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Kyoto University
Photoelastic Study on Influence of Spine Fusion upon the Adjacent Vertebrae

by

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(Chairman: Prof. Dr. Torai Iwahara)

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INTRODUCTION

The condition in which the vertebrae are uniting osseously each other, is represented by that of congenital anomalies such as Klippel-Feil's syndrome, post-inflammatory ones such as those seen after tuberculosi or osteomyelitis of the spine, and artificial ones, seen in the spine fusions.

In the congenital synostosis of the spine, as shown in eight cases of operation of Iwahara et al. (1961) and one case of Tomita (1962) in which delayed palsy appears, spinal movement in a long time requires the exceeding motion at the intervertebral discs just above and below synostosis, and make them the Locus minoris resistenteia against injuries. Therefore, dynamic consideration should be given to it's evaluation.

On the other hand, osseous union of the vertebrae after inflammation or vertebral fusion, the block formation in short, is considered to behave in the same way as the congenital synostosis, in a long time after the block formation. And therefore it is important to know the condition of the vertebral column after the block formation from the dynamic aspects.

But there are few investigations on this problem, except only photoelastic studies by Arima (1960), Otani (1965), and a vibration study by Kitamura (1960).

Otani, in his work, has mentioned that anterior 2/3 interbody fusion in antero-posterior diameter or more is desirable. The author, promoting this problem further, analyse the influence of vertebral fusion on the adjacent vertebrae, and disc plates by means of measuring stress distribution through two-dimentioned photoelastic study.

MATERIAL OF THE INVESTIGATIONS

Diallylphthalate (D. A. P.) plates which are recommended by Nishida (1943) are used for the material of these investigations. Size of these plates is 0.6 cm thick and 30 cm square, and the specimens are obtained from the centre of plates where the initial stress is free.

The size of the vertebral body and the intervertebral disc is decided according to data of Ito (1923) (Table 1), and the height of the disc is a half of the height of
vertebral body at the anterior margin, as OTANI's (1963) data indicates.

**Table 1** Measurement of height and antero-posterior diameter of the lumbar vertebrae (Sited from Ito's investigation)

<table>
<thead>
<tr>
<th></th>
<th>Height of the each vertebra (Average)</th>
<th>Distance between anterior margin and gravity axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st lumbar</td>
<td>22.37 (mm)</td>
<td>18.40 (mm)</td>
</tr>
<tr>
<td>2nd lumbar</td>
<td>22.77</td>
<td>17.80</td>
</tr>
<tr>
<td>3rd lumbar</td>
<td>22.80</td>
<td>17.90</td>
</tr>
<tr>
<td>4th lumbar</td>
<td>23.23</td>
<td>18.00</td>
</tr>
<tr>
<td>5th lumbar</td>
<td>21.90</td>
<td>19.20</td>
</tr>
<tr>
<td>1st sacral</td>
<td>—</td>
<td>19.20</td>
</tr>
</tbody>
</table>

The inclination of the various part of the column is decided according to UCHINISHI's (1965) data which was calculated from 114 X-ray of sagittal view of lumbosacral region of normal adults (Table 2).

**Table 2** Angle of the each component of the column (Sited from UCHINISHI's data)

<table>
<thead>
<tr>
<th></th>
<th>Angle corresponding to Ferguson's angle</th>
<th>Angle between the two vertebrae</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd lumbar</td>
<td>-14.5</td>
<td>10.9</td>
</tr>
<tr>
<td>3rd lumbar</td>
<td>-5.7</td>
<td>11.7</td>
</tr>
<tr>
<td>4th lumbar</td>
<td>4.6</td>
<td>14.0</td>
</tr>
<tr>
<td>5th lumbar</td>
<td>18.5</td>
<td>15.7</td>
</tr>
<tr>
<td>1st sacral</td>
<td>36.9</td>
<td>15.7</td>
</tr>
</tbody>
</table>

In this method, the specimens of vertebral column from the 2nd to the upper half of the 1st sacral spine are made.

Specimens consist of nine kinds, such as:

i) Normal vertebral column as the control (non-fusion column).

ii) Two specimens of the whole interbody space fusion, one is of the 4th and the 5th lumbar vertebral body fusion, and the other is of the 5th lumbar and the 1st sacral body.

iii) Two specimens of anterior 2/3 interbody fusion in anteroposterior diameter, one is the 4th and the 5th lumbar vertebral body fusion, and the other is of the 5th lumbar and the 1st sacral body.

iv) Two specimens of posterior 2/3 interbody fusion in anteroposterior diameter, one is of the 4th and the 5th lumbar vertebral body fusion, and the other is of the 5th and the 1st sacral body fusion.

v) Two specimens of the vertebral arch fusion, so called the posterior fusion, and one is of the 4th and the 5th lumbar vertebral arch fusion, and the other is of the 5th and the 1st sacral arch fusion. In these cases, the space of fusion is same as that of iii) and iv), above.

YOUNG's medius and photoelastic sensitivity of these plates are as Table 3.
PHOTOELASTIC STUDY ON INFLUENCE OF SPINE FUSION

Table 3 Photoelastic characteristics of the materials

<table>
<thead>
<tr>
<th></th>
<th>thickness</th>
<th>YOUNG's modulus</th>
<th>photoelastic sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal lumbar vertebral column</td>
<td>5.45 (mm)</td>
<td>138.5 (kg/mm²)</td>
<td>0.870 (mm/kg)</td>
</tr>
<tr>
<td>Whole interbody space fusion</td>
<td>5.35</td>
<td>185.9</td>
<td>0.874</td>
</tr>
<tr>
<td>Ant. 2/3 I-B. S. F. in A-P diam.</td>
<td>5.25</td>
<td>155.8</td>
<td>0.765</td>
</tr>
<tr>
<td>Post. 2/3 I-B. S. F. in A-P diam.</td>
<td>5.35</td>
<td>185.9</td>
<td>0.874</td>
</tr>
<tr>
<td>Vertebral arch fusion</td>
<td>5.50</td>
<td>120.4</td>
<td>0.897</td>
</tr>
<tr>
<td>Disc plates (common to all)</td>
<td>5.80</td>
<td>27.9</td>
<td>1.407</td>
</tr>
</tbody>
</table>

**PRINCIPLES OF PHOTOELASTIC EXPERIMENTS**

**Isocromatic Lines:**
Isocromatic lines are obtained by taking two plates of photograph, namely the dark fielded and the light fielded.

When the specimen is given load in the system of photoelastic polariscope, which has two quarter wave plates, polarizer and analyser, photoelastic fringe patterns are elicited.

This couple of photograph, which consist of a dark field photograph and a light field one is indispensable for the photoelastic study in order to analyse stress distribution.

**Isoclinic Lines:**
These are the lines which connect each point where the direction of stress is equal. By describing these lines, the principal stress lines are decided.

**Principal Stress Lines:**
Theses lines mean a group of curves which indicate the direction of stress easily.

**Stress Distribution:**
Photoelastic fringe patterns are proportionate to differential stress in the midst of the specimen. So on the free boundary, fringe order indicates amount of stress at that place.

Stress is calculated as follows;

\[
\sigma = \frac{N}{\alpha t}
\]

\( \sigma \) : amount of stress (kg/mm²)

\( N \) : fringe order

\( t \) : thickness of specimen (mm)

\( \alpha \) : photoelastic sensitivity (mm/kg)

**METHOD OF LOADING**

There are many concepts on the axis of gravity of human body in standing position, but there exists no established theory yet.

ASMUSSEN (1962)\(^9\) has insisted that the axis of gravity falls about 1 cm anteriorly from the margin of the 4th lumbar spine. BRAUNE & FISCHER, ITO (1923)\(^{23}\) and MESCHEIN (1960)\(^{34}\) have described that it falls on the upper surface of the 1st sacral spine. UCHINISHI (1965)\(^{55}\) has mentioned that the 3rd lumbar spine is settled horizontally in the standing neutral position, and the axis of gravity falls down at a right angle to it.

BRAUNE & FISCHER and ITO have argued that the gravity axis links the anterior margin of the 2nd and the 7th cervical spines, after passing in front of the thoracic
Experiment I: The Spine Fusions of the 4th and the 5th Lumbar Vertebrae

i) Normal vertebral column: Isochromatic lines are as Fig. 2; Isoclinic lines are as Fig. 3; Principal stress lines are as Fig. 4; and stress distribution is as Table 4 and Fig. 5.

According to them, the axis of gravity at the part of the 2nd lumbar spine exists slightly anteriorly from the center of the vertebral body. In the author's investigations, load of about 50 kg will be given at that place (Fig. 1).

Stress is analysed in this loading method and in photoelastic measurements mentioned above. But specimens are different in thickness, Young's modulus and photoelastic sensitivity each other, and so correction must be done in the following equation.

\[ \sigma = \frac{N}{t} \times \frac{t}{t_0} \times \frac{\alpha_0}{\alpha} \times \frac{p_0}{p} \quad (2) \]

where:
- \( t \): thickness of the normal vertebral column (mm)
- \( \alpha \): photoelastic sensitivity of the normal column (mm/kg)
- \( p_0 \): load to the normal column (kg)
- \( p \): load to the various specimen (kg)

**PROCEDURE OF EXPERIMENTS**

Experiment I: The Spine Fusions of the 4th and the 5th Lumbar Vertebrae

i) Normal vertebral column: Isochromatic lines are as Fig. 2; Isoclinic lines are as Fig. 3; Principal stress lines are as Fig. 4; and stress distribution is as Table 4 and Fig. 5.

ii) The whole interbody space fusion: Isochromatic lines are as Fig. 6; Isoclinic lines are as Fig. 7; Principal stress lines are as Fig. 8; and stress distribution is as Table 4

<table>
<thead>
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<tbody>
<tr>
<td>Lower L3</td>
<td>0.841 (kg/mm²)</td>
<td>0.681</td>
<td>0.909</td>
<td>0.812</td>
<td>0.980</td>
</tr>
<tr>
<td>L3-S1 Disc</td>
<td>0.890</td>
<td>0.720</td>
<td>0.980</td>
<td>0.980</td>
<td>1.540</td>
</tr>
<tr>
<td>L3-S1 Disc</td>
<td>0.306</td>
<td>0.440</td>
<td>0.369</td>
<td>0.490</td>
<td>0.480</td>
</tr>
<tr>
<td>Upper S1</td>
<td>0.480</td>
<td>0.480</td>
<td>0.249</td>
<td>0.235</td>
<td>0.490</td>
</tr>
<tr>
<td>Lower L4</td>
<td>0.841</td>
<td>0.681</td>
<td>0.900</td>
<td>0.720</td>
<td>0.940</td>
</tr>
<tr>
<td>L4-S5 Disc</td>
<td>0.735</td>
<td>0.620</td>
<td>0.525</td>
<td>0.680</td>
<td>1.090</td>
</tr>
</tbody>
</table>
and Fig. 9.

iii) The anterior 2/3 interbody fusion in antero-posterior diameter: Isochromatic lines are as Fig. 10; Isoclinic lines are as Fig. 11; Principal stress lines are as Fig. 12; and stress distribution is as Table 4 and Fig. 13.

iv) The posterior 2/3 interbody fusion in antero-posterior diameter: Isochromatic lines are as Fig. 14; Isoclinic lines are as Fig. 15; Principal stress lines are as Fig. 16; and stress distribution is as Table 4 and Fig. 17.

v) The vertebral arch fusion: Isochromatics are as Fig. 18; Isoclinics are as Fig. 19; Principal stress lines are as Fig. 20; and stress distribution is as Table 4 and Fig. 21.

Experiment II: The Vertebral Fusion of the 5th Lumbar and the 1st Sacral Vertebrae

i) The whole interbody space fusion: Isochromatic lines are as Fig. 22; Isoclinic lines are as Fig. 23; Principal stress lines are as Fig. 24; and stress distribution is as Table 4 and Fig. 25.

ii) The anterior 2/3 interbody fusion in antero-posterior diameter: Isochromatic lines are as Fig. 26; Isoclinic lines are as Fig. 27; Principal stress lines are as Fig. 28; and stress distribution is as Table 4 and Fig. 29.

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![Fig. 2](image_url)  
**Fig. 2** Isochromatics in the normal spinal column

**Fig. 2-a** Dark field  
**Fig. 2-b** Light field

At the spinous processes the fringe order is 0. At the vertebral bodies, the fringe order is highest at the posterior margins from the 2nd vertebral body to the 5th. The maximum is 4.0, and it exists at the posterolower part of the 3rd lumbar body and at the posteroupper part of the 4th lumbar.

The anterior part of the lumbar column is mainly occupied by negative fringes.
iii) The posterior 2/3 interbody fusion in antero-posterior diameter: Isochromatic lines are as Fig. 30; Isoclinic lines are as Fig. 31; Principal stress lines are as Fig. 32; and stress distribution is as Table 4 and Fig. 33.

iv) The vertebral arch fusion: Isochromatics are as Fig. 34; Isoclinics are as Fig. 35; Principle stress lines are as Fig. 36; and stress distribution is as Table 4 and Fig. 37.

Fig. 3 Isoclinics of the normal column  
There is the singular point at anterior part of the intervertebral disc place between L3 and L4. The anterior part from the point, there exists a tensile stress. The isoclinics concentrate on the upper edge of each vertebral arch.

Fig. 4 Principal stress lines in the normal column  
The principal stress lines demonstrate that the stress mainly concentrates in the posterior part of the column. At the anterior margin of the column there is tensile stress.

Fig. 5 Stress distribution in the normal column  
Stress is estimated according to the equation (1) and (2). The maximum is 0.841 kg/mm² at the postero-lower part of L₃ and postero-upper part of L₄. At the posterior margin of the intervertebral disc plate L₂₋₄ is 0.890 kg/mm².
Fig. 6 Isochromatics in the whole interbody space fusion

Fig. 6-a. Dark field

Isochromatics are resembling those of the normal column. Fringe order 4 is located at L₄ and L₅. L₃ is the same in the postero-lower margin. At the intervertebral disc L₃-L₄, the maximum is 10.

Fig. 6-b. Light field

Fig. 7 Isoclinics in the whole interbody space fusion

These are also resembling to those of the normal column. The location of the singular point is same.
Fig. 8 The principal stress lines of the whole interbody space fusion
Compressive stress is mainly concentrated in the posterior part of the column.

Fig. 9 Stress distribution in the whole interbody space fusion
As demonstrated in Fig. 9 and Table 1, 0.681 kg/mm² at L₃, 0.720 kg/mm² at L₃₋₁ plate, 0.440 kg/mm² at L₄₋₁ plate.

Fig. 10 Isochromatics of the anterior 2/3 A-F diameter interbody fusion
Fig. 10-a Dark field
3.5 fringe is at the posterolower part of L₃₋₁ plate. 0.5 fringe is at the anterior margin of L₃. The postero-upper part of S₁₋₁ is 0.5 and at the anterior margin the fringe order is 3.0.
Fig. 11 Isoclines of the anterior interbody fusion
The singular points are at the L₃₋₄ disc plate and the posterior part of the grafted bone.

Fig. 12 Principal stress lines of the anterior 2/3 A–P diameter interbody fusion
At the postero-lower part of L₃ and the postero-upper part of S₁, trajectories slightly remove towards anterior margin.

Fig. 13 Stress distribution of the anterior 2/3 A–P diameter interbody fusion
As Fig. 13 and Table 1 demonstrate, the maximum stress at the lower part of L₃ is 0.909 kg/mm² and 0.980 kg/mm² at the L₃₋₄ disc plate. At the disc plate between L₃ and S₁, there is 0.369 kg/mm² and at the upper part of the S₁, there is 0.249 kg/mm².
**Fig. 14** Isochromatics of the posterior 2/3 A-P diameter interbody fusion

**Fig. 14-a** Dark field

The maximum fringe order of L₃ is 4 at the postero-lower part of it. The maximum of L₃₋₄ is 9 at the posterior margin. At the part below the fusion the maximum fringe apt to move anteriorly.

**Fig. 15** Isochlinies of the posterior 2/3 diameter interbody fusion

The singular points are at L₃₋₄ disc plate and the anterior part of the grafted bone.

**Fig. 16** Principal stress lines of the posterior 2/3 diameter interbody fusion

These lines apt to move posteriorly at the part above the fusion. But at the part below, this inclination is not so clear as above.
Fig. 17 Stress distribution of the posterior 2/3 diameter fusion

As Fig. 17 and Table 1, 0.812 kg/mm² is at the postero-lower part of L3. 0.980 kg/mm² at L4-5 disc plate. At the part below the fusion the maximum stress is at slightly anterior part from the posterior margin. At the posterior margin of L5-S1 disc plate, 0.490 kg/mm², and at the posterior-upper part of S1, there exists 0.235 kg/mm².

Fig. 18 Isochromatics of the vertebral arch fusion

Fig. 18-a Dark field

At the L3-4 disc plate, the maximum fringe, 12.8, is at the posterior margin. At the postero-lower part of L3, there is 4.6 fringes. At the disc plate and spinal body below the fusion, the fringe order is 3.0 and 1.5 at the posterior margin respectively.

Fig. 18-b Light field
Fig. 19 Isoclines of the vertebral arch fusion
The singular points are at L3-4 disc plate and the fused arch.

Fig. 20 Principal stress lines of the vertebral arch fusion
Principal stress lines are conspicuously move towards posteriorly at the parts above and below the fusion.

Fig. 21 Stress distribution of the vertebral arch fusion
As Fig. 21 and Table 4 shows, the maximum stress at L3 and L3-4 plate is 0.980 kg/mm² and 1.540 kg/mm² respectively. At the L5-S₁ plate, it is 0.480 kg/mm², and at the postero-upper part of S₁ is 0.490 kg/mm².
PHOTOELASTIC STUDY ON INFLUENCE OF SPINE FUSION

Fig. 22 Isochromatics of the whole interbody space fusion

Fig. 22-a Dark field  Fig. 22-b Light field

Alike to Fig. 6. At the upper surface of S1, from 1.5 and to 2.5 fringes occupy all over the surface evenly. It may be considered that stress works evenly on the sacrum in this type of fusion.

Fig. 23 Isoclinics of the whole interbody space fusion

Little difference from Fig. 7. The singular point exist at the border of L3 spinal body and L3-4 disc plate.

Fig. 24 Principal stress lines of the whole interbody fusion

These lines are same as Fig. 8.
Fig. 25 Stress distribution of the whole interbody space fusion

As Fig. 25 and Table 4 demonstrate, at the postero-lower part of L4, stress is 0.681 kg/mm² and 0.620 kg/mm² at the L₄₋₅ disc plate. At the anterior margin of the L₄₋₅ disc plate, stress is 0.122 kg/mm².

Fig. 26 Isochromatics of the anterior 2/3 A–P diameter interbody fusion

Fig. 26-a Dark field

Fig. 26-b Light field

At the postero-lower part of L₄, the fringe order is 4.0. At the posterior margin of the disc, it is 8.5.
PHOTOELASTIC STUDY ON INFLUENCE OF SPINE FUSION

Fig. 27 Isoclinics of the anterior 2/3 A-P diameter interbody fusion
The singular points are at L₃-₄ disc plate and in the grafted bone.

Fig. 28 Principal stress lines of the anterior 2/3 A-P diameter interbody fusion
At the upper parts above the fusion, trajectories are slightly removig anteriorly.

Fig. 29 Stress distribution of the anterior 2/3 A-P diameter interbody fusion
At the posterior lower part of L₄, stress of 0.900 kg/mm² exists, and at the posterior margin of L₃-₄ disc plate, 0.525 kg/mm² acts.
Fig. 30  Isochromatics of the posterior 2/3 A-P diameter interbody fusion
Fig. 30-a  Dark field
At L₁ there is 3.5 fringes. At the posterior margin of L₁₅ disc plate, there exist 7.5 fringes.

Fig. 31  Isochoomes of the posterior 2/3 A-P diameter interbody fusion
The singular or air points are at the L₃-₄ disc plate and in the grafted bone.

Fig. 32  Principal stress lines of the posterior 2/3 A-P diameter interbody fusion
Trajectories slightly concentrated in the posterior part above the fusion.
Fig. 33 Stress distribution of the posterior 2/3 A–P diameter interbody fusion

Stress of L₄ postero-lower part is 0.720 kg/mm², 0.680 kg/mm² at the posterior margin of L₁₋₅ disc plate.

Fig. 34 Isochromatics of the vertebral arch fusion

Fig. 34-a Dark field

Fig. 34-b Light field

The maximum fringe at the postero-lower part of L₄ is 5.4. At the posterior margin of L₁₋₅ disc plate, it is 9.0.
Fig. 35 Isoclinics of the vertebral arch fusion

These are complicated like Fig. 19, and singular points are at the anterior part of L₃-₄ disc plate and at the fused vertebral arch.

Fig. 36 Trajectories of the vertebral arch fusion

Though not conspicuous as in the case of the 4th and the 5th lumbar vertebral arch fusion, trajectories remove towards posterioly.

Fig. 37 Stress distribution of the vertebral arch fusion

As shown in Fig. 37 and Table 4, the maximum is at the posterior margin of the column. At the postero-lower part of L₄, 0.940 kg/mm² acts and at the posterior margin of the L₄-₅ disc plate, 1.090 kg/mm² of stress acts.
RESULTS OF EXPERIMENTS

I) Normal vertebral column: The compression occupies the posterior large part and the tension occupies the anterior part of the column from the 2nd lumbar vertebra to the 5th. At the L₅-S₁ intervertebral disc and the 1st sacral vertebra, stress apts to distribute evenly. The tension disappears and the maximum of compression reduces. The maximum stress of the vertebral bodies is 0.841 kg/mm² at the 3rd and 4th lumbar vertebrae, and the maximum stress of the intervertebral discs is 0.890 kg/mm² at the L₃-L₄ intervertebral disc.

II) The whole interbody space fusion: Trajectories are same as that of the normal vertebral column. Difference of stress at the part above and below the fusion is little between this type of fusion and the normal column, and therefore this type of fusion is to be said excellent from the dynamical or kinetic view.

III) The anterior 2/3 interbody fusion in antero-posterior diameter: Trajectories are localized on the grafted part in the fused vertebrae. At the parts above and below fusion, the maximum stress is considered to be localized a little anteriorly from the posterior margin of the column. Compressive stress at the posterior margin of the lower L₃ in the case of L₄ and L₅ fusion is 0.909 kg/mm², and it is 108.1% of the normal at the same place. At the L₃-L₄ disc plate, it is 0.980 kg/mm² and is 110.1% of the normal. At the L₅-S₁ disc plate, it is 0.369 kg/mm² and at the 1st sacral vertebra, it is 0.249 kg/mm². In the case of L₃ and S₁ fusion, it is 0.900 kg/mm² at the L₄ and it coincides in 107.0% of the normal column.

IV) The posterior interbody fusion in 2/3 antero-posterior diameter: Trajectories are slightly localized on the grafted part in the fused vertebrae. They apt to move posteriorly in slight degree at the part above fusion. In this type of fusion, the maximum stress is at the posterior margin of the column, and 0.812 kg/mm² at the lower L₃ and 0.980 kg/mm² at the L₃-L₄ intervertebral disc. These two are 96.5% and 112.3% of the normal.

V) The vertebral arch fusion: Trajectories are much localized on the posterior margin of the column at the part above fusion and at the part below. The maximum stress is:

![Graph showing maximum stress of various fusions](image)
stress of the adjacent place of fusion is at the posterior margin of the column. At the lower L₃, maximum stress is 0.980 kg/mm², and it is 116.4% of the normal, and at the L₄-L₅ intervertebral disc, the maximum is 1.540 kg/mm², 171.9%. In the case of the 5th lumbar and 1st sacral vertebral fusion, the max. stress at the L₄ is 0.940 kg/mm², 110.9%, and at the L₄-L₅ intervertebral disc, the max. is 1.090 kg/mm², 30.2%. At the L₅-S₁ intervertebral disc, the lower adjacent disc of fusion, the max. stress is 0.480 kg/mm².

These data are illustrated in Table 4 and Fig. 38.

DISCUSSION

Considerations on Photoelastic Study

Dynamic considerations on vertebral column are very important to solve the mechanism of vertebral or cord injuries, disc degeneration and deforming changes of vertebral bodies. ARIGA (1935)¹¹, NAGURA (1939)¹⁹, AOIKE (1942)²³ and OGAWA (1960)⁴² reported the data about solidity of vertebral bodies and disc plates, and ARIGA decided the YOUNG's modulus of vertebral bodies and disc plates to be 265.5 kg/cm² and 107.23 kg/cm² respectively. But all these experiments are those using the post-mortem specimen and there is no consideration on the inner structure of the vertebral column.

Photoelastic study started in BREWSTER (1815), and it has been used in the field of engineering and architecture because it is useful to calculate stress distribution. Since ZAK (1935)⁴⁷, MILCH (1939)³⁶, MASABAYASHI (1950)³², AJIMA (1953)⁵⁹ and others have induced it mainly into orthopedics and odontology.

Though the photoelastic study is experiments using artificial models, the principles on the dynamical standpoint are same as human body, and results obtained from the experiments can be considered to be corresponding with the clinical features.

Considerations on Vertebral Fusion

Since WATKINS (1886) or HADRA (1891) tried to fuse the spinous processes using silver wire, three types of vertebral fusion are prevailing nowadays. They are the vertebral body fusion by anterior approach and by posterior approach, and the vertebral arch fusion which we call the posterior fusion.

In the vertebral arch fusion actually started in ALBEE (1911)¹¹ and HENLE, many methodical variations by HIBBUS, HENRY-GEIST (1933)¹⁹, CALVE and so on, followed. BOSWORTH (1945)¹³ reported the clothes-pin method, and it is usually used for the lumbosacral fusion.

However, SHAW (1956)⁴⁸ and Ut (1960)⁵⁴ have found frequent occurrence of pseudoarthrosis and fracture of grafted bone in the vertebral arch fusion. They have discussed that it may have resulted from the problem of the graft-bed and existence of "lever" mechanism. YAMASHITA et al. (1963)⁶⁰ also have observed the unsuccessful fusion and fracture of the grafted bone in twenty three cases among thirty posterior fusions. According to OTANI, the posterior fusion is inferior to the anterior body fusion from the point of stress distribution and concentration.

Even though this type of fusion is easy and popular, it should be considered to have disadvantages in dynamical view.

On the other hand, the interbody fusion by anterior approach in which two types of
operation took part, namely fusion of transperitoneal approach by Capener (1932)\textsuperscript{14}, Burnes, Mercer, Speed (1938)\textsuperscript{49} and so on, and that of extraperitoneal approach by Iwahara (1944)\textsuperscript{25} has many indications for spondylolysis, spondylolisthesis, disc hernia, spondylitis tuberculosis and so on. In these types of operations the anterior part of vertebral bodies is widely exposed, and vertebral bodies can be fused sufficiently. Iwahara et al. (1963)\textsuperscript{27} have discussed that when the grafted bone is too small, there often occur "Umbauzone" in the anterior body fusion. Mitani (1966)\textsuperscript{37} has observed a case of "Umbauzone" after anterior fusion, where inserted too small graft and re-operation had to be done because of newly ossified bone.

The trial to fuse vertebral bodies after removal of disc hernia in order to prevent instability from degenerated disc plates, started in Jaslows (1946)\textsuperscript{23}. Since then Cloward (1953)\textsuperscript{13,14}, James et al., DuToit, Wiltberger (1957)\textsuperscript{58}, Dommis (1959)\textsuperscript{49} and others published the similar method of spine fusion. It is considered to be useful not only in disc hernia, but in spondylolysis and spondylolisthesis of slight degree. Yamaguchi et al. (1964)\textsuperscript{61} have reported this method of operation is useful in reducing the lumbar lordosis in forty six cases.

In photoelastic results mentioned above, there exists tensile stress in the anterior part of the vertebral body and compressive stress in the posterior large part of the column. When the graft is inserted between the bodies, at the portion where compression exists, the consolidation or bony union will be well expected. The reason is due to the fact that if the graft occupies the place where tension exists, the contact between the graft and the graft-bed is not enough, and if it exists at the place of compressive stress, contact between the two is sufficient and the moderate compression influences profitably on the bony union. Therefore, the graft is desired to be inserted at the place of compressive stress.

From this point of view, the large graft is required to be inserted. In the case of spinal interbody fusion, even though it may be by anterior or posterior approach, the graft should be inserted at the part where compression stress exists.

The fact that too small graft sometimes results in the occurrence of "Umbauzone", may be thought to depend on this photoelastic consideration.

As mentioned above, spine fusion has usually three types of operation, but each of them should be said to have necessity of dynamic criticism.

Influence of Spine Fusion

Nozaki (1934)\textsuperscript{11} discussed uselessness of Albew's operation, as five cases among seven were unsuccessful. Ut has found high frequency of pseudoarthrosis and fracture of the graft in cases of the vertebral arch fusion by H shaped graft. He has insisted, as the cause of it, on mobility of the lumbosacral region, problem of graft-bed and lever mechanism in the posterior part of the vertebral column.

Hasegawa (1956)\textsuperscript{21} and Mensor (1955)\textsuperscript{14} have mentioned that the lower lumbar region have much mobility. Therefore, stress-change by body motion easily produces the above mentioned changes in the grafted bone.

Unander-Scharin (1950)\textsuperscript{55}, Anderson (1956)\textsuperscript{23} and De Palma (1959)\textsuperscript{48} reported one case of acquired spondylolysis after spine fusion, respectively. Three cases of Sullivan et al. (1960)\textsuperscript{49}, six cases of Harris et al. (1963)\textsuperscript{20} and five cases of Rombold (1965)\textsuperscript{49} are also spondylolysis at the uppermost vertebra of spine fusion, and except one case of the
interbody fusion of Unander-Scharin, all of them are of the posterior fusion. Harris
has argued that the cause of acquired spondylolysis is rotation combined with flexion, and
that a unilateral fracture of part interarticuralis is made on the side on which the rotation
is made from back to front. Further, flexion and extention alone is not causing fracture
of it.

In the case of the vertebral arch fusion, the arch of the uppermost vertebral of fusion
and the disc plate just above fusion are, as mentioned in author’s investigations, of con-
centrated compressive stress, and they are near the fulcrum of lever mechanism in lumbo-
sacral motion. Therefore, they are considered to be the weakpoint from mechanical view.

Concerning to influence of spine fusion on the adjacent intervertebral disc plates and
vertebrae, there are few previous investigations.

Watanabe (1959) has observed in his experiments using dogs, that the anterior
interbody fusion does not make any change in the adjacent disc plates. However, Unander-
Scharin (1950) found seven cases of disc degeneration in the disc plate just above the
osteosynthesis among eighty cases of the posterior fusion. He has presumed that the disc
just above the osteosynthesis is exposed immediatly to increased tear and wear. In such
manner, the vertebral arch fusion should be said to have problems above influence on the
vertebral column after the operation.

On the other hand, Armstrong (1958) has quoted that pressure on the disc greatly
increased by the “lever” action which comes into play when the arms are used. If the
nucleus pulposus of a lower lumbar disc is considered as the fulcrum of movement and a
heavy object is lifted with the hands, the arm and trunk form a long anterior “lever”.
The erectores spinae act posteriorly as a much shorter “lever”. Therefore, if a weight of
100 lb. is lifted, the discs subjected to a total pressure of 1600 lb., because the ratio between
the anterior and posterior lever is computed as about 15 to 1. Bartelink (1957) has
observed in his study, using E. M. G. and small balloon in the stomach, that such large
amount of pressure does not act on the discs, but less pressure acts owing to the abdominal
fluid ball and contraction of transverse and oblique abdominal muscles.

Agreeing with the two, a large amount of pressure is thought to act on the disc plates,
and role of pressure toward the disc lesions is also thought important. Schmorl and
Junghanns (1957) have pointed out that the rupture of annulus fibrosus from disc
degeneration happens to lead to occurence of Spondylosis deformans. In such respects,
stress concentration in the posterior part of the vertebral column, especially of the disc just
above the osteosynthesis, has importance to clinical appearances.

On the other hand, about mobility of the vertebral column after spine fusion, Suzuki
(1958) has described that mobility of the column gets to reduce about three months
after the operation, but that in a year after the operation, the column becomes to get
almost the same mobility as before. But in this work, the further follow-up after one
year is not made and the compensatory mobility near the fusion is not described. Atsuta
(1957 and 1958) has mentioned, concerning to the mobility of the vertebral column
after removal of cast fixation in the cases of spine injuries, the places above the affected
spine obtain more mobility than the below. Matsumura (1960) found more mobility
in the portion above the affected spine than in the portion below, in the cases of spon-
dylitis tuberculosa. Both of them are to be said to suggest change of mobility in the
region above the block formation.

JINNAI (1939) made Spondylosis deformans in the spine of rabbits by bending towards anterior direction after spine injuries. MIYAZAKI (1948) also made Spondylosis deformans by repeated anterior bending alone.

In such ways, when the adjacent portion of the block formation or the vertebral fusion obtains a compensatory mobility to some extent, and when the block formation or the fusion is in the lumbosacral region where much pressure acts, the portion leads to disc degeneration, Spondylosis deformans or other osteoarthritic changes.

In the author's investigations, stress concentration in the disc plates and vertebral bodies just above the vertebral fusion, especially in the case of the vertebral arch fusion, is considered to make themselves Locus minoris resistentiae of the vertebral column. The Locus minoris resistentiae leads to the clinical appearances as mentioned above.

However, the interbody fusion in which vertebral bodies are fused enough in antero-posterior diameter, even though it is by anterior or posterior approach, shows a slight change of stress at the adjacent disc plates and vertebrae. From the clinical view, influence of the intervertebral fusion, when it is done in the sufficient space, may be thought little.

SUMMARY

Through two-dimentioned photoelastic study, in order to solve the influence of the vertebral fusion, the author obtained following results.

1) Stress concentrates mainly in the part of the inserted graft. But in the case of interbody fusion, it is slight and in the case of the vertebral arch fusion stress concentration is conspicuous.

2) Stress change at the disc plates and vertebral bodies just above and below the spine fusion is conspicuous in the vertebral arch fusion.

3) In the whole interbody space fusion, the maximum stress at the disc plates and vertebral bodies just above and below the fusion is almost the same as that of the normal vertebral column.

4) In the anterior 2/3 interbody fusion in A.-P. diameter, the maximum stress at the disc plate just above the the fusion is more than that of the non-fusion column by 10% and at the just below it is more by 16.9%.

5) In the posterior 2/3 interbody fusion in A.-P. diameter, the maximum stress at the disc plate just above the fusion is more than that of the non-fusion column by 12.3% and at the just below it is less by 4.7%.

6) In the vertebral arch fusion, stress concentrates at the posterior margin of the disc plate just above the osteosynthesis. The maximum is more than that of the non-fusion column by 71.9% in 4th and 5th lumbar spine fusion, and by 30.2% in 5th lumbar and 1st sacral spine fusion. At the postero-inferior margin of the vertebral body just above the spine fusion, the maximum stress is more by 16.4% and 10.9%, respectively. At the disc plate, just below the fusion, stress is more by 32.4% in 4th and 5th lumbar spine fusion.

7) In the vertebral arch fusion, the adjacent portion of the fusion is influenced by fusion. It becomes the Locus minoris resistentiae and has possibility or resulting in disc degeneration, Spondylosis deformans or other osteoarthritic changes.
8) In the interbody fusion fused sufficiently, the adjacent portion is considered to make less changes.

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脊椎の癒着が隣接椎に及ぼす影響に関する
光弾性実験的研究

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脊椎の癒着を示すものとして先天性椎癒着症、脊椎カリエス等による塊椎形成、また人工的に癒
合せめる脊椎固定術などがある。

この癒着した脊椎が隣接椎に与える影響を力学的に明らかにせんと二次元光弾性実験を行なった。

実験方法：DAP 薬局を用い第 2 腰椎より第 1 仙椎上部に至る正常腰椎柱、第 4 ・ 5 腰椎間並びに第 5 腰
椎・第 1 仙椎間の椎体前後径付近、椎体前方部 2/3 固定、椎体後方部 2/3 固定、椎体固定、合計 9 コ
の光弾性模型を作成し、等色線、等屈線、主応力線並
びに応力分布曲線を求め、応力値を計算し比較検討す
る。

実験結果：i）椎体前後径付近は主応力線も正常腰
椎柱と変わりなく、応力値の変動も小で力学的に安定し
ている。ii）椎体前方部固定群は主応力線は固定部
分を一様に走向し、隣接椎間板、隣接椎間の応力最大値は第 4 ・ 5 腰椎間でそれぞれ上部 0.980 kg/mm²、0.909kg/mm²、下部 0.569kg/mm²、0.249kg/mm²、第 5 腰椎・第 1 仙椎間では 0.525kg/mm²、0.900kg/mm²である。iii）椎体後方部固定群では主応力線は固定部分を走向し、隣接椎間板・隣接椎の応力最大値は第 4 ・ 5 腰椎間でそれぞれ上部 0.980 kg/mm²、0.812 kg/mm²、下部 0.490 kg/mm²、0.235kg/mm²、第 5 腰椎・第 1 仙椎間で 0.680 kg/mm²、0.720kg/mm²である。iv）椎弓固定群では主応力線は固定隣接部で椎体後部に集中し、特に第 4 ・ 5
腰椎間固定では著明である。隣接椎間板・隣接椎の応力最大値は第 4 ・ 5 腰椎間でそれぞれ上部 1.540kg/mm²、0.980kg/mm²、下部 0.480kg/mm²、0.490kg/mm²である。

第 5 腰椎・第 1 仙椎間固定ではそれぞれ 1.090 kg/mm²、0.940kg/mm²である。

結論：i）固定上・下椎間板、上・下椎に於ける応
力値の変化は椎弓固定に著明である。ii）応力値の変
化は椎体固定にあっては非固定正常腰椎柱の約 20％以
内であるに対して、椎弓固定では約 70％に達する。
iii）椎弓固定による椎体間板、隣接椎の挙げ
板は固定によって影響され、抵抗脆弱部として後続の
椎間板変性、変形性脊椎症等の発生を結びつき得る。
iv）充分に固定された椎体固定の場合にはこの可能性
は少ないと考えられる。