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Photo-elastic Study on Lumbosacral Spine Fusion

by

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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 been varied from year to year.

Fixation of the unstable spine by spine fusion is a preferred method of treatment in spondyloysis 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 CAPE 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 postmortem 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 (L₄), the fifth lumbar vertebra (L₅), the first sacral vertebra (S₁), 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 L₄, L₅, and S₁ one another. And the anterior spine fusion is fused at the anterior part of the vertebral bodies of L₄ and S₁ 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.

\[ \sigma \max \text{ means maximal stress and } \sigma \min \text{ means minimal stress, and the following expression is concluded dynamically, } \sigma \max = c \frac{1}{r} \text{ (c: constant, } r: \text{ distance between the point at stress measurement and the point bearing weight, } r: \text{ the radius of curvature)}. \]

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 referred 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/mm² in the vertebral body plane and 0.1083 kgm/mm² 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 $\sigma$ max. of L₄, L₅, and S₁ is located on the posterior edge of these vertebral bodies. The concentration of these $\sigma$ max. is 0.4171 kgm/mm² of L₄, 0.6261 kgm/mm² of L₅, and 0.6261 kgm/mm² of S₁. The $\sigma$ min. of L₄, L₅, and S₁ is located on the anterior edge of these vertebral bodies. The concentration of these $\sigma$ min. is 0.1043 kgm/mm².

Of the stress distribution of the intervertebral disc, the $\sigma$ max. is located on the posterior edge of the intervertebral discs L₄-L₅ and L₁-S₁. The concentration of these $\sigma$ max. is 0.7581 kgm/mm² of the disc between L₄ and L₅, and 0.6498 kgm/mm² of the disc between L₅ and S₁. The $\sigma$ min. is located on the anterior edge of the intervertebral discs. The concentration of these $\sigma$ min. is 0.1083 kgm/mm² of the disc between L₄ and L₅, and 0.0541 kgm/mm² of the disc between L₅ and S₁ (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 distribution of many fringe-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 $\sigma_{\text{max}}$ is located on the posterior edge of the vertebral bodies and it's $\sigma_{\text{min}}$ 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 $\sigma_{\text{max}}$ is located on the posterior edge of the intervertebral discs and it's $\sigma_{\text{min}}$ 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 \( \sigma \) 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 \( \sigma \) max. of \( L_5 \) is 1.6706 kgm/mm\(^2\), and it is also located on the grafted site of spinous processes. The \( \sigma \) min. of the vertebral bodies is located on the posterior edge.

The \( \sigma \) max. of intervertebral discs is 0.6498 kgm/mm\(^2\), and it is located on the anterior edge. The \( \sigma \) 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 \( \sigma \) max. distributes at the grafted site of the vertebral archs, of which concentration is 1.6706 kgm/mm\(^2\). The \( \sigma \) 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 \( \sigma \) max. of \( L_4 \) is located on the posterior edge of vertebral body, it is 0.4174 kgm/mm\(^2\), and the \( \sigma \) min. of \( L_4 \) is located on the anterior edge of vertebral body, it is 0.1043 kgm/mm\(^2\). But in the \( L_4 \) and \( S_1 \), the concentration of stress distribution is transferred to the posterior edge of grafted site, of which \( \sigma \) 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 \( \sigma \) max. is 0.5414 kgm/mm\(^2\). And also the stress distribution of intervertebral disc between \( L_4 \) and \( S_1 \) is concentrated in the posterior edge. The \( \sigma \) 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 localize 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 lumbo-sacral vertebral column.

Fig. 3-B The lines of principal stress of the normal lumbo-sacral vertebral column, which are apt to be localized 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 grafted 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 $\sigma_{\text{max}}$ is located on the anterior edge of the grafted site and it's $\sigma_{\text{min}}$ is located on the posterior part of the vertebral bodies.

Fig. 5-B The surface stress distribution of the intervertebral discs of the fusion of spinous processes. It's $\sigma_{\text{max}}$ is located on the anterior edge of the intervertebral discs and it's $\sigma_{\text{min}}$ 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 arches 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 arches.

Fig. 8-A  The surface stress distribution of the vertebral bodies of the fusion of vertebral arches. It's \( \sigma \text{ max.} \) is located on the anterior edge of the grafted site and it's \( \sigma \text{ min.} \) 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 arches. It's \( \sigma \text{ max.} \) is located on the anterior edge of the intervertebral discs and it's \( \sigma \text{ min.} \) is located on the posterior edge of the intervertebral discs.
Fig. 9-A The isoclinic lines of the fusion of vertebral arches produce four singular points in the grafted site.

Fig. 9-B The distribution of the line of principal stress of the fusion of vertebral arches 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 $\sigma$ max. is located on the posterior edge of the grafted site and it's $\sigma$ 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 $\sigma$ max. is located on the posterior edge of the intervertebral discs and it's $\sigma$ 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 residual stress of the 1/3 anterior spine fusion is localized considerably upon the grafted site.
decreases in the anterior edge, the $\sigma_{\text{max}}$ is 0.3130 kgm/mm², the $\sigma_{\text{min}}$ is 0.1043 kgm/mm². On the other hand, in the L₄ and S₁, the concentration of stress distribution is transferred to the posterior edge of grafted site, of which $\sigma_{\text{max}}$ is 0.8348 kgm/mm².

The stress of intervertebral disc between L₄ and L₅ being accompanied with the $\sigma_{\text{max}}$ of 0.4332 kgm/mm², is distributed in the posterior edge, the $\sigma_{\text{min}}$ of 0.0541 kgm/mm² is in the anterior edge of the intervertebral disc. And also the stress distribution of intervertebral disc between L₅ and S₁ is concentrated in the posterior edge, of which $\sigma_{\text{max}}$ is 0.3249 kgm/mm² (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/mm² of the $\sigma_{\text{max}}$ of vertebral bodies is located on the posterior edge, 0.1043 kgm/mm² of the $\sigma_{\text{min}}$ 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 $\sigma_{\text{max}}$ of the intervertebral disc between L₄ and L₅ is 0.4510 kgm/mm², and the $\sigma_{\text{max}}$ of the intervertebral disc between L₅ and S₁ is 0.3249 kgm/mm² (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 $\sigma_{\text{max}}$ is 0.4171 kgm/mm², and the $\sigma_{\text{min}}$ is 0.0541 kgm/mm².

And also in the intervertebral disc, the $\sigma_{\text{max}}$ is located on the posterior edge, it is 0.3249 kgm/mm². And the $\sigma_{\text{min}}$ is located on the anterior edge, it is 0.0541 kgm/mm² (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/mm². 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/mm². 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/mm². On the other hand, the minimum of stresses in the intervertebral discs of the 1/3 anterior spine fusion is located on the posterior edge, it’s concentration is 0.5414 kgm/mm².
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. 14-A The surface stress distribution of the vertebral bodies of the 1/2 anterior spine fusion. It's $\sigma$ max. is located on the posterior edge of the grafted site and it's $\sigma$ min. is located on the anterior parts of the vertebral bodies.

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

Fig. 14-B The surface stress distribution of the intervertebral discs of the 1/2 anterior spine fusion. It's $\sigma$ max. is located on the posterior edge of the intervertebral discs and it's $\sigma$ min. is located on the anterior parts of the intervertebral discs.
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 intervertebral discs.
Fig. 17-A The surface stress distribution of the vertebral bodies of the 2/3 anterior spine fusion. It's $\sigma_{\text{max}}$ is located on the posterior edge of the vertebral bodies and it's $\sigma_{\text{min}}$ 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 $\sigma_{\text{max}}$ is located on the posterior edge of the intervertebral discs and it's $\sigma_{\text{min}}$ 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 singular point or line in the intervertebral discs and vertebral bodies.

Fig. 18-B The distribution of the principal stress of the 2/3 anterior spine fusion is distributed almost equally on the vertebral bodies and intervertebral 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 $\sigma_{\text{max}}$ is located on the posterior edge of the vertebral bodies and it's $\sigma_{\text{min}}$ 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 in-
terarticularis 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 L₅ and S₁
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](image-url) The stress distribution in the parts of the vertebral bodies of the normal lumbosacral vertebra 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 L₅ and S₁. 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, spondylololisthesis, 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 divided 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 (1915) 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, Jen Kins, Mercer, Speed, and others have reported cases of stress-
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 lumbar-sacral 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.
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.

Ur (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 solid 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 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

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<tr>
<td>Limitation of over stretch + Stiffness</td>
<td>12 cases</td>
</tr>
<tr>
<td>Stiffness</td>
<td>8</td>
</tr>
<tr>
<td>Limitation of over stretch</td>
<td>6</td>
</tr>
<tr>
<td>Decreased lordosis + Stiffness</td>
<td>3</td>
</tr>
<tr>
<td>Decreased lordosis + Limitation of over stretch</td>
<td>3</td>
</tr>
<tr>
<td>Normal</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Roentgenographic Findings of the Grafted Bone of Posterior Spine Fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Pseudoarthrosis-like line&quot; upper margin of bone graft</td>
<td>14</td>
</tr>
<tr>
<td>lower margin of bone graft</td>
<td>7</td>
</tr>
<tr>
<td>upper and lower margin of bone graft</td>
<td>1</td>
</tr>
<tr>
<td>Fracture</td>
<td>3</td>
</tr>
<tr>
<td>Osseous union</td>
<td>4</td>
</tr>
<tr>
<td>Fracture + &quot;Pseudoarthrosis-like line&quot;</td>
<td>1</td>
</tr>
<tr>
<td>Acquired spondylolysis</td>
<td>2</td>
</tr>
<tr>
<td>Unknown</td>
<td>5</td>
</tr>
</tbody>
</table>
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 \( \left( \sigma = \frac{1}{c} \right) \), and thus it has been proved photo-elastically that the fusion of vertebral arches is superior to the fusion of spinous processes. Ondrouč (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 acquired spondyloysis 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 spondyloysis 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 is satisfactory 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

<table>
<thead>
<tr>
<th>Type of &quot;Umbauzone&quot;</th>
<th>Osseous Union</th>
<th>lower margin of upper vertebral body</th>
<th>intermediate type</th>
<th>interspace type</th>
<th>upper margin of lower vertebral body</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Cases</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site of Lesion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L4-L5</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>L5-S1</td>
<td>12</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Site of bone graft</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>~1/3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1/3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>1/2</td>
<td>8</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1/2~</td>
<td>8</td>
<td>8</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

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, its stress decreases approximately 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 its 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 spondylolysis-
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 L₄-S₁, 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 occurs as a sequel to anterior spine fusion, and actually, the author 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 “Pseudoarthrosis-like line,” or “Umbauzone” is apt to occur at the margin of bone graft. Even if the posterior spine fusion is solid without “Pseudoarthrosis-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 occurs 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 approximately 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 intervertebral discs of the fused segment as a sequel to anterior spine fusion remains now in doubt.

The author wishes his grateful acknowledgement to Prof. Dr. ToRAI IWAKARA of Keio University and Dr. MASATAKA NISHIDA of Rikagaku-Kenkyusho for their encouragement and guidance throughout this investigation.
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脊柱固定術の光弾性実験的研究

大 谷 清

脊柱固定術の椎間板の光弾性実験的研究は、昭和17年以降、脊柱疾患の治療法の一つとして注目されている。特に椎間板の光弾性実験は、脊柱固定術の正確な評価を可能にし、脊柱疾患の治療法の進歩を支える重要な研究分野である。

実験材料：脊柱固定術後、脊柱固定板が固定されている椎間板。

実験方法：脊柱固定術後の椎間板を対象として、光弾性実験を行い、椎間板の応力分布を評価する。

実験結果：脊柱固定術後、椎間板の応力は著しく低下し、脊柱の力学的安定性が増大していることが確認された。

まとめ：脊柱固定術の効果を評価することが可能な光弾性実験の導入は、脊柱疾患の治療法の進歩に寄与することが期待される。
び全体固定では椎体に1/2平行に応力が分布する。椎間板では1/3及び1/2固定で後縁に局所的に応力集中が見られるが、2/3及び全体固定ではほぼ平行に応力が分布する。

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11.7gm/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いるが、まこと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。