
原 著

Photoelastic Study on Influence of Spine Fusion upon the Adjacent Vertebrae

by

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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 tuberculosis 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)²⁴⁾ and one case of TOMITA (1962)⁵²⁾ 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 resistentiae 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)⁵¹⁾, OTANI (1965)⁴³⁾, and a vibration study by KITAMURA (1960)³⁰⁾.

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-dimensioned photoelastic study.

MATERIAL OF THE INVESTIGATIONS

Diallylphthalate (D. A. P.) plates which are recommended by NISHIDA (1943)⁴⁰⁾ 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)²³⁾ (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)²⁶⁾ data indicates.

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

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

The inclination of the various part of the column is decided according to UCHINISHI's (1965)⁵³⁾ 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)

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

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 fusion.
- 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.

Table 3 Photoelastic characteristics of the materials

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

PRINCIPLES OF PHOTOELASTIC EXPERIMENTS

Isochromatic Lines :

Isochromatic 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 ;

$$\sigma = \frac{N}{t\alpha} \dots\dots\dots (1)$$

σ : amount of stress (kg/mm²)

N : fringe order

t : thickness of specimen (mm)

α : 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)⁸ 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 MESCHAN (1960)³⁵ have described that it falls on the upper surface of the 1st sacral spine. UCHINISHI (1965)⁵³ 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

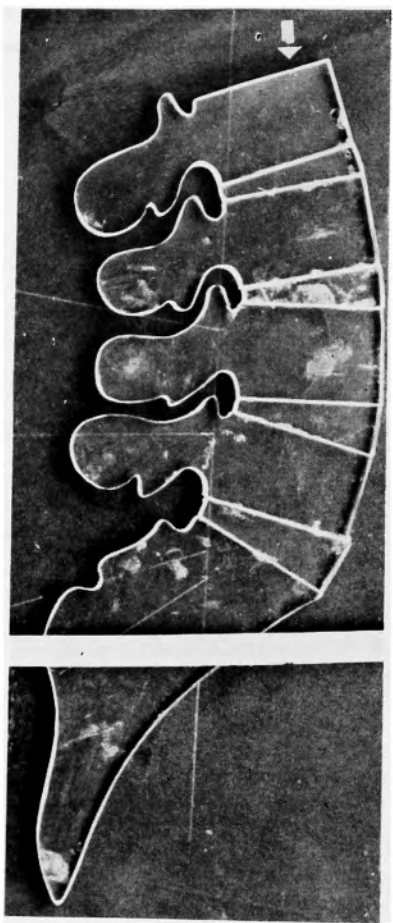


Fig. 1 Method of loading

The gravity axis is coincident at the part of marking in L₂.

vertebral column, it meets the anterior margin of the 1st lumbar spine, and falls on the anterior part of the upper surface of the 1st sacral spine, after passing in the midst of the lumbar column.

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 medius and photoelastic sensitivity each other, and so correction must be done in the following equation.

$$\sigma = \frac{N}{t\alpha} \times \frac{t}{t_0} \times \frac{\alpha}{\alpha_0} \times \frac{p_0}{p} \dots\dots (2)$$

- t : thickness of the normal vertebral column (mm)
- α : photoelastic sensitivity of the normal column (mm/kg)
- p₀ : 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 4 Stress at the posterior margin of the vertebral column

		Normal Col.	Whole Fus.	Ant. 2/3 S. Fus.	Post. 2/3 S. Fus.	Ver. Arch. Fus.
L ₁ & L ₅ Fus.	Lower L ₃	0.841 (kg/mm ²)	0.681	0.909	0.812	0.980
	L ₃₋₄ Disc	0.890	0.720	0.980	0.980	1.540
	L _{5-S} ₁ Disc	0.306	0.440	0.369	0.490	0.480
	Upper S ₁	0.480	0.480	0.249	0.235	0.490
L ₃ & S ₁ Fus.	Lower L ₄	0.841	0.681	0.900	0.720	0.940
	L ₄₋₅ Disc	0.735	0.620	0.525	0.680	1.090

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.

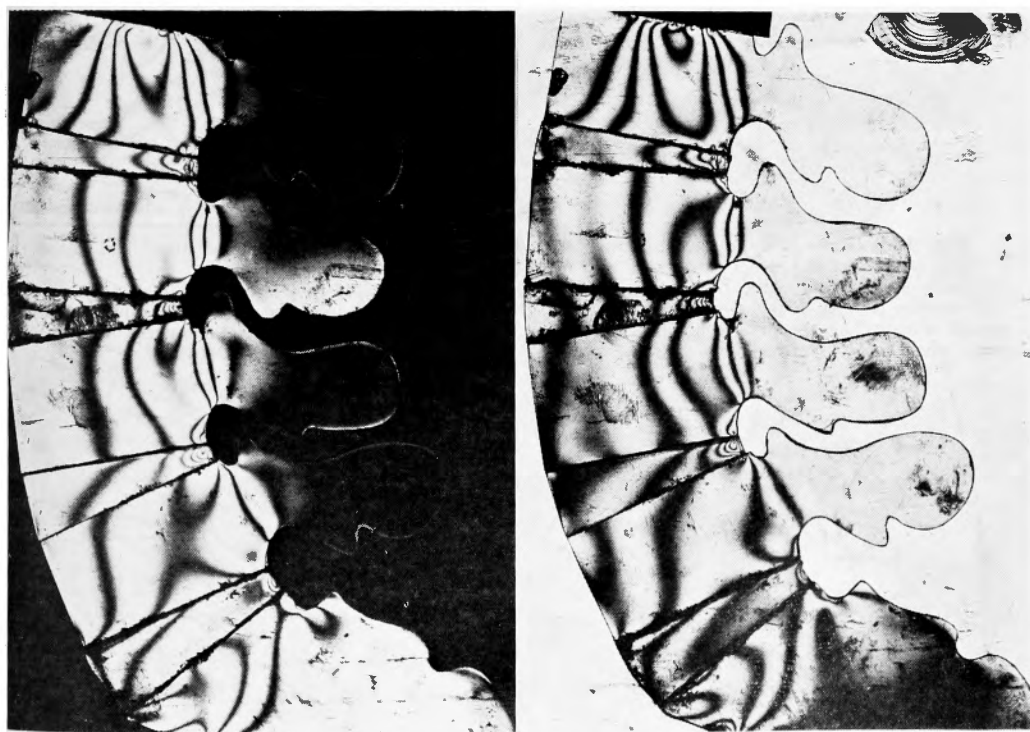


Fig. 2 Isochromatics in the normal spinal column

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 postero-lower part of the 3rd lumbar body and at the postero-upper 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.

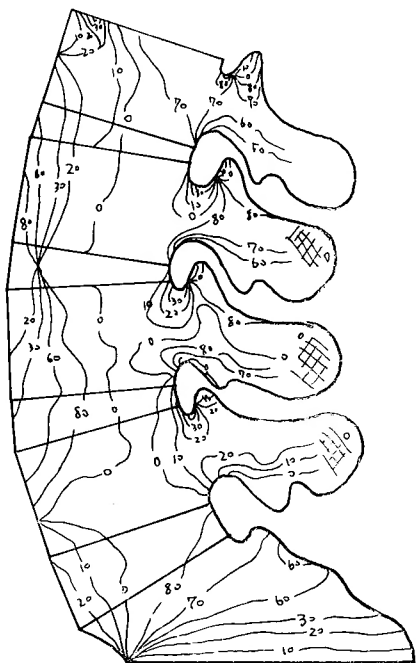


Fig. 3 Isoclinics of the normal column

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.

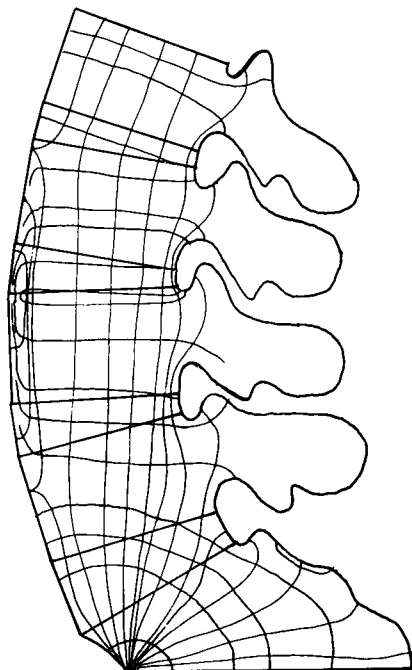


Fig. 4 Principal stress lines in the normal column

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.

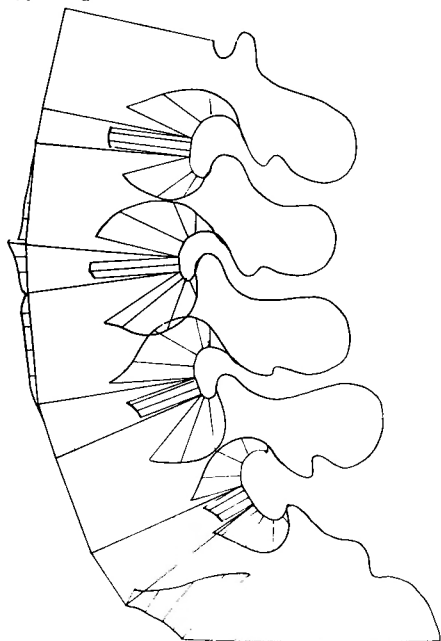


Fig. 5 Stress distribution in the normal column

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 L₃₋₄ is 0.890 kg/mm².



Fig. 6 Isochromatics in the whole interbody space fusion

Fig. 6-a. Dark field

Fig. 6-b. Light field

Isochromatics are resembling those of the normal column. Fringe order 4 is located at L_4 and L_5 . L_3 is the same in the postero-lower margin. At the intervertebral disc L_3-L_4 , the maximum is 10.

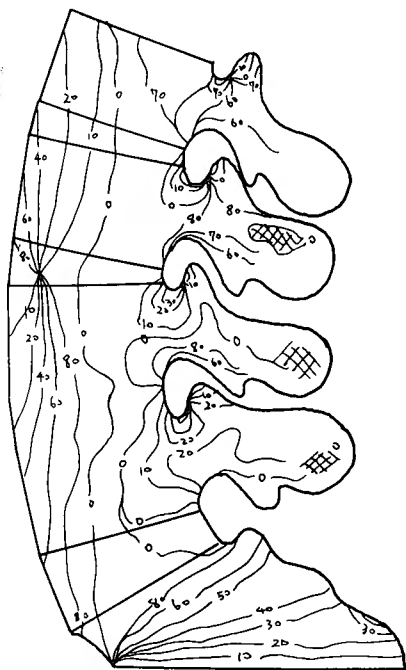


Fig. 7 Isoclinics in the whole interbody space fusion

These are also resembling to those of the normal column. The location of the singular point is same.

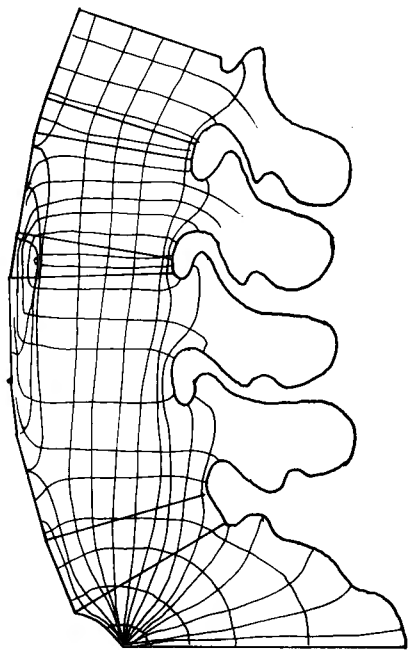


Fig. 8 The principal stress lines of the whole interbody space fusion

Compressive stress is mainly concentrated in the posterior part of the column.

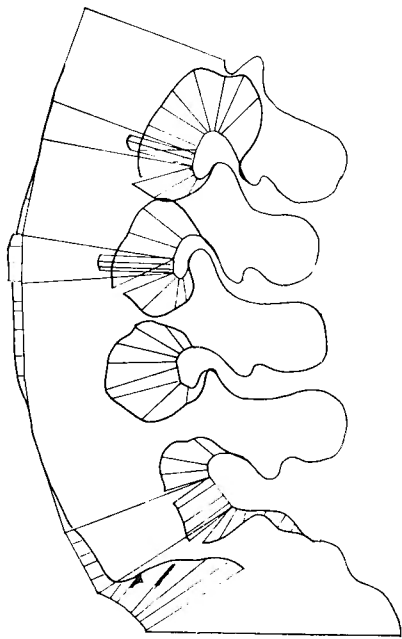


Fig. 9 Stress distribution in the whole interbody space fusion

As demonstrated in Fig. 9 and Table 4, 0.681 kg/mm² at L₃, 0.720 kg/mm² at L₃₋₄ plate, 0.440 kg/mm² at L_{5-S₁} plate.

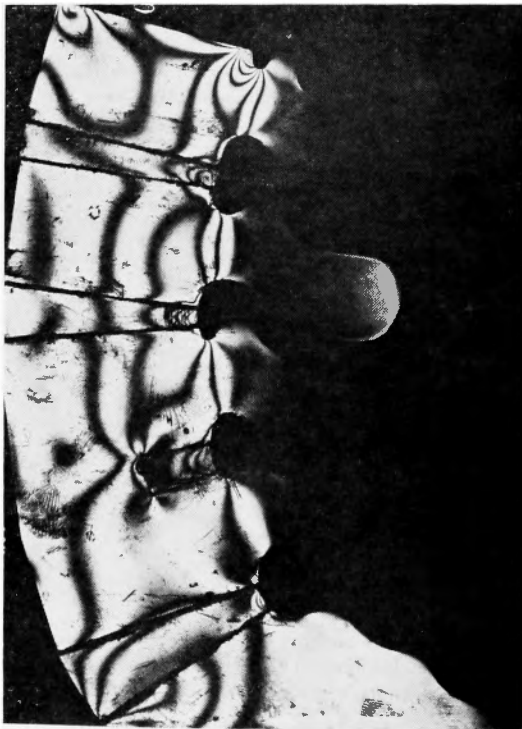


Fig. 10 Isochromatics of the anterior 2/3 A-F diameter interbody fusion
Fig. 10-a Dark field

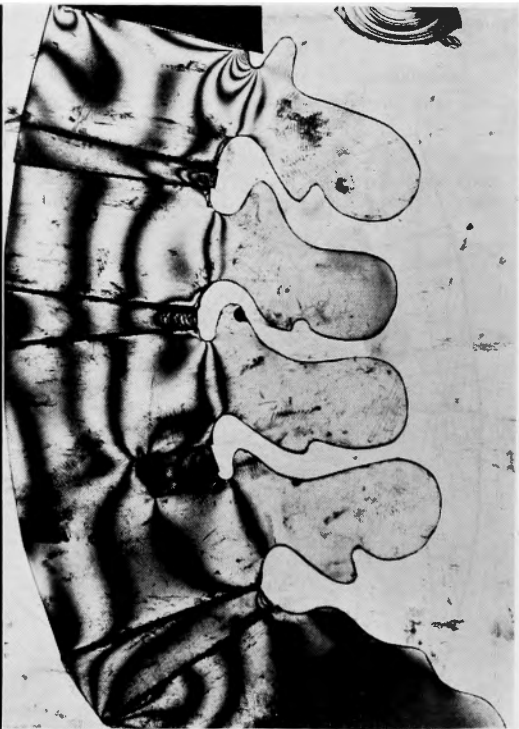


Fig. 10-b Light field

+3.5 fringe is at the postero-lower part of L₃. -0.5 fringe is at the anterior margin of L₃. The postero-upper part of S₁'s is 0.5 and at the anterior margin the fringe order is 3.0.

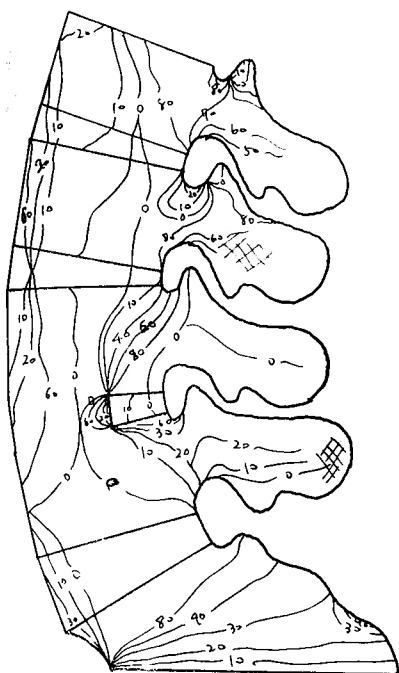


Fig. 11 Isoclinics of the anterior interbody fusion

The singular points are at the L_{3-4} disc plate and the posterior part of the grafted bone.

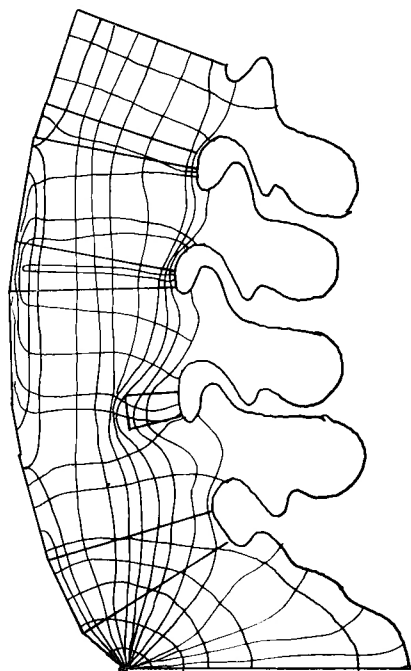


Fig. 12 Principal stress lines of the anterior 2/3 A-P diameter interbody fusion

At the postero-lower part of L_3 and the postero-upper part of S_1 , trajectories slightly remove towards anterior margin.

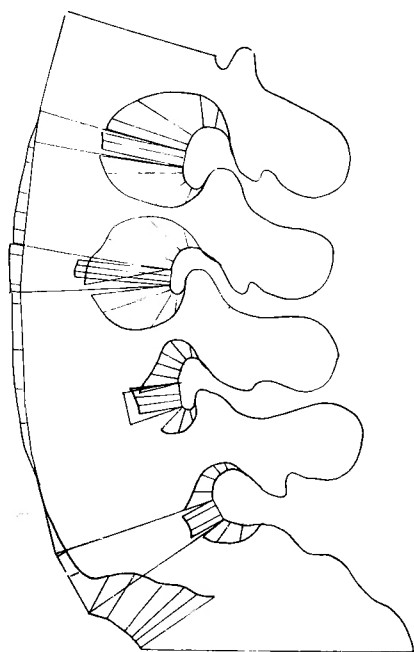


Fig. 13 Stress distribution of the anterior 2/3 A-P diameter interbody fusion

As Fig. 13 and Table 1 demonstrate, the maximum stress at the lower part of L_3 is 0.909 kg/mm^2 and 0.980 kg/mm^2 at the L_{3-4} disc plate. At the disc plate between L_5 and S_1 , there is 0.369 kg/mm^2 and at the upper part of the S_1 , there is 0.249 kg/mm^2 .

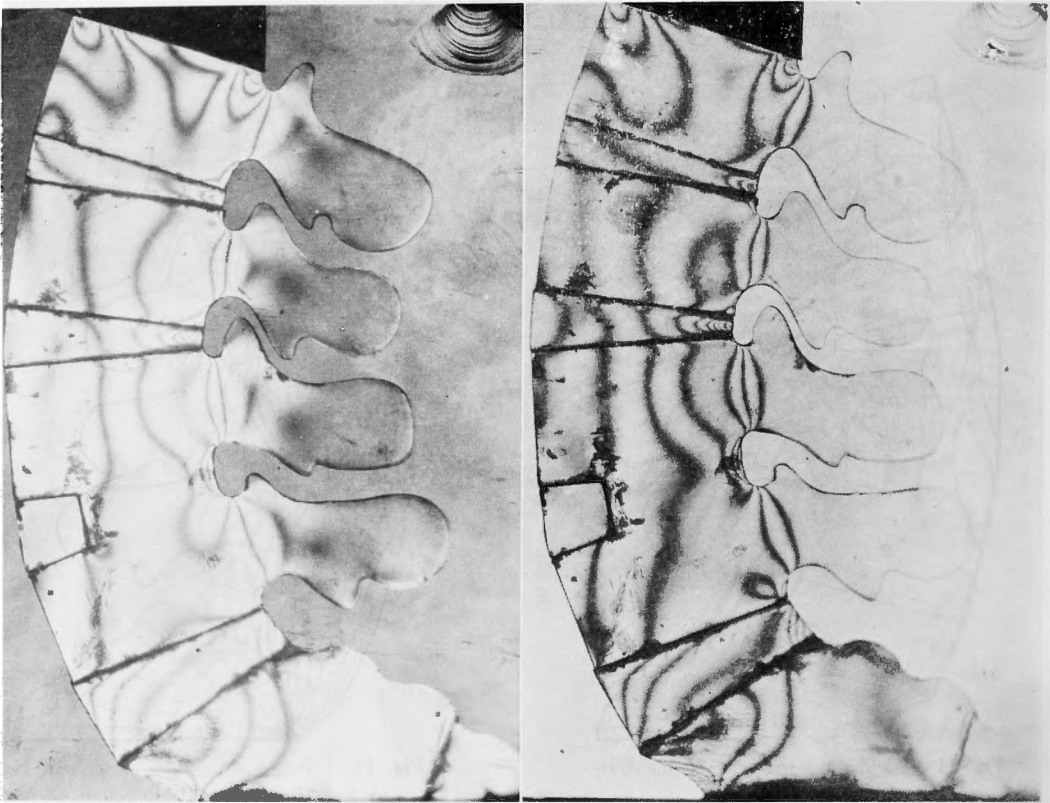


Fig. 14 Isochromatics of the posterior 2/3 A-P diameter interbody fusion
Fig. 14-a Dark field **Fig. 14-b** Light field

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.

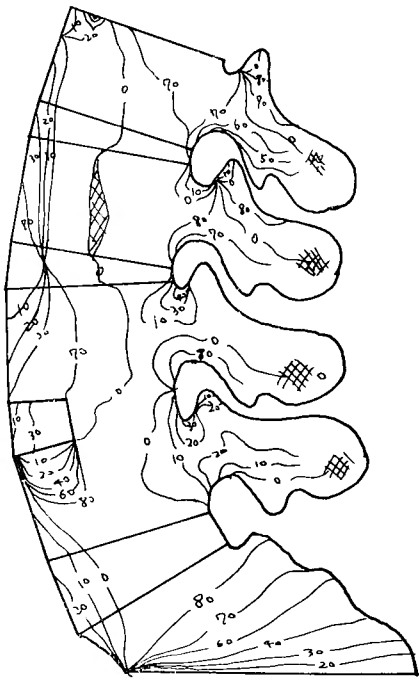


Fig. 15 Isoclinics of the posterior 2/3 diameter interbody fusion

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

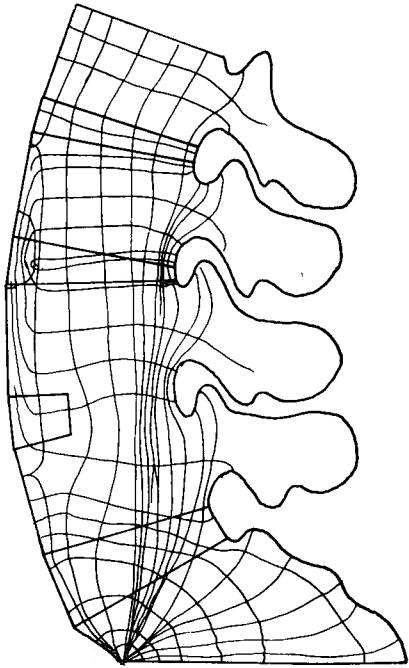


Fig. 16 Principal stress lines of the posterior 2/3 diameter interbody fusion

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.

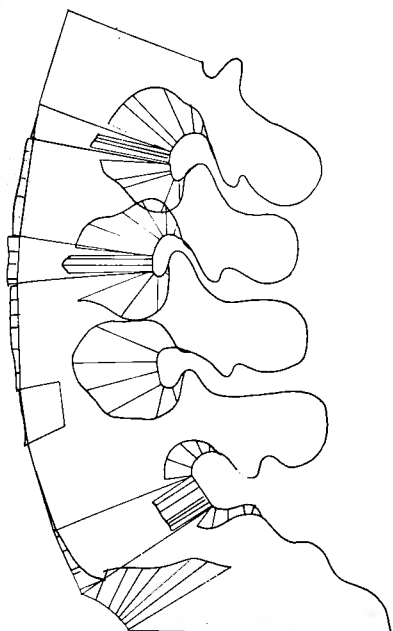


Fig. 17 Stress distribution of the posterior 2/3 diameter fusion

As Fig. 17 and Table 1, 0.812 kg/mm^2 is at the postero-lower part of L_3 . 0.980 kg/mm^2 at L_{3-4} 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 L_5-S_1 disc plate, 0.490 kg/mm^2 , and at the postero-upper part of S_1 , there exists 0.235 kg/mm^2 .

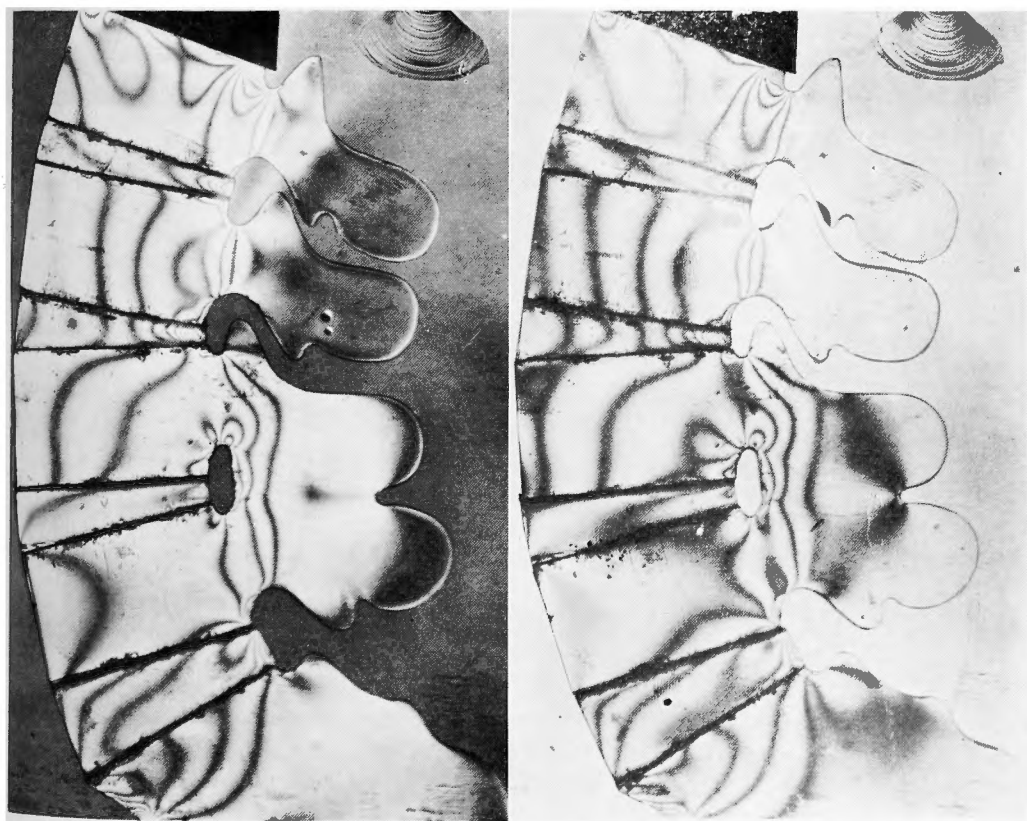


Fig. 18 Isochromatics of the vertebral arch fusion

Fig. 18-a Dark field

Fig. 18-b Light field

At the L_{3-4} disc plate, the maximum fringe, 12.8 exists at the posterior margin. At the postero-lower part of L_3 , 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.

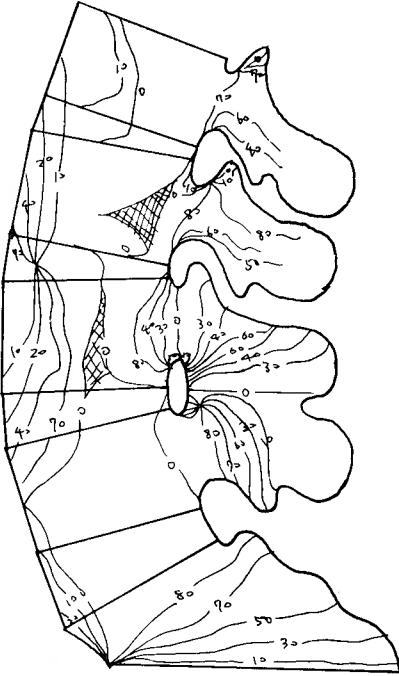


Fig. 19 Isoclinics of the vertebral arch fusion
The singular points are at L₃₋₄ disc plate and the fused arch.

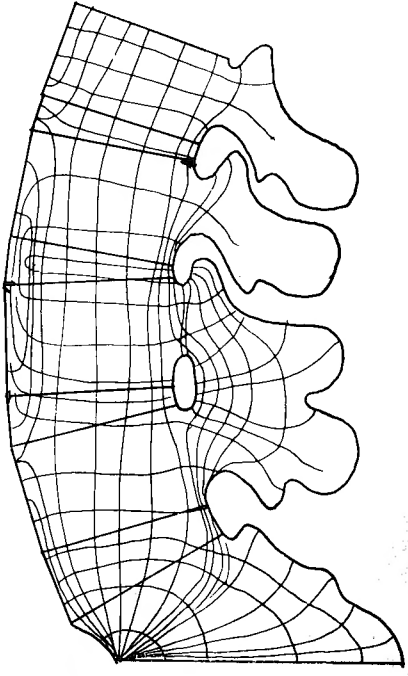


Fig. 20 Principal stress lines of the vertebral arch fusion

Principal stress lines are conspicuously move to-wards posteriorly at the parts above and below the fusion.

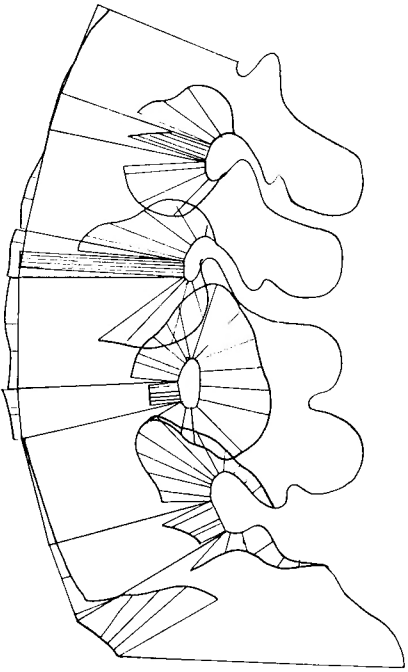


Fig. 21 Stress distribution of the vertebral arch fusion

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.

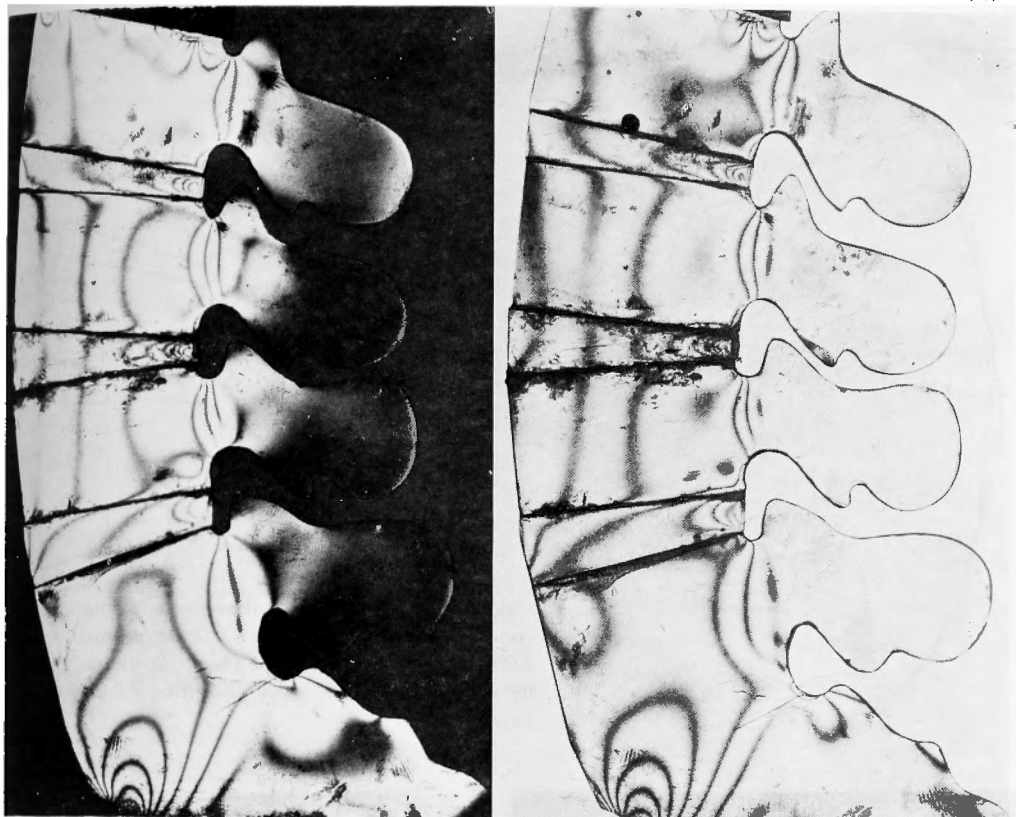


Fig. 22 Isochromatics of the whole interbody space fusion

Fig. 22-a Dark field

Fig. 22-b Light field

Alike to Fig. 6. At the upper surface of S_1 , 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.

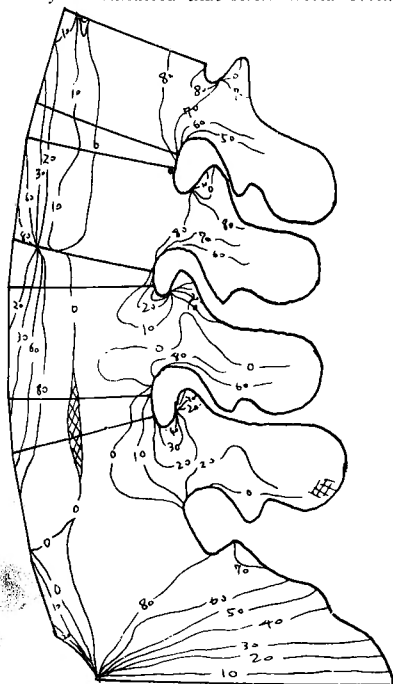


Fig. 23 Isoclinics of the whole interbody space fusion

Little difference from Fig. 7. The singular point exist at the border of L_3 spinal body and L_{3-4} disc plate.

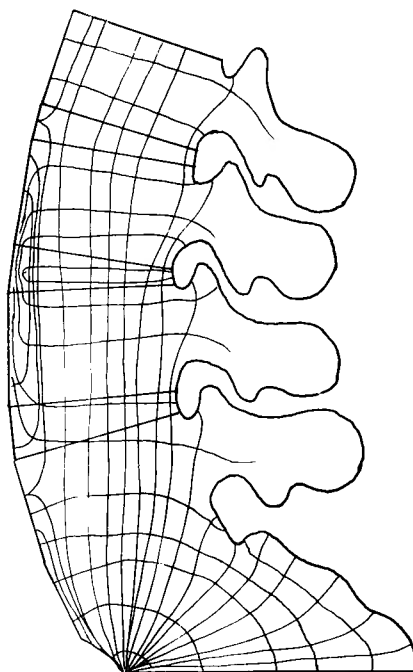


Fig. 24 Principal stress lines of the whole interbody fusion

These lines are same as Fig. 8.

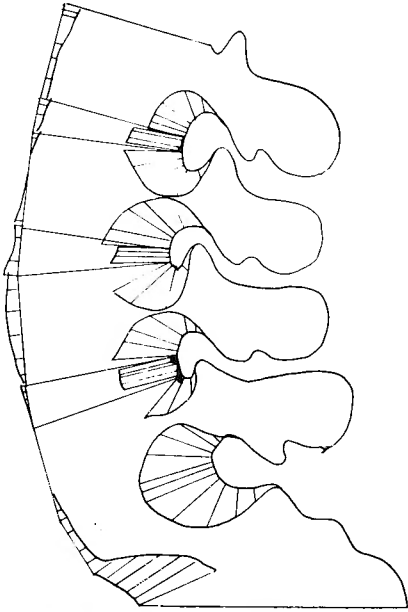


Fig. 25 Stress distribution of the whole interbody space fusion

As Fig. 25 and Table 4 demonstrate, at the postero-lower part of L4, stress is 0.681 kg/mm^2 and 0.620 kg/mm^2 at the L₄₋₅ disc plate. At the anterior margin of the L₄₋₅ disc plate, stress is 0.122 kg/mm^2 .

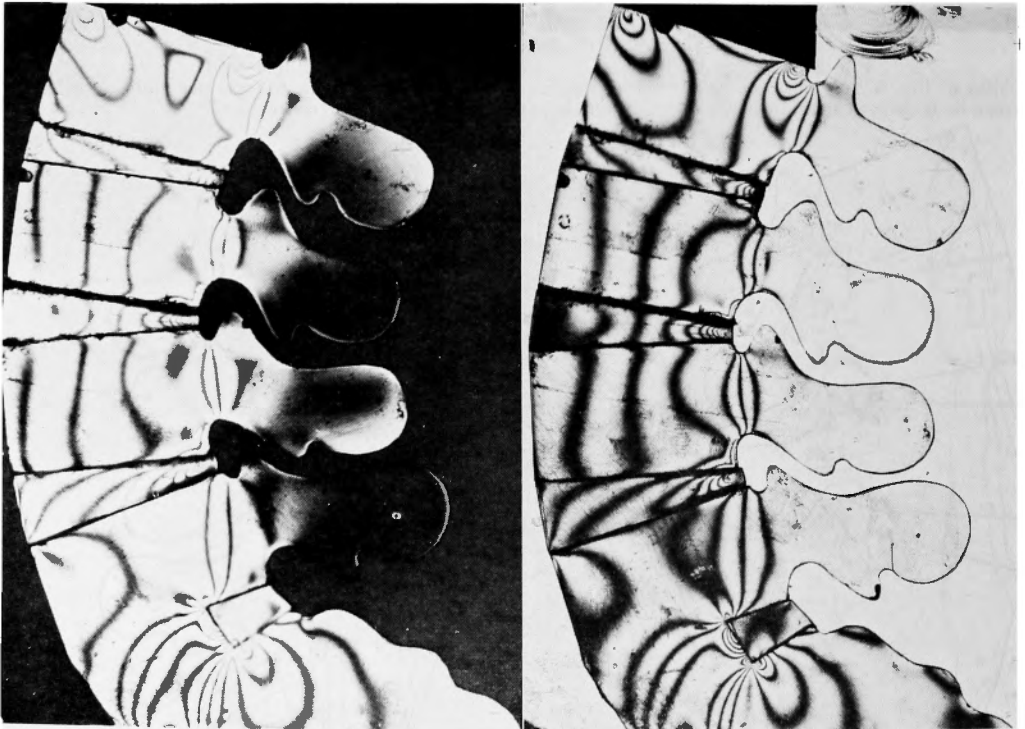


Fig. 26 Isochromatics of the anterior 2/3 A-P diameter interbody fusion

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.

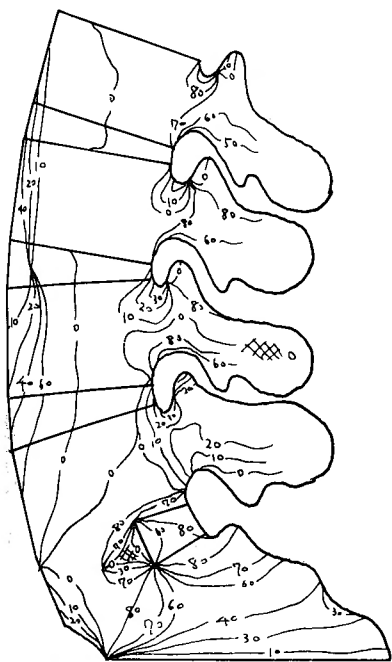


Fig. 27 Isoclinics of the anterior 2/3 A-P diameter interbody fusion

The singular points are at L_{3-4} disc plate and in the grafted bone.

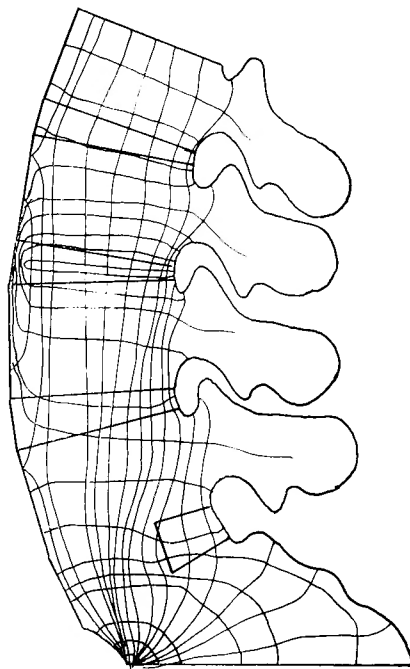


Fig. 28 Principal stress lines of the anterior 2/3 A-P diameter interbody fusion

At the upper parts above the fusion, trajectories are slightly removing anteriorly.

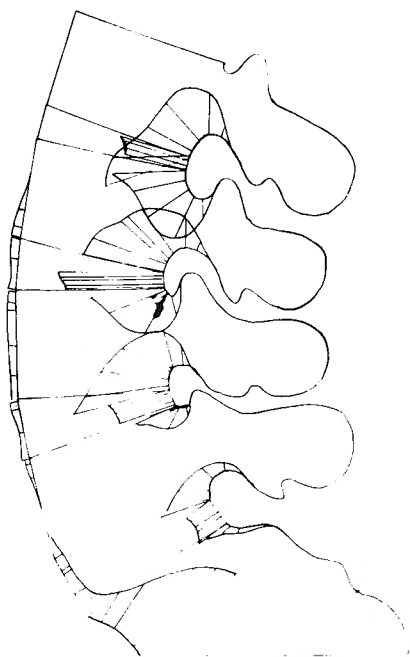


Fig. 29 Stress distribution of the anterior 2/3 A-P diameter interbody fusion

At the postero-lower part of L_4 , stress of 0.900 kg/mm^2 exists, and at the posterior margin of L_{4-5} disc plate, 0.525 kg/mm^2 acts.

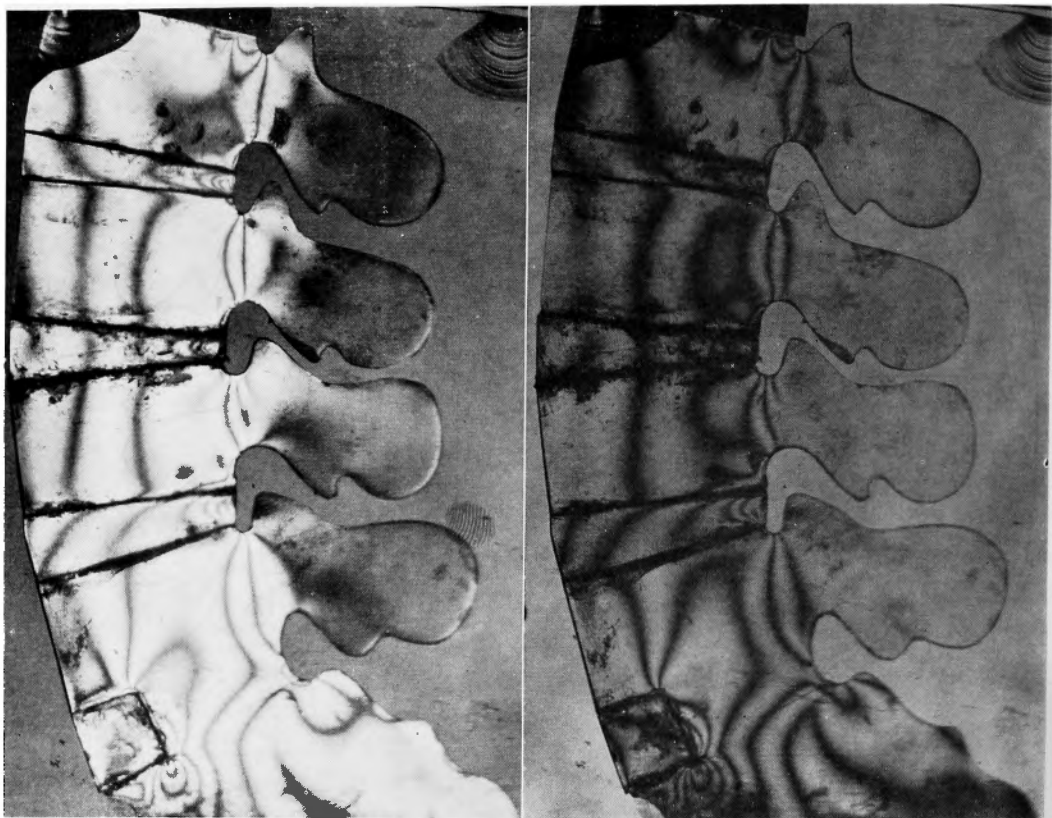


Fig. 30 Isochromatics of the posterior 2/3 A-P diameter interbody fusion

Fig. 30-a Dark field

Fig. 30-b Light field

At L_4 there is 3.5 fringes. At the posterior margin of L_{4-5} disc plate, there exist 7.5 fringes.

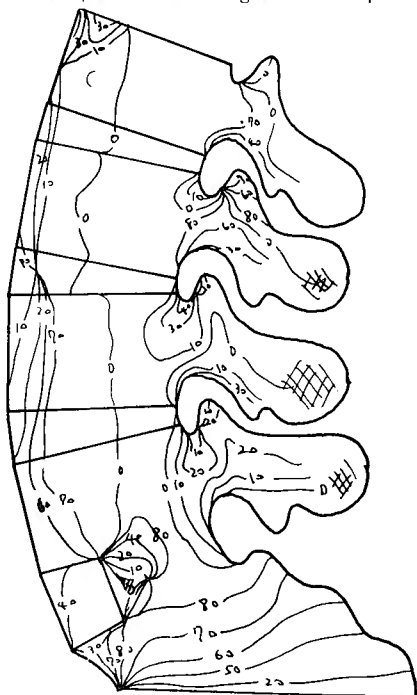


Fig. 31 Isoclines of the posterior 2/3 A-P diameter interbody fusion

The singular or zero points are at the L_{3-4} disc plate and in the grafted bone.

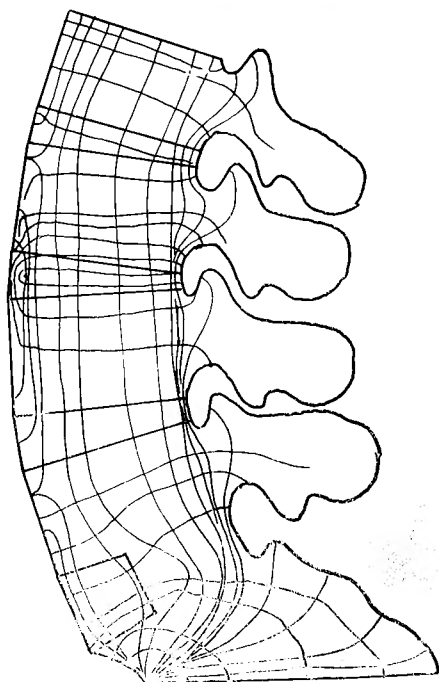


Fig. 32 Principal stress lines of the posterior 2/3 A-P diameter interbody fusion

Trajectories slightly concentrated in the posterior part above the fusion.

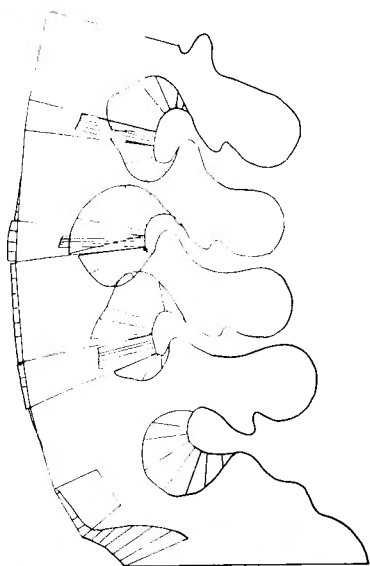


Fig. 33 Stress distribution of the posterior 2/3 A-P diameter interbody fusion

Stress of L_4 postero-lower part is 0.720 kg/mm^2 , 0.680 kg/mm^2 at the posterior margin of L_{4-5} disc plate.

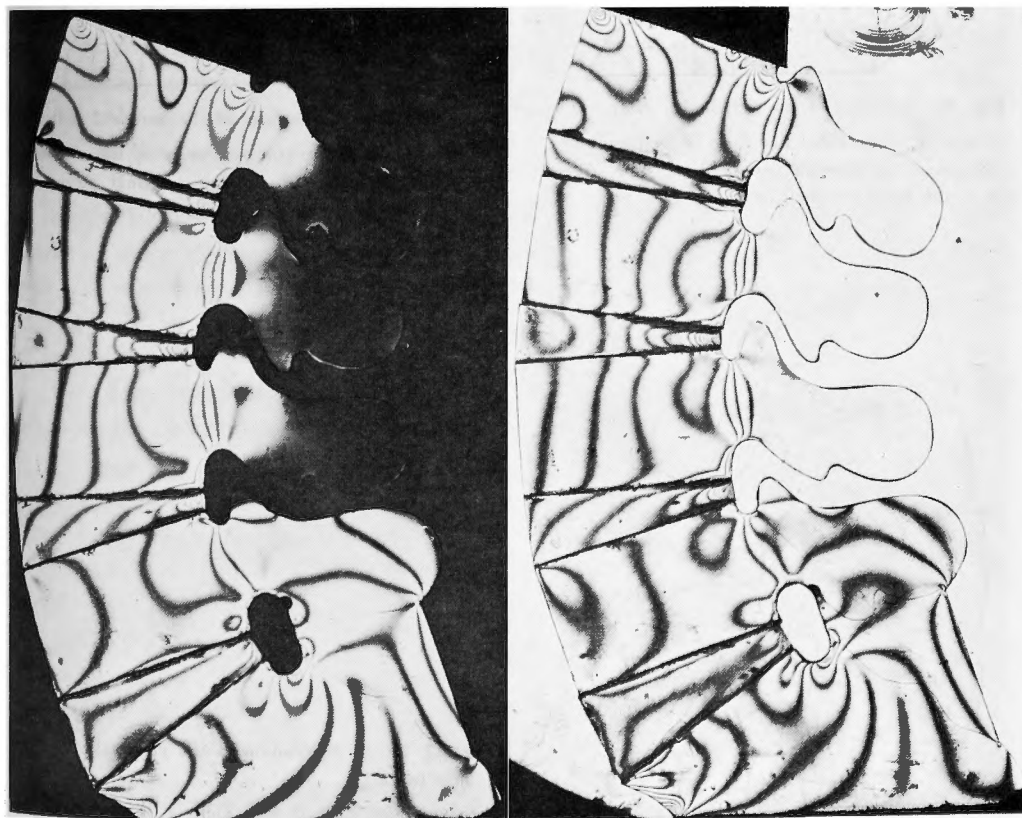


Fig. 34 Isochromatics of the vertebral arch fusion

Fig. 34-a Dark field

Fig. 34-b Light field

The maximum fringe at the postero-lower part of L_4 is 5.4. At the posterior margin of L_{4-5} disc plate, it is 9.0.

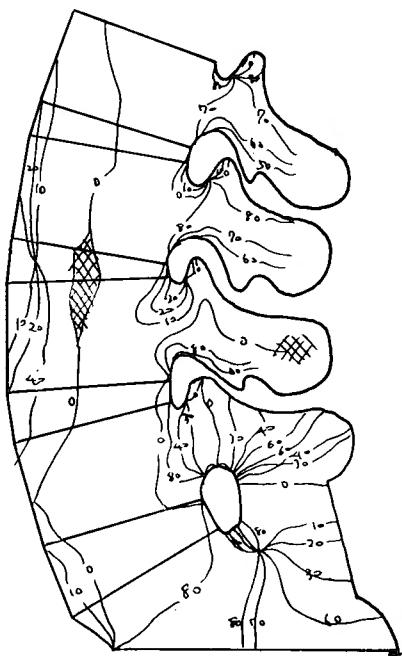


Fig. 35 Isoclinics of the vertebral arch fusion

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.

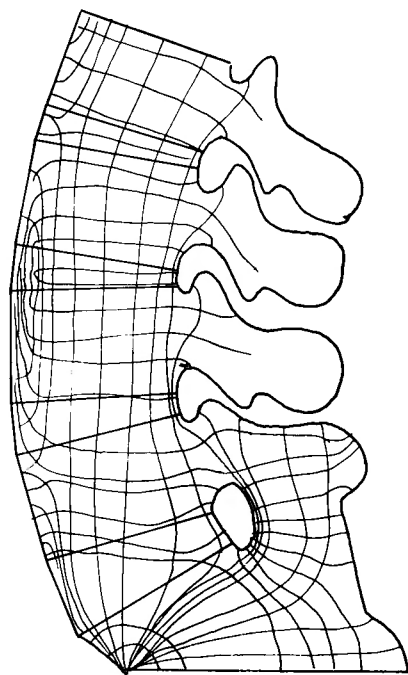


Fig. 36 Trajectories of the vertebral arch fusion

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

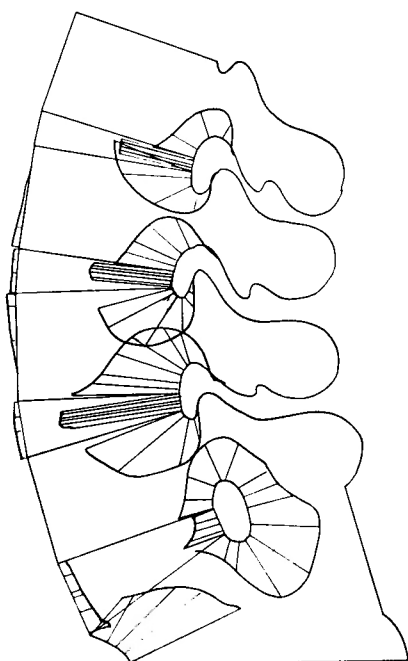


Fig. 37 Stress distribution of the vertebral arch fusion

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 L_5-S_1 intervertebral disc and the 1st sacral vertebra, stress apt to distribute evenly. The tension disappears and the maximum of compression reduces. The maximum stress of the vertebral bodies is 0.841 kg/mm^2 at the 3rd and 4th lumbar vertebrae, and the maximum stress of the intervertebral discs is 0.890 kg/mm^2 at the L_3-L_4 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 L_3 in the case of L_4 and L_5 fusion is 0.909 kg/mm^2 , and it is 108.1% of the normal at the same place. At the L_3-L_4 disc plate, it is 0.980 kg/mm^2 and is 110.1 % of the normal. At the L_5-S_1 disc plate, it is 0.369 kg/mm^2 and at the 1st sacral vertebra, it is 0.249 kg/mm^2 . In the case of L_5 and S_1 fusion, it is 0.900 kg/mm^2 at the L_4 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/mm^2 at the lower L_3 and 0.980 kg/mm^2 at the L_3-L_4 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

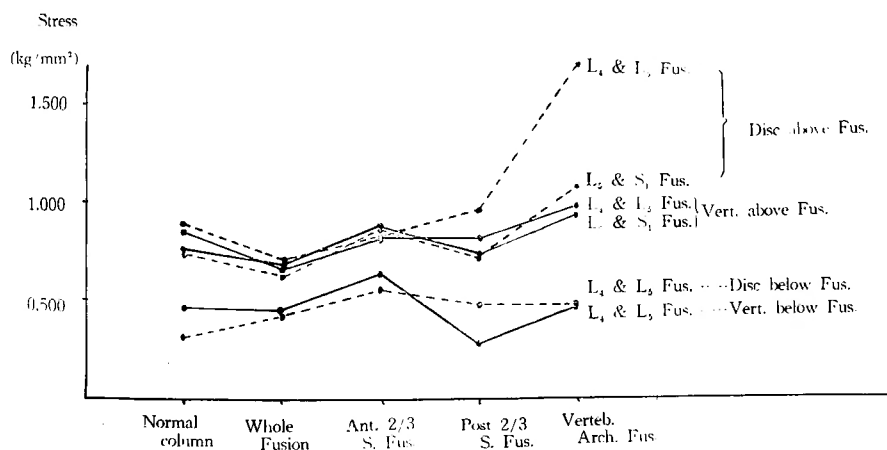


Fig. 38 The maximum stress of the various fusions

stress of the adjacent place of fusion is at the posterior margin of the column. At the lower L_3 , maximum stress is 0.980 kg/mm^2 , and it is 116.4 % of the normal, and at the L_2 - L_4 intervertebral disc, the maximum is 1.540 kg/mm^2 , 171.9 %. In the case of the 5th lumbar and 1st sacral vertebral fusion, the max. stress at the L_4 is 0.940 kg/mm^2 , 110.9 %, and at the L_4 - L_5 intervertebral disc, the max. is 1.090 kg/mm^2 , 30.2 %. At the L_5 - S_1 intervertebral disc, the lower adjacent disc of fusion, the max. stress is 0.480 kg/mm^2 .

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)⁴¹⁾, NAGURA (1939)³⁹⁾, AOIKE (1942)³⁾ 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/cm^2 and 107.23 kg/cm^2 respectively. But all these experiments are those using the post-mortem specimen and there is no consideration on the inner stress 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)⁶²⁾ analysed the stress in tooth, MILCH (1939)³⁶⁾, MASABAYASHI (1950)³²⁾, YAJIMA (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 so we call the posterior fusion.

In the vertebral arch fusion actually started in ALBEE (1911)¹⁾ and HENLE, many methodical variations by HIBBUS, HENRY-GEIST (1933)²²⁾, 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 UI (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 dismerits in dynamical view.

On the other hand, the interbody fusion by anterior approach in which two types of

operation take part, namely fusion of transperitoneal approach by CAPENER (1932)¹⁴⁾, BURNES, MERCER, SPEED (1938)⁴⁹⁾ and so on, and that of extraperitoneal approach by IWAHARA (1944)²⁵⁾ has many indications for spondylolysis, spondylolisthesis, disc hernia, spondylitis tuberculosa 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)²⁷⁾ have discussed that when the grafted bone is too small, there often occur "Umbauzone" in the anterior body fusion. MITANI (1966)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 JASLOW (1946)²⁸⁾. Since then CLOWARD (1953)¹⁵⁾¹⁶⁾, JAMES et al., DU TOIT, WILTBERGER (1957)⁵⁸⁾, DOMMISSE (1959)⁵⁹⁾ and other 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)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 some times 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)⁴¹⁾ discussed uselessness of ALBEE's operation, as five cases among seven were unsuccessful. UI 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)²¹⁾ and MENSOR (1955)³⁴⁾ 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)⁶⁵⁾, ANDERSON (1956)²⁾ and DE PALMA (1959)¹⁸⁾ reported one case of acquired spondylolysis after spine fusion, respectively. Three cases of SULLIVAN et al. (1960)⁶⁰⁾, six cases of HARRIS et al. (1963)²⁰⁾ and five cases of ROMBOLD (1965)⁴⁶⁾ 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 interarticularis is made on the side on which the rotation is made from back to front. Further, flexion and extension 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 concentrated compressive stress, and they are near the fulcrum of lever mechanism in lumbosacral 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)⁵⁷⁾ 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)⁵⁸⁾ 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 immediately 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)⁷⁾ 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)¹²⁾ 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)⁴⁷⁾ have pointed out that the rupture of annulus fibrosus from disc degeneration happens to lead to occurrence 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)⁵¹⁾ 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 (1957⁹⁾ and 1958¹⁰⁾) 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)³³⁾ found more mobility in the portion above the affected spine than in the portion below, in the cases of spondylitis tuberculosa. Both of them are to be said to suggest change of mobility in the

region above the block formation.

JINNAI (1939)²⁹⁾ made Spondylosis deformans in the spine of rabbits by bending towards anterior direction after spine injuries. MIYAZAKI (1948)³⁸⁾ 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-dimensioned 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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和文抄録

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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山 口 雅 成

脊椎の癒合癒着を示すものとして先天性椎脊癒合症、脊椎カリエス等による塊椎形成、また人工的に癒合せしめる脊柱固定術などがある。

この癒合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 樹脂を用い第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固定、同椎体前方部2/3固定、同椎体後方部2/3固定、同椎弓固定、合計9コの光弾性模型を作成し、等色線、等傾線、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) 椎体前後径固定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) 椎体前方部固定群では主応力線は固定部分を一様に走向し、隣接椎間板、隣接椎に於ける応力最大値は第4・5腰椎固定でそれぞれ上部0.980 kg/mm²、0.909 kg/mm²、下部0.369 kg/mm²、0.249 kg/mm²、第5腰椎・第1仙椎固定では0.525 kg/mm²、0.900 kg/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腰椎固定でそれぞれ上部0.980 kg/mm²、0.812 kg/mm²、下部0.490 kg/mm²、0.235 kg/mm²、第5腰椎・第1仙椎固定で0.680 kg/mm²、0.720 kg/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腰椎固定でそれぞれ上部1.540 kg/mm²、0.980 kg/mm²、下部で0.480 kg/mm²、0.490 kg/mm²である。第5腰椎・第1仙椎固定ではそれぞれ1.090 kg/mm²、0.940 kg/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つ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) 椎弓固定にあつては隣接椎間板、隣接椎等の隣接部は固定によつて影響され、抵抗脆弱部として爾後の椎間板変性、変形性脊椎症等の発生と結びつき得る。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。