space, the 1/3 and 1/2 anterior spine fusion has localized stresses in the posterior edge of the grafted sites, but in the 2/3 anterior spine fusion and whole fusion, the concentration of stresses is distributed almost equally in the vertebral bodies and grafted sites. And the intervertebral discs of the 1/3 and 1/2 anterior spine fusion have localized stresses in the posterior edge of the discs, but the intervertebral discs of the 2/3 anterior spine fusion and whole fusion have the stresses distributed equally in the intervertebral discs (Fig. 25 and 26). The anterior directed stress at the posterior edge of the grafted sites of the various anterior spine fusion is 224.3 gm/mm² in the 1/3 anterior spine fusion, 94.4 gm/mm² in the 1/2 anterior spine fusion, 14.2 gm/mm² in the 2/3 anterior spine fusion, and 10.3 gm/mm² in the whole fusion. That is, the 2/3 anterior spine fusion and whole fusion have much more less anterior directed stress than the others (Fig. 27).

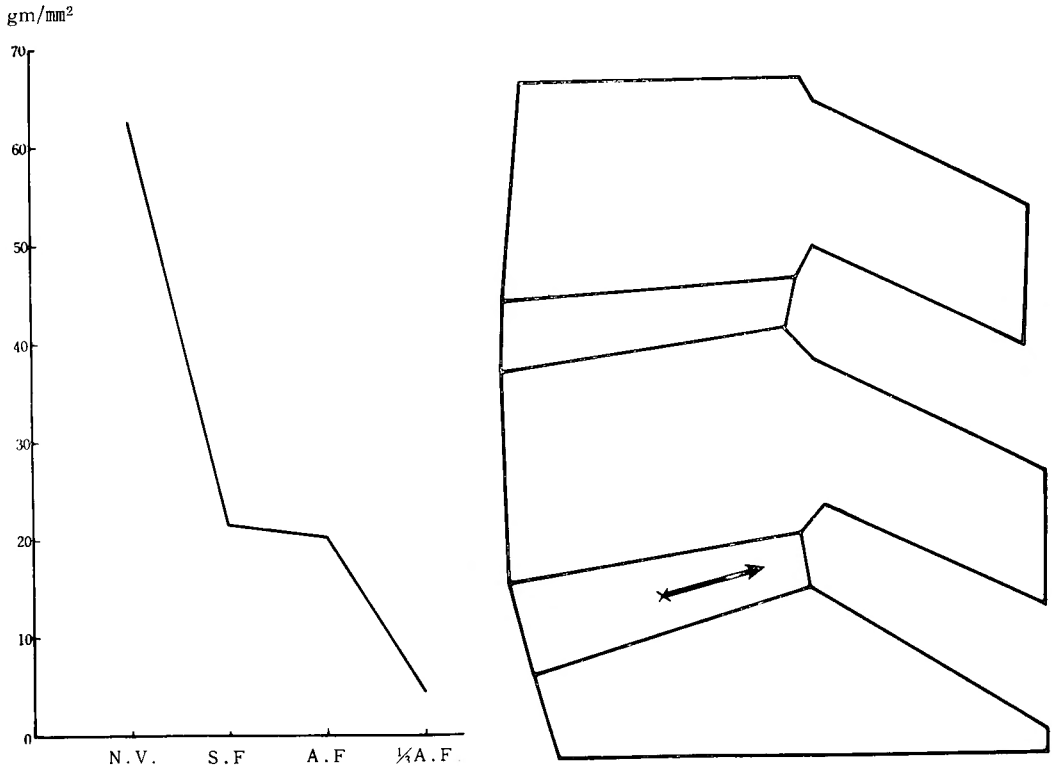


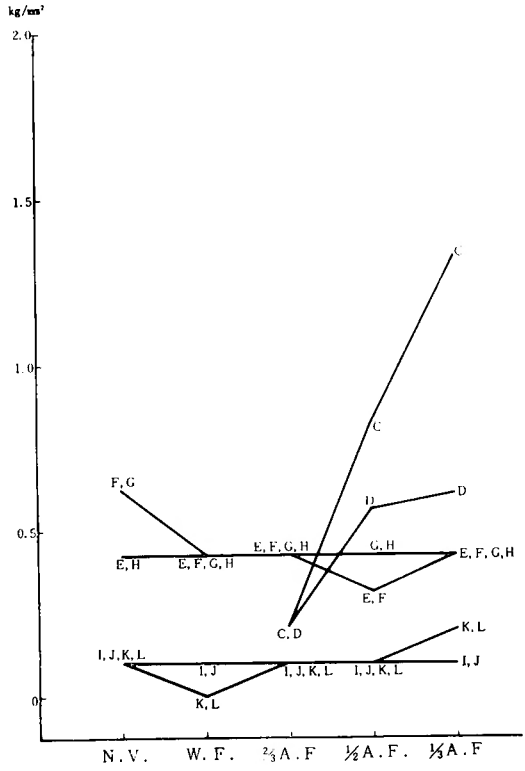
Fig. 24 The distribution of the posterior-directed stress in the center of intervertebral disc between L_5 and S_1. The posterior directed stress is decreased by the spine fusion.

It is photo-elastically concluded that the 2/3 anterior spine fusion and whole fusion are most stable.

CONSIDERATION

In the course of a survey of the surgical treatment for spondylolysis, spondylolisthesis, and other unstable vertebral column as a sequel to various agencies, the lumbar and lumbo-sacral spine fusion has been established as the standard method. The spine fusions are roughly devided into the anterior and posterior spine fusion, and the former is the method by which the bodies of the vertebrae are fused, the latter is usually done by mid-posterior approach by which the vertebral archs and the spinous processes are fused.

The operation for posterior spine fusion was based upon the principle originated by ALBEE and HIBBS in 1911. In 1931, GIBSON, in an attempt to obtain firmer fixation in fusion of the spine, devised so-called the clothespin graft. BOSWORTH (1945) employed a double clothespin graft which he had developed independently for use in spondylolysis and spondylolisthesis. The anterior spine fusion was conceived for the first time by CAPENER in 1923. BURNS (1932) performed the first fusion operation by transperitoneal approach. Since then, JENKINS, MERCER, SPEED, and others have reported cases [illegible]ess-



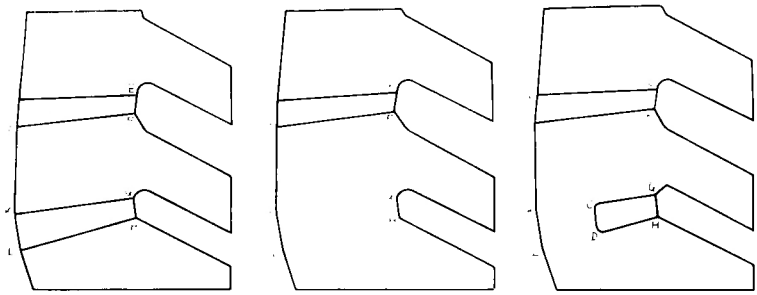
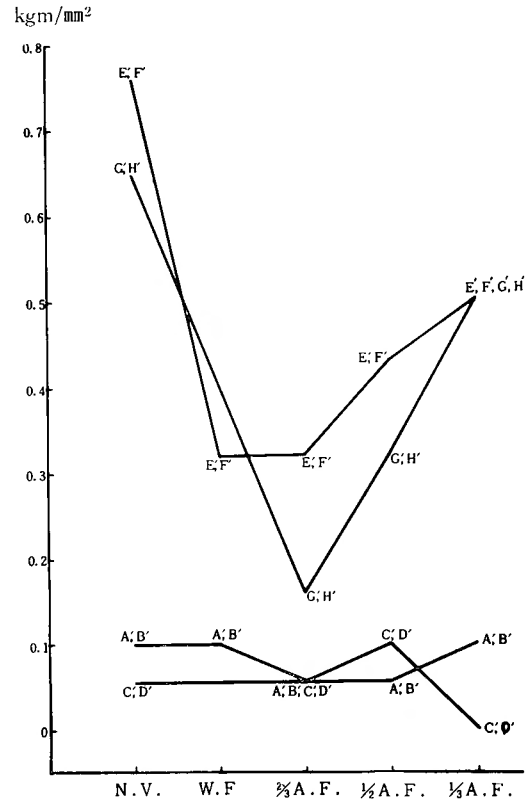


Fig. 25 The stress distribution in the parts of the vertebral bodies of the normal lumbosacral vertebral column, the various anterior spine fusions, and the whole fusion of the intervertebral space. The stress is distributed almost equally in the vertebral bodies of the 2/3 anterior spine fusion and whole fusion.



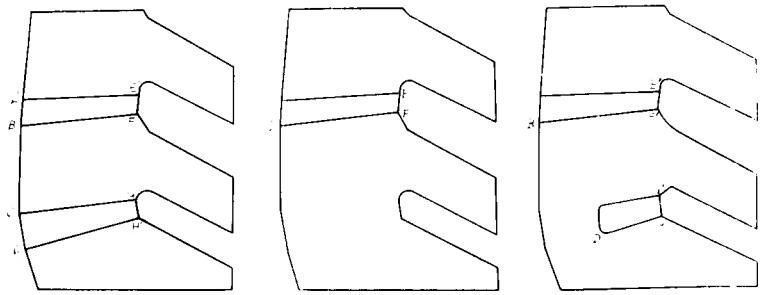


Fig. 26 The stress distribution in the parts of the intervertebral discs of the normal lumbosacral vertebral column, the various anterior spine fusion, and the whole fusion of the intervertebral space. The stress is distributed almost equally in the intervertebral discs of the 2/3 anterior spine fusion and whole fusion.

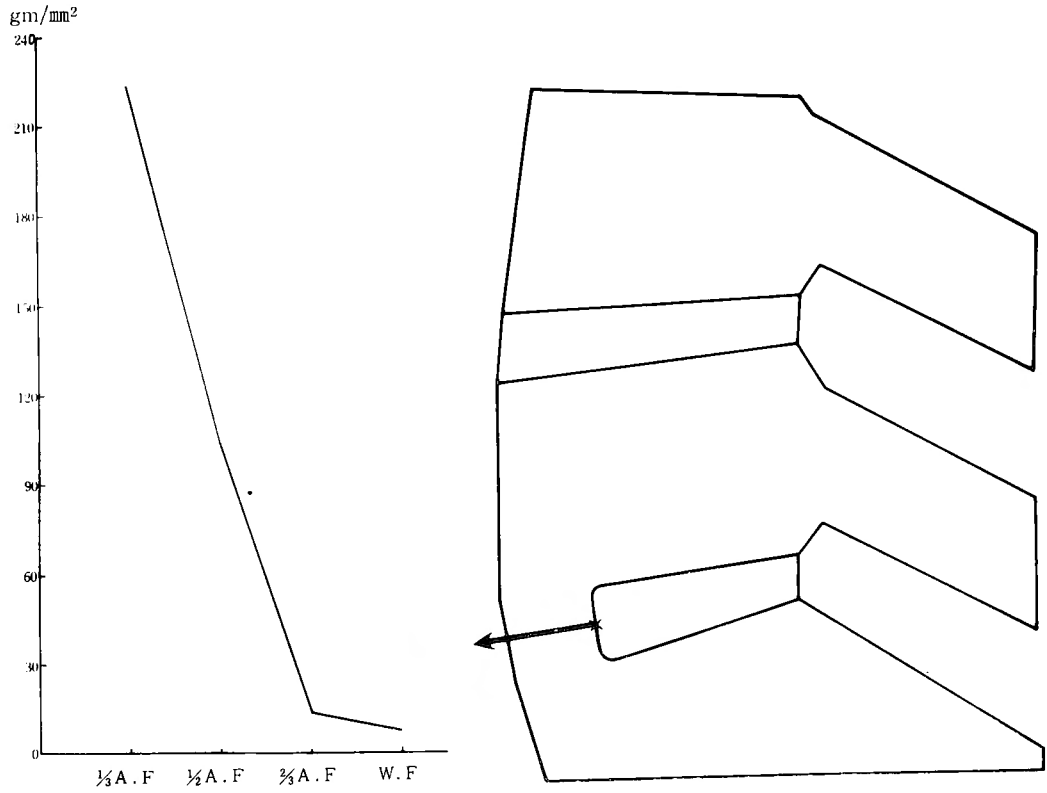


Fig. 27 The distribution of the anterior directed stress in the posterior edge of the grafted site of the various anterior spine fusion and the whole fusion of the intervertebral space. The antriordirected stress is much less in the 2/3 anterior spine fusion and whole fusion.

fully treated by the anterior spine fusion. In 1942, IWAHARA published the extraperitoneal approach for anterior spine fusion, and in 1961, he reported the results of spine fusion by his method and the details of his operation technic were described in NIHON GEKA SHUJUTSU ZENSHO.

UI (1960) reported the results of posterior spine fusion by the clothespin method at Keio university Hospital for past twelve years, and according to his reports, from 1946 through 1957, the posterior spine fusion was done on 73 cases, in which 37 cases were available for the personal investigation on the long time follow-up. It was purpose of this method to fuse an unstable vertebral column as a sequel to laminectomy for the treatment of herniated intervertebral disc. The clinical results of posterior spine fusion were almost satisfactory, that is, of the patients treated by posterior spine fusion, 30 percent were rated as the unchanged or a little improved, and 70 percent belong to the improved, almost cured, and entirely cured groups. But the limitation of movement in the lumbar region which disappeared prior to operation became one of the causes of patient's complaints (Table 1). Roentgenographic findings of the grafted sites following posterior spine fusion follow: of the 37 cases, 22 cases reveal the "Umbauzone" or "Pseudoarthrosis-like line" in the bone graft, 3 cases reveal the fracture of the bone graft with sold fusion,

2 cases reveal the acquired spondylolysis through the pars interarticularis of the uppermost vertebra of the fused segment, and a case reveals the fracture and the "Umbauzone". That is, the result of roentgenographic findings is not satisfactory (Table 2). The "Umbauzone" or "Pseudoarthrosis-like line" appears frequently at the upper margin of bone graft. The clinical results mentioned above may be demonstrated by the photo-elastic study. The stress distribution of posterior spine fusion is concentrated in the bone graft, especially the upper margin of bone graft, and the appearance of singular point consisted of the isoclinic lines proves the distribution of two different stresses in the bone graft. That is, the small bone graft is affected by the compression stress in one side and the traction stress in another side, and thus it is dynamically under the unstable condition. The new stress distribution differently appears in the bone graft, which affects to decrease the stress in the bone graft. It is called the shearing stress. The larger the concentration of stress in the bone graft, the larger the shearing stress. It is apparently considered from the photo-elastic study that the distribution of shearing stress is localized much more in the upper margin of the bone graft than the lower margin. Of course, it is not doubtful that the concentration of shearing stress in the bone graft corresponds fairly with the development of "Umbauzone" or "Pseudoarthrosis-like line" in the bone graft.

Roentgenographically, of the cases of posterior spine fusion with sold fusion, some case has the development of fracture of bone graft due to the shearing stress, and some case has the development of acquired spondylolysis in the pars interarticularis of the uppermost vertebra of the fused segment. HARRIS (1963) reported 6 cases of a aquired spondylolysis as a sequel to posterior spine fusion, of which cases's autopsy specimen showed some pathological attenuation of the pars interarticularis. The stresses of movement which are concentrated at the junction of a fused and a mobile segments of the lumbar spine are transmitted through the pars interarticularis of the uppermost vertebra of the fused segment. The cross sectional area of the pars interarticularis is small, and repeated bending stress

Table 1 Limitation of Movement in the Lumbar Region as a Sequel to Posterior Spine Fusion

Limitation of over stretch + Stiffness	12 cases
Stiffness	8
Limitation of over stretch	6
Decreased lordosis + Stiffness	3
Decreased lordosis + Limitation of over stretch	3
Normal	5

Table 2 Roentgenographic Findings of the Grafted Bone of Posterior Spine Fusion

"Pseudoarthrosis-like line"	upper margin of bone graft	14	22 cases
	lower margin of bone graft	7	
	upper and lower margin of bone graft	1	
Fracture			3
Osseous union			4
Fracture + "Pseudoarthrosis-like line"			1
Acquired spondylolysis			2
Unknown			5

in this region which are get strong by the limitation of movement in the lumbar region may eventually produce a fatigue fracture of bone graft. This sequence suggests a pathological attenuation of the pars interarticularis. Of course, it is considered that the affection of posterior spine fusion is not only in the pars interarticularis of the uppermost vertebra of the fused segment, but also in the upper and lower vertebral bodies and intervertebral discs of the fused segment.

The nearer to the weight bearing axis, the smaller the concentration of stress distribution $\left(\sigma = c\frac{1}{\sigma}\right)$, and thus it has been proved photo-elastically that the fusion of vertebral archs is superior to the fusion of spinous processes. ONDROUCH (1963) disclosed dynamically and pathologically that the cartilage and bone tissues under the repeated mechanical over-loading develop the degenerative and osteoarthritic lesions and frequently the cyst formation at last. In the posterior spine fusion, there are the localized stresses in the anterior parts of the vertebral bodies and intervertebral discs. Therefore, the cases of solid fusion without "Umbauzone" are apt to have the development of fracture in the bone graft or a aquired spondylolysis or a degenerative and osteoarthritic lesion in the vertebral bodies and intervertebral discs as a sequel to posterior spine fusion for a long time. There are the cases had the progression of slipping despite good consolidation of the bone graft after posterior fusion for spondylolysis and spondylolisthesis. It may be said that the causative factors of this slipping are mainly due to the progression of mobilization at the junction between vertebral bodies and intervertebral discs in consequence of degeneration of discs and osteoarthritic lesion of vertebral bodies. Even the complaints of the patients are improved postoperatively, a long term follow-up observation is necessary to know the final out-come of posterior spine fusion, and for the postoperative limitation of vertebral column the results of clinical follow-up study of posterior spine fusion issatisfactory despite showing "Umbauzone" at the margins of bone graft.

The 1/3 anterior spine fusion is superior to the posterior spine fusion photo-elastically, because the 1/3 anterior spine fusion is more equaller than the posterior spine fusion in the distribution of stress in the bone graft, but comparing with the various anterior spine fusions, the 1/3 anterior spine fusion has more localized stresses in the bone graft than the other anterior spine fusion, and more-over, from the fact of an appearance of singular line in the bone graft of 1/3 anterior spine fusion, it is certain that the bone graft of 1/3 anterior spine fusion is affected by the shearing stress which is stronger in the upper margin of bone graft than the lower margin. The singular line or point disappears in the bone graft of anterior spine fusion having the more longer diameter than one-third A-P diameter of vertebra.

The photo-elastic study suggests the clinical results of anterior spine fusion. According to IWAHARA's reports of anterior spine fusion by his method at KEIO University Hospital, in any case which does not have "Umbauzone" at the grafted sites, the size of bone graft is no less than 1/3 in A-P diameter of the vertebra. "Umbauzone" develops frequently at the lower margin of the vertebral body above the grafted area (Table 3). The stress in the anterior spine fusion which is fused by the bone graft having the two-third, or more longer in A-P diameter of the body of the affected vertebra almost equally

Table 3 Roentgenographic Findings of the Grafted Bone of Anterior Spine Fusion

		Osseous Union	Type of "Umbauzone"			
			lower margin of upper vertebral body	intermediate type	interspace type	upper margin of lower vertebral body
No. of Cases		18	9	5	4	3
Site of Lesion	L_4-L_5	6	3	2	2	2
	L_5-S_1	12	6	3	2	1
Size of bone graft (A-P diameter of vertebral body)	~1/3	1	3	1	1	1
	1/3	1	1	1	2	1
	1/2	8	2	3	0	1
	1/2~	8	8	0	1	0

distributes on the vertebral bodies and intervertebral discs. Therefore, it is obvious that if the bone graft of anterior spine fusion is small, the increase of osteoarthritic lesion in the vertebral bodies promotes year after year despite good consolidation, but the increase of osteoarthritic lesion is prevented by the fusion of spine having the sufficiently large bone graft.

The anterior-directed stress at the posterior margin of the bone graft of 1/3 anterior spine fusion is larger than the other anterior spine fusions, and in the 2/3 or more anterior spine fusion, it's stress decreases approximetly under the one-tenth of the 1/3 anterior spine fusion. The concentration of anterior-directed stress distribution at the posterior margin of the bone graft affects apparently the formation of "Umbauzone". The posterior-directed stress of the nucleus pulposus is lessened by the spine fusion. In reviewing the records of the patients with spondylolysis and spondylolisthesis, 10.7 per-cent had approximately sciatic pain, and a much larger number had vague referred pain and paraesthesia of the buttocks, hips, and thighs. When spondylolysis and spondylolisthesis is complicated by the presence of a nerve-root compression syndrom, surgical removal of the pathologic disc and excision of all fibrocartilaginous tissue from vertebrae must precede fusion of the spine. This is natural because anterior spine fusion has been widely used as one of the radical treatments for the radicular symptoms.

The patients with spondylolysis or spondylolisthesis show frequently the increased lumbar lordosis. It is considered that the shearing stress in the pars interarticularis promoted by increasing lordosis has close correlation to the etiology of spondylolysis and spondylolisthesis as STEWART mentioned (1956). Therefore, it is the most important point in the treatment for spondylolysis and spondylolisthesis to gain decreased lumbar lordosis. For this purpose, it is attempted that shell plaster should be made in the decreased lumbar lordosis position prior to operation and intervertebral space, particularly it's posterior portion, must be widened, and the larger bone graft is inserted into that widened intervertebral space at operation in order to gain decreased lumbar lordosis.

Currently, the etiology of spondylolysis and spondylolisthesis, and the pain causing etiological agents in spondylolysis and spondylolisthesis still remains in doubt. Therefore, it may fairly be said that there is no satisfactory treatment for spondylolysis and spondylolis-

thesis. And also, the anterior spine fusion we use for spondylolysis and spondylolisthesis as the routine procedure is not satisfactory as sufficient, but it has been proved experimentally and clinically that the anterior spine fusion is superior to any other methods.

Some problem still remains in the anterior spine fusion. The trough into which a bone graft of two-thirds or more A–P diameter of the body of the affected vertebra is inserted should be made approximately right angle to the weight bearing axis of the spinal column. Especially, the case of L_5–S_1, the anterior part of the inferior margin of the body of the fifth lumbar vertebra and the posterior part of the superior margin of the first sacral vertebra should be deeply digged respectively, in order to strengthen the compression stress to the inserted bone graft. As the author knows the development of acquired spondylolysis at the pars interarticularis of the uppermost vertebra of the fused segment as a sequel to posterior spine fusion, it should be considered that there is an affection upon the above and below vertebrae and intervertebral discs of the fused segment. That is, it is suggested that the increase of osteoarthritic and degenerative lesions at the above and below vertebrae and intervertebral discs of the fused segment occures as a sequel to anterior spine fusion, and actually, the auther has the two cases of solid anterior spine fusion having apparently increase of osteoarthritic lesion at the upper intervertebral joint of the involved spine. But this problem may be recently solved experimentally.

CONCLUSION

(1) The posterior spine fusion is dynamically unstable, thus, the "Pseudoathrosis-like line," or "Umbauzone" is aptt o occure at the margin of bone graft. Even if the posterior spine fusion is solid without "Poeudoarthrosis-like line" or "Umbauzone", the fracture at the bone graft, the acquired spondylolysis at the pars interarticularis of the uppermost vertebra of the fused segment, or the increase of osteoarthritic or degenerative lesions at the vertebral bodies and intervertebral discs occures frequently.

(2) The author believes that the anterior spine fusion for spondylolysis, spondylolisthesis, and other unstable vertebral column as a sequel to various agencies is the most rational and efficient method.

(3) The bone graft for the anterior spine fusion should be made large enough, having two-thirds or more A–P diameter of the body of the affected vertebra.

(4) It may be suggested that the trough for anterior spine fusion should be made aproximately right angle to the weight bearing axis of the spinal column, that is, in the direction so as not to be affected by the shearing stress, and such as to gain the decreased lumbar lordosis.

(5) It may be said that the anterior spine fusion we use for spondylolysis and spondylolisthesis is not satisfactory treatment as sufficient. The affection upon the above and below vertebrae and intervetebral discs of the fused segment as a sequel to anterior spine fusion remains now in doubt.

The author wishes his grateful acknoledgement to Prof. Dr. TORAI IWAHARA of Keio University and Dr. MASATAKA NISHIDA of Rikagaku-Kenkyusho for their encouragement and guidance throughout this investigation.

REFERENCES

1) Iwahara, Ikeda, and Hirabayashi : Results of Anterior Spine Fusion by Extraperitoneal Approach for Spondylolysis and Spondylolisthesis, J. Jap. Orthop. Ass., **35** : 13, 1963.
2) Kirita : Results of Spondylolysis and Spondylolisthesis Treated by Arthrodesis, The Central Jap. J. Orthop. and Traumatic Surg., **2** : 75, 1959.
3) Amako : Etiology of Spondylolysis, J. Jap. Orthop. Ass., **34** : 1411, 1961.
4) Arima : Photo-elastic Study of Spine Fusion, Med. J. Kagoshima Univ., **11** : 2335, 1960.
5) Iwahara : A New Methods of Vertebral Body Fusion, Surgery, **8** : 271, 1941.
6) Nishida : Measurement of Stress, Corona, 1943.
7) R. I. Harris and J. J. Wiley Wiley : Acquired Spondylolysis as a Sequal to Spine Fusion, J. Bone and Joint Surg., **45-A** : 1159, 1963.
8) Iwahara and Ohtani : Review of X-ray Films Showing Lumbosacral Intervertebral Disc, Clinical Radiology, **8** : 167, 1963.
9) Masabayashi : Photo-elastic Study on Bone Forms, J. Jap. Orthop. Ass., **28** : 37, 1954.
10) De Palma, A. F. and Marone, P. J. : Spondylolysis Following Spine Fusion, Clin. Orthop., **15** : 208, 1959.
11) Runge, C. F. : Rentgenographic Examination of the Lumbosacral Spine in Routine Preemployment Examination, J. Bone and Joint Surg., **36-A** : 75, 1954.
12) Hammond, G. : Review of Seventythree Cases of Spondylolisthesis Treated by Arthrodesis, J. Ame. Med. Ass., **163** : 175. 1957.
13) Hensell, V. : Erfahrungen mit der Ventralen Extraperitonealen Wirbelverblockung, Arch. u. Dtsch. Chir., Bd. **288** : 209, 1958.
14) Matsuo : Investigation of the Patient of Spondylolysis and Spondylolisthesis for 26 Years at Clinic of Orthop. Surg. of Keio Univ., J. Jap. Orthop. Surg., **29** : 74, 1955.
15) Suzuki : Treatment for Spondylolysis and Spondylolisthesis, J. Jap. Orthop. Surg., **32** : 991, 1958.
16) Takahashi : Experimental Study, on Anterior Spine Fusion by Fused Vertebral Body, J. Keio Med. Society, **36** : 1618, 1959.
17) Ui : Follow-up Study on Posterior Spine Fusion, Operation, **14** : 792, 1960.
18) Ariga : Experimental and Clinical Study on Development cf Compression Fracture of Vertebral Body, Med. J. Hokkaido, **13** . 2226, 1953.
19) Watkins, M. B. : Posterolateral Bonegrafting for Fusion of the Lumbar and Lumbosacral Spine, J. Bone and Joint Surg., **41-A** : 388, 1959.
20) Yano : Criticism on Spine Fusion for Spondylolysis and Spondylolisthesis, J. Jap. Accident Med. Ass., **1** : 308, 1957.
21) Shima : Study on Spondylolysis and Spondylolisthesis, Igaku Kenkyu, **45** : 907, 1940.
22) Lauent, L. E. : Spondylolisthesis, A Study of 53 Cases Treated by Spine Fusion and 32 Cases Treated by Laminectomie, Acta Orthop. Scandinavica, Supplementum 35, 1958.
23) Albee, Fred H. : A Report of Bone Transplantation and Osteoplasty in the Treatment of Pott's Diease of Spine, New York M. J. **95** : 469, 1912.
24) Bosworts, D. M. : Clothespin Graft of the Spine for Spondylolisthesis and Laminal Defects, Am. J. Surg. **67** : 61, 1945.
25) A. S. Ondrouch, Pragve : Cyst Formation in Osteoarthritis, J. Bone and Joint Surg., **45-B** : 755, 1963.
26) Jenkins, J. A. . Spondylolisthesis, Brit. J, Surg., **24** : 80, 1936.
27) Speed, Kellogg : Spondylolisthesis ; Treatment by Anterior Bone Graft, Arch. Surg., **37** · 175, 1938.
28) T. D. Stewart : Examination of the Possibility that Certain Skeletal Characters Predispose to Defects in the Lumbar Neural Arches, Clinical Orthopaedics, **8** : 41, 1956.

和文抄録

脊柱固定術の光弾性実験的研究

慶応義塾大学医学部整形外科学教室（主任：岩原寅猪教授）

大　谷　　清

慶大整形外科では脊椎分離症及びより症に対して昭和17年以来腹膜外経路法による前方脊柱固定術を行つており，その臨床成績はすでに発表されている．

私は理化学研究所光弾性研究室の協力を得て脊柱固定の二次元光弾性実験を行つた．

実験模型は屍体脊柱及び20才代から30才代の免荷位における腰椎4，5中心側面単純レ線写真の統計的計測結果をもとにして作り，材料はD.A.P.樹脂で，硬度は屍体の椎体及び椎間板のヤング率にほゞ等しい椎体260，椎間板110とし，加重力はいづれも60 kgmである．

実験Ⅰ：正常状態，前方1/3固定，椎弓固定及び棘突起固定の比較

実験部位は前方固定で腰椎5，仙椎1間を，椎弓固定及び棘突起固定で腰椎4，5，仙椎1間である．

正常状態　椎体はその後縁に応力集中が見られ，その最大値は0.6261 kgm/mm² であり，椎間板でも同様後縁に応力が集中し，その最大値は0.7581 kgm/mm²である．等傾曲線，主応力線を求めると椎体，椎間板共に後部に主応力線の集中する傾向が見られる．

前方1/3固定　移植片内面に応力は集中し，その最大値は1.2522 kgm/mm² であり，椎間板は後縁に応力集中が見られ，その最大値は0.5415 kgm/mm² である．等傾曲線，主応力線を求めると移植片に主応力線が集中し，特異線を認める．

椎弓固定　移植片内面に応力が集中し，その最大値は1.6706 kgm/mm² であり，椎間板は前縁に応力が集中し，その最大値は0.6498 kgm/mm²である．等傾曲線，主応力線は移植片に4個の特異点を作り，主応力線の集中が見られる．

棘突起固定　移植片内面に応力が集中し，その最大値は1.8723 kgm/mm² で，椎間板は前縁に応力が集中し，その最大値は0.6498 kgm/mm²である．等傾曲線，主応力線は移植片に2個の特異点と主応力線の集中が見られる．

実験Ⅱ：各種前方固定の比較

実験部位は腰椎5，仙椎1間である．

前方1/3固定　前記の通りである．

前方1/2固定　椎体では移植片内面に応力が集中し，その最大値は0.4332 kgm/mm² である．主応力線は椎体，椎間板にほぼ平等に分布する．

前方2/3固定　椎体では移植片内面よりも椎体後縁に応力は集中し，その最大値は0.4171 kgm/mm² であり，椎間板は後縁に応力が集中し，その最大値は0.3249 kgm/mm²である．主応力線は椎体，椎間板ともにほぼ平等に分布する．

椎間全体固定　椎体では後縁に応力が集中し，その最大値は0.4171 kgm/mm² で，椎間板でもその後縁に応力が集中し，その最大値は0.3249 kgm/mm²である主応力線は椎体，椎間板ともほぼ平等に分布する．

総括ならびに考按

正常状態，前方1/3固定，椎弓固定及び棘突起固定について，椎体各所の応力を測定するといづれも移植片内面に応力は集中するが棘突起固定で1.8723 kgm/mm²とその値は最大で，前方固定で1.2522kgm/mm²とその値は最小である．椎間板各所の応力分布は棘突起及び椎弓固定では前縁に，前方固定では後縁に応力集中を見るが，その値は前二者で0.6498 kgm/mm²，後者0.4515 kgm/mm²である．即ち棘突起固定，椎弓固定では移植片に限局性に大きな力が働き，前方固定に比して力学的に不安定状態にあり，偽関節形成が起り易いと云える．

腰椎5，仙椎1間椎間板中央で後方へ向う応力を測定すると正常状態が最大で，椎弓固定，前方固定では小さく，殊に前方固定が最小で，その値は4.32 kgm/mm²で，正常状態の1/10以下である．即ち椎体固定を行うと椎間板髄核の後方突出力を減少させる．

前方1/3固定，1/2固定，2/3固定及び全体固定について椎体各所の応力を測定すると1/3及び1/2固定では移植片内面に限局性に応力集中が見られるが，2/3及

び全体固定では椎体にほぼ平等に応力が分布する．椎間板では1/3及び1/2固定で後縁に限局性に応力集中が見られるが，2/3及び全体固定ではほぼ平等に応力が分布する．

移植片内面で前方へ向う応力を測定すると，1/3固定で221.3gm/mm²，1/2固定で94.4gm/mm²と非常に大きく，2/3固定で14.7gm/mm²，全体固定で10.3gm/mm²と1/3及び1/2固定に比べ非常に小さい．

我々は前方固定術で固定範囲がせまい場合，所謂骨改質層を作り手術に失敗した例を経験しておるが，まさにその事実を裏づけるものである．

以上の実験から前方2/3以上を固定した場合が力学的に最も安定していると結論する．