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THE DEVELOPMENT OF SPINAL DEFORMITY IN EXPERIMENTAL SCOLIOSIS

BY

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Jarl-Erik Michelsson

I. INTRODUCTION
PURPOSE OF THE INVESTIGATION

In 1957, LINDEMANN stated that BIESALSKI was right in calling scoliosis the old *crux orthopaedica*. He based his opinion on the fact that the development of this condition has remained obscure, although the most eminent specialists have been trying for two-hundred years to solve its problem. In spite of the progress made in the research on scoliosis, particularly during the last decades, about 90 per cent of cases must be described as idiopathic, according to COBB.

The methods available for the treatment of scoliosis are unsatisfactory. There is no reliable therapy to prevent the progression of an idiopathic scoliosis, and opinions differ concerning the usefulness of operative measures (HIRSCH). Spinal fusion is generally regarded as the best operation, although usually only partial correction has been achieved (JAMES, MAU, PONSETI).

PONSETI has stated that the problem of idiopathic scoliosis cannot be regarded as solved until the nature of the disease has been clarified and the causative deficiency can be corrected. »In all other fields within the scope of surgery it is by experiment that a decision as to the correct form of therapy has been reached. It is to be hoped that the study of scoliosis may also reap some benefit from work of this kind» (ARND).

Although the problem of scoliosis has been the object of many experimental investigations, the initiating mechanism of provoked scoliosis has not been subjected to closer study.

For several years, A. LANGENSKIÖLD and I have made systematic and unbiassed experiments on rabbits and pigs in order to clarify the pathogenesis of scoliosis and, if possible, find a basis for new methods of therapy. This work has been performed in part by both of us, in part by myself. Our previous results have been published in two papers: »Experimental Progressive Scoliosis in the Rabbit» (1961) and »The Pathogenesis of Experimental Progressive Scoliosis» (1962). In these we described various operations which frequently led to progressive and severe structural scoliosis. The operations most effectively inducing scoliosis were resection of the dorsal ends of ribs and hemilaminectomy. A factor which these operations had in common was the resection of posterior costotransverse ligaments. In both rabbits and pigs transection of these ligaments alone sometimes led to progressive scoliosis of the same type as is seen in man. It is known that the costotransverse ligaments play an important part in transmitting normal muscle tone to the spine. These structures seem to be necessary for both the maintenance of the equilibrium and the symmetrical growth of the spine.

The purpose of the present study was to investigate the initiating mechanism and the evolution of the change of various structures in experimental scoliosis.

II. SURVEY OF THE LITERATURE

»In no other type of deformity is there encountered such a magnitude of intricate and baffling problems as one is confronted with in scoliosis. This is a condition that has spurred speculation and investigation to a remarkable degree, and the great web of literature woven around the subject might well dismay even the most assiduous of readers». These words were written by MICHELE in 1963.

Different theories concerning the pathology, aetiology, pathogenesis and therapy of scoliosis have been thoroughly described in Handbuch der Orthopädie, Band II, 1958.

A. Certain features of the pathology of human scoliosis

Classification. From the standpoint of aetiology and pathogenesis, scoliosis can be classified as myopathic, osteopathic, neuropathic or idiopathic. The last-mentioned group is by far the largest (COBB). Clinically, a distinction can be made between functional and structural scoliosis. In functional scoliosis there are no permanent adaptive changes of the spine, and spontaneous straightening is possible, while the structural form is characterized by adaptive deformities of bones and soft parts, and spontaneous straightening can no longer take place (KLEINBERG, LOVETT, MICHELE).

Pathological changes. In structural scoliosis the lateral deviation is associated with rotation of certain vertebrae in the curves, except in pleural scoliosis (BISGARD). Mostly there is one primary curve, and this is usually associated with one or more compensatory curves. In structural scoliosis the curves are rigid (KLEINBERG). The commonest site of the primary curve is the caudal part of the thoracic spine, and in about 80 per cent of cases the convexity is directed to the right (SHANDS & EISBERG). Structural changes occur in both the spine and its vicinity. The severest vertebral changes are found at the apices of the curves. Rib hump is a common finding in thoracic scoliosis (JENTSCHURA, KLEINBERG).

B. Vertebral growth in man and animals

The growth of the human vertebra is not fully understood, but it is generally accepted that the vertebral body grows in length by means of plates of epiphyseal cartilage on the cranial and caudal surfaces (BICK & COPEL, BISGARD & MUSSELMAN, COVENTRY & al., SCHMORL).

During growth, the cranial and caudal surfaces of the human vertebral body exhibit a ring-shaped structure, the apophysis, by SCHMORL called »Randleiste». Animals, *e.g.* the rabbit and the pig, have a disc-shaped epiphyseal nucleus corresponding to this epiphyseal ring (BEADLE, PACHER, SMITH & WALMSLEY). The vertebral apophyses do not essentially participate in the longitudinal growth of the vertebral bodies (BICK & COPEL).

In mammals, as well as in man, longitudinal growth of the vertebral bodies takes place at the epiphyseal plates (BEADLE, BISGARD & MUSSELMAN, PACHER, STILWELL).

C. Earlier experimental studies on scoliosis

Before A. LANGENSKIÖLD and I started our studies many experimental investigations had been performed in order to induce scoliosis in laboratory animals, but they had not always been systematic, and in most cases only slight or no scoliosis had resulted.

1. *Transection or excision of muscles alone.* In addition to various groups of dorsal muscles, the following muscles have been either excised or transected alone: the trapezius, the latissimus dorsi, the sacrospinalis, the pectorales, the iliopsoas, the scaleni, abdominal muscles, the psoas major and intercostal muscles. As a rule, however, only slight or no scoliosis has been produced (ARND, CAREY, FREY, MARCONI, MILES, PLAGEMANN, PUSCH, SCHWARTZMANN & MILES, SOMERVILLE, STILWELL).

2. *Transection or excision of muscles and ligaments* at the dorsolumbar borderline (PUSCH) or resection of one or both sacrospinal muscles and interspinous and flaval ligaments (STILWELL) has induced kyphosis or scoliosis.

3. *Denervation of muscles.* Transection of the phrenic, intercostal or various spinal nerves has occasionally led to slight scoliosis (BISGARD, FREY, v. LESSER, MARCONI, MILES).

4. *Rib resection* has been performed in various ways. Scoliosis has resulted only in certain cases (BISGARD, DRACHTER, HUETER, PLAGEMANN). Rib resection in conjunction with fixation of contralateral ribs has produced slight scoliosis (FREY).

5. *Fixation of the spine* in an abnormal position has been performed by attaching the tail to the scapular region (MATSUOKA, MAU, MÜLLER, RIBBERT, UNGER, WULLSTEIN) or by fixing it in plaster (PLAGEMANN) or with metal (PAP). Occasionally scoliosis or kyphosis has been induced. In some cases slight scoliosis has been obtained by the *fixation of ribs or transverse processes* (FREY, PITZEN). Severe scoliosis (lordosis and rotation) has resulted from the *fixation of spinous processes* alone (GOTTLIEB & al.) and in conjunction with cauterization of vertebral arches (SOMERVILLE).

6. *Operations on vertebrae.* Resection of transverse processes has sometimes led to slight scoliosis (PLAGEMANN, VAVRDA), while cauterization of arches has failed to induce this condition (SOMERVILLE). Resection or stapling of the cranial or caudal growth zones of vertebral bodies has usually led to scoliosis with the concavity towards the operated side (BISGARD & MUSSELMAN, GHILLINI, HAAS, MOSER, NACHLAS & BORDEN), and damage to the neurocentral junction on one side has resulted in slight scoliosis (OTTANDER). Resection of both epiphyses of vertebral bodies and neurocentral junctions has provoked slight scoliosis (PACHER). Furthermore, this condition has been induced by hemilaminectomy in conjunction with transection of spinal nerves in the lumbar region (TROUPP).

7. *Radiation* with X-rays or radium has sometimes resulted in scoliosis (ARKIN & SIMON, ENGEL, ENGEL & RICHTER).

8. *Other methods.* Sometimes scoliosis has resulted from various kinds of pleural damage (BISGARD), experimentally induced lathyrism (AMATO & BOMBELLI, DURAISWAMI, DURIEZ & al., PONSETI, PONSETI & BAIRD, PONSETI & SHEPHARD), oxygen deficiency (DEGENHARDT, RÜTT & GRUETER), renal damage (BLUMENSAAT), unilateral labyrinthine ablation (DE KLEYN & BRAND, MAGNUS) abnormal labyrinthine stimulation (POOS & WALTER), disarticulation of an extremity (v. FRISCH), provoked luxation of the hip or pseudoarthrosis of the femur (FREY).

Our own earlier experimental investigations have been described in two papers mentioned on page 9.

III. MATERIAL AND METHODS

A. Laboratory animals

The present study is based on the results of operations on 800 growing rabbits and 66 growing pigs. These numbers include the animals on which our previous studies were performed. The rabbits were operated on at the age of six to eighty days, the pigs at the age of fourteen to sixty days.

B. General operative technique

Anaesthesia. The rabbits were operated on under local anaesthesia (0.25 per cent Xylocain without exadrine) and the pigs under deep general anaesthesia using Trilene.

Extent and location of the operations. As a rule, the operations on both rabbits and pigs were made at the levels of five vertebrae or corresponding ribs. The thoracic operations on rabbits were performed in the caudal region of the thoracic spine, mostly at the sixth to tenth thoracic vertebrae or the corresponding ribs, and the lumbar operations were made at the first to fifth lumbar vertebrae (the rabbit has seven lumbar vertebrae). On the pigs, only thoracic operations were performed, as a rule at the seventh to eleventh thoracic vertebrae (the pig has thirteen to sixteen thoracic vertebrae). The operations were usually performed unilaterally and on the right side, since in the majority of cases human scoliosis is right convex (SHANDS & EISBERG). For the sake of comparison, unilateral operations were also performed on the left side, but the results corresponded to those obtained after operations on the right side.

Surgical approach. As a rule, a dorsal longitudinal midline incision in the skin was made. On the side of the operation, parts of the trapezius and the latissimus dorsi were freed from spinous processes, when necessary, and at the deeper operations the sacrospinalis and the other deep back muscles were also freed from spinous processes and arches. In some cases the operation was performed between the different parts of the sacrospinalis or laterally of this muscle.

Operative complications. At the more extensive operations pneumothorax was a common complication, but its effect on the position of the spine was negligible. At hemilaminectomy spinal nerves were sometimes injured. Fatal haemorrhages were rare and mortality during or immediately following the operations was relatively low.

Antibiotics. Immediately after operation most rabbits were given an injection of penicillin, and the pigs were given penicillin and streptomycin intramuscularly for some days after operation. Occasionally antibiotics were applied locally during the operation. The frequency of postoperative infection and the mortality were somewhat lower in the animals given antibiotics than in the remainder.

C. Methods of selective resection, transection, transposition or electrocoagulation of structures in the spine or its vicinity

Generally speaking, corresponding structures occur in the spine and its vicinity in man, the pig and the rabbit (Ellenberger & Baum, Krause).

The role of various structures in maintaining the position of the spine was studied by resection, transection, transposition or electrocoagulation of different muscles, ligaments, nerves and/or bones. The different operations are listed in Table I. They were all performed on rabbits, but only some were performed on pigs. In the majority of cases the operation was unilaterally performed, as a rule at five levels, and involved only one kind of structure. These operations are here called »simple». In some cases operations involving more than one kind of structure (»combined operations») were performed either on the same side or on both sides of the spine. See page 28.

D. Methods of fixing different parts of the skeleton to each other

On growing rabbits and pigs various parts of the skeleton (spinous processes, transverse processes and/or ribs) were unilaterally fixed to each other with nylon thread. Depending on the size of the animal, one or more

TABLE I. — *Operations performed for the purpose of testing their possible effect on the growing spine.*

All operations were unilaterally performed, as a rule at five levels.
+ Scoliosis usually resulted
± Persistent structural scoliosis sometimes resulted
— Scoliosis only occasionally resulted
Oper. no. indicates the order in which the different operations were taken into use. (See text on page 15).

Oper. no.	Operation	Rabbits			Pigs		
		No. of animals	Funct. scoliosis	Struct. scoliosis	No. of animals	Funct. scoliosis	Struct. scoliosis
	A. OPERATIONS ON MUSCLES AND/OR LIGAMENTS						
	1. *Transection or resection of muscles and/or ligaments*						
I A	Resection of the sacrospinalis	24	—	—			
I B	Resection of all muscles attached to the spinous processes and the arches	10	—	—			
VII	Resection of the transversocostal muscles	13	—	—			
XXXI	Transection of the intertransverse ligaments	3	—	—			
XXVII	Transection of the costotransverse ligaments......	59	+	±	7	+	+
XIX	Transection of the ligaments of the tubercles of the ribs	3	—	—			
XVIII	Transection of the ligaments of the heads of the ribs	38	+	+			
XX	Transection of the ligaments attached to the dorsal ends of the ribs	17	+	+	2	+	+
XXV	Transection of the intercostal muscles	9	+	±	3	+	+
XXVII	Transection of all muscles and ligaments between the transverse processes and between these and the arches in the lumbar spine	8	+	+			
XXXII	Transection of the iliopsoas	1	—	—			
XXXIII	Transection of the gluteus medius	1	—	—			

Oper. no.	Operation	Rabbits			Pigs		
		No. of animals	Funct. scoliosis	Struct. scoliosis	No. of animals	Funct. scoliosis	Struct. scoliosis
	2. *Transposition of muscles*						
XIII	Transposition of the rhomboid muscles to ribs on the same side	4	—	—			
XIV	Transposition of the rhomboid muscles to contralateral ribs	7	—	—			
XV	Transposition of the rhomboid muscles and the trapezius to contralateral ribs	6	—	—			
	B. OPERATIONS ON NERVES						
III	Transection of the intercostal nerves	13	+	±			
XII	Transection of the phrenic nerve	6	—	—			
	C. OPERATIONS ON BONES						
XXIV	Hemilaminectomy in the thoracic spine	56	+	+	2	±	±
XXIV	Hemilaminectomy in the lumbar spine	9	+	+			
XXIX	Transversectomy in the thoracic spine	7	+	±			
XXIX	Transversectomy in the lumbar spine	2	+	+			
XVII	Resection of the heads of the ribs	14	+	+	1	+	+
XXI	Provoked epiphysiolysis of the heads of the ribs or transection of the necks of the ribs	16	+	±			
VI	Resection of the dorsal ends of the ribs	125	+	+	25	+	+
V A	Transection of the ribs laterally of their tubercles	2	—	—			
II	Transection of the thoracic wall lateral to the tubercles of the ribs	8	+	+			
V B	Resection of the ribs laterally of their tubercles	25	+	+			
XI	Electrocoagulation of the ventral growth zones of the ribs	3	—	—			
XXVI	Resection of the ventral growth zones of the ribs	4	—	—			

nylon threads were tied around the parts to be fixed. In addition to unilateral fixation of ribs, transection of certain structures on the other side was performed on some rabbits. The fixative operations and their results are described in detail on page 49.

E. Methods of investigation

Both living animals and specimens were studied *by ocular inspection.* Furthermore, photographs were taken when indicated.

Radiological investigation. The position of the spine was radiologically recorded in all animals. The first radiographs were taken immediately after operation in the case of most of the rabbits and some pigs. Subsequently, radiographs were usually taken at short intervals as long as the animal survived and often also post mortem. In many cases the animal was dissected and radiographs of the specimens were taken. When radiographs were taken in the anteroposterior projection, for technical reasons the animals were usually kept in the dorsal position. For the sake of comparison, radiographs were also taken with the living animal lying as freely as possible face down, or standing on its legs, but the position of the spine was in these cases more or less the same as when the animal was kept on its back. Lateral views were also taken, but not in all cases.

Measurement of the degree of scoliosis (lateral deviation of the primary curve of the spine) was performed by COBB's method. On radiographs, intersecting perpendiculars were drawn from the superior surface of the cranial vertebra and the inferior surface of the caudal vertebra of the curve. The complementary angle indicated the degree of scoliosis. Absolute values for the lateral deviation of the spine cannot be obtained by this or any other method (JENTSCHURA, KLEINBERG). Changes of less than 10 degrees in the lateral deviation of the spine were therefore as a rule not taken into account in this study.

Measurement of different parts of vertebrae was performed with calipers.

Marking of growing vertebrae was performed with vitallium screws on some pigs in order to study the growth changes in scoliosis.

Histological investigation. A number of rabbit vertebrae were histologically investigated. After fixation in neutral formalin and decalcination in EDTA (ethylenediaminetetra-acetic acid) the specimens were embedded in paraffin, sectioned in the frontal or transverse planes and stained with haematoxylin VAN GIESON.

IV. RESULTS

A. The immediate effect of different operations on the position of the spine

Immediately after the different surgical procedures (see Table I, page 20) the position of the spine was radiologically recorded in the anteroposterior projection in the majority of rabbits and some pigs. As appears in Table I, no lateral deviation of the spine resulted from 14 of the 29 different operations, while 15 operations usually led to initial scoliosis which could also be called functional, since no adaptive structural changes had yet developed. The results of the operations inducing scoliosis are described in detail on page 20.

After the following unilateral operations neither initial (functional) nor later, structural scoliosis developed:

Resection of the deep back muscles in the thoracic region.

Transposition of various back muscles.

Transection of intertransverse ligaments.

Transection of the ligaments of the tubercles of ribs.

Transection of muscles in the hip region (the iliopsoas and gluteal muscles).

Transection of the phrenic nerve.

Partial hemilaminectomy (not including the articular processes) in the thoracic spine.

Transection of ribs at a site far laterally of their tubercles.

Resection or electrocoagulation of the ventral ends of ribs.

Usually no appreciable initial scoliosis developed immediately after operations in which various skeletal parts were fixed to each other with nylon thread. The results of these operations are described in detail on page 49.

B. The functional scoliosis developing immediately after operation

Provocation of functional scoliosis in rabbits by operation on a single kind of stabilizing structure

Fifteen of the 29 operations listed in Table I, performed on different structures in the spine or its vicinity, immediately led to scoliosis which was convex to the side of the operation. All these procedures involved either resection or transection of muscles, ligaments, nerves and/or bones. The results of the operations provoking scoliosis are compiled in Table II. The table shows that the scoliosis induced by the different operations varied in degree. Wide variations in degree also occurred after the same operation. This may be due to variations in the operative technique, to the non-stationary character of scoliosis, the depth of the anaesthesia and the general condition of the animal at the examination, etc. Even though no absolute conclusions concerning the quantitative effect of the different operations undertaken in order to induce scoliosis can be drawn from the present studies, certain tendencies are discernible. Figs. 1 a—h illustrate functional scoliosis after different operations.

Resection of the dorsal ends of ribs led to the severest functional scoliosis encountered in the present study. When rib resection was done laterally of the tubercles of the ribs, the resulting scoliosis was usually much slighter. The more laterally the resection was performed and the smaller the pieces resected, the slighter was the scoliosis provoked. When *transection of the ribs and intercostal nerves and vessels* was done laterally of the tubercles of the ribs, the resulting scoliosis was as a rule relatively slight.

Resection or provoked epiphysiolysis of the heads of ribs or *transection of the ligaments of the heads of ribs* usually resulted in rather severe scoliosis.

Transection of both external and internal intercostal muscles led to relatively severe scoliosis. The effect on the position of the spine of the different parts of the intercostal muscles is described on page 26.

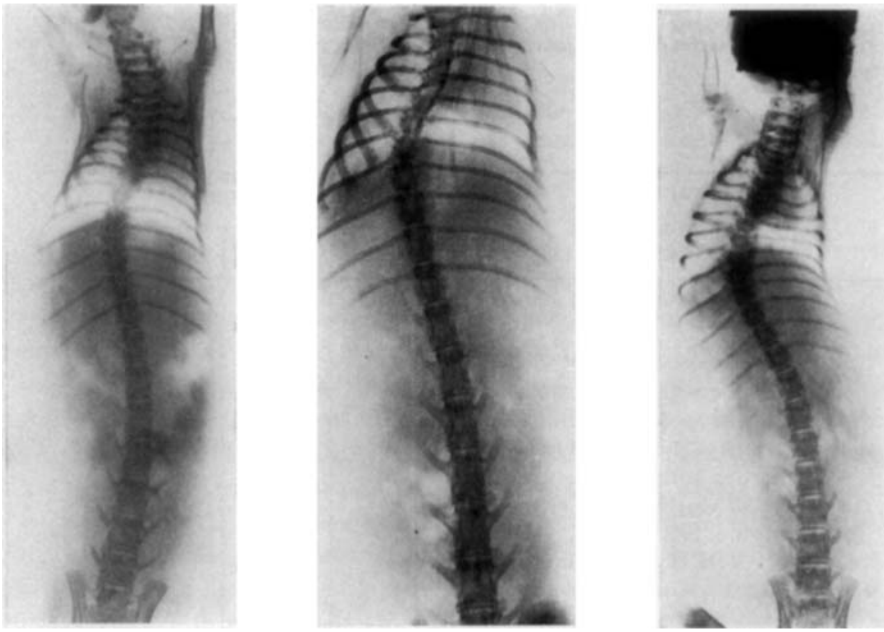
Hemilaminectomy in the thoracic spine provoked scoliosis which depended on the extent of the operation. The more laterally the removal of bone was extended, the severer was the resulting scoliosis. The most radical operations involved resection of the arch from the base of the spinous process to the base of the transverse process.

TABLE II. — *Functional scoliosis in rabbits which developed immediately after resection or transection of different structures in the spine or its vicinity.*

All operations were performed unilaterally at five levels.

Operation	Scoliosis in degrees			No. of rabbits
	Average	Min.	Max.	
Thoracic operations				
Resection of the dorsal ends of the ribs including both costal joint surfaces	51	25	87	125
Resection of the heads of the ribs	51	35	69	14
Provoked epiphysiolysis of the heads of the ribs or section of the necks of the ribs ..	51	33	65	16
Transection of the ligaments of the heads of the ribs	49	27	80	38
Transection of the intercostal muscles	49	28	70	9
Transection of the anterior and posterior costotransverse ligaments	44	18	78	59
Hemilaminectomy......................	44	20	70	56
Transection of the ligaments attached to the dorsal ends of the ribs	38	25	60	17
Transection of the intercostal nerves......	37	15	55	13
Resection of the ribs laterally of their tubercles	35	15	75	25
Transection of the thoracic wall	21	0	45	8
Transversectomy	18	0	42	7
Lumbar operations				
Transection of all muscles and ligaments between the transverse processes and between these and the arches	40	15	70	8
Transversectomy	23	20	26	2
Hemilaminectomy......................	17	0	35	9
			Total	406

Transection of the costotransverse ligaments alone resulted in scoliosis which was on the average equally severe as that induced by hemilaminectomy. It should be borne in mind that when hemilaminectomy was radically performed, the posterior costotransverse ligament was also resected.



a b c

Fig. 1. Rabbits. Initial scoliosis immediately resulting from eight different operations involving different structures in the spine or its vicinity. The operations were performed unilaterally on the right side at five levels. *a.* Transection of the costotransverse ligaments. *b.* Hemilaminectomy. *c.* Transection of the ligaments of the heads of the ribs. *d.* Transection of the necks of the ribs. *e.* Resection of the heads of the ribs. *f.* Transection of the ligaments attached to the dorsal ends of the ribs. *g.* Transection of the intercostal muscles. *h.* Resection of the dorsal ends of the ribs.

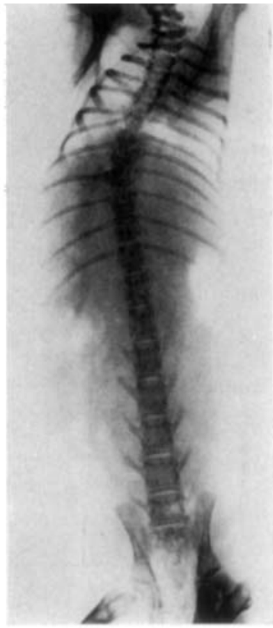
Transection of all ligaments attaching the dorsal ends of ribs to the spine provoked scoliosis which was somewhat slighter than that resulting from the majority of the other scoliosis-provoking operations on this part of the rib.

Transection of intercostal nerves led to moderate, and *transversectomy in the thoracic spine* to slight scoliosis.

Of the operations performed on the lumbar spine, transection of all muscles and ligaments attached to arches and transverse processes led to much severer scoliosis than *transversectomy* or *hemilaminectomy*.

d

e



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g

h

Dependence of the scoliosis on the extent of the operation

In order to study the relationship between initial scoliosis and the extent of the operation, one and the same procedure was unilaterally performed, but at different numbers of levels, and both on different animals and on one and the same animal step by step, though in one sequence. After each operative phase the position of the spine was immediately radiologically recorded.

Transection of the costotransverse ligaments was done on 5 rabbits of the same litter at different numbers of levels. The results are shown in Table III.

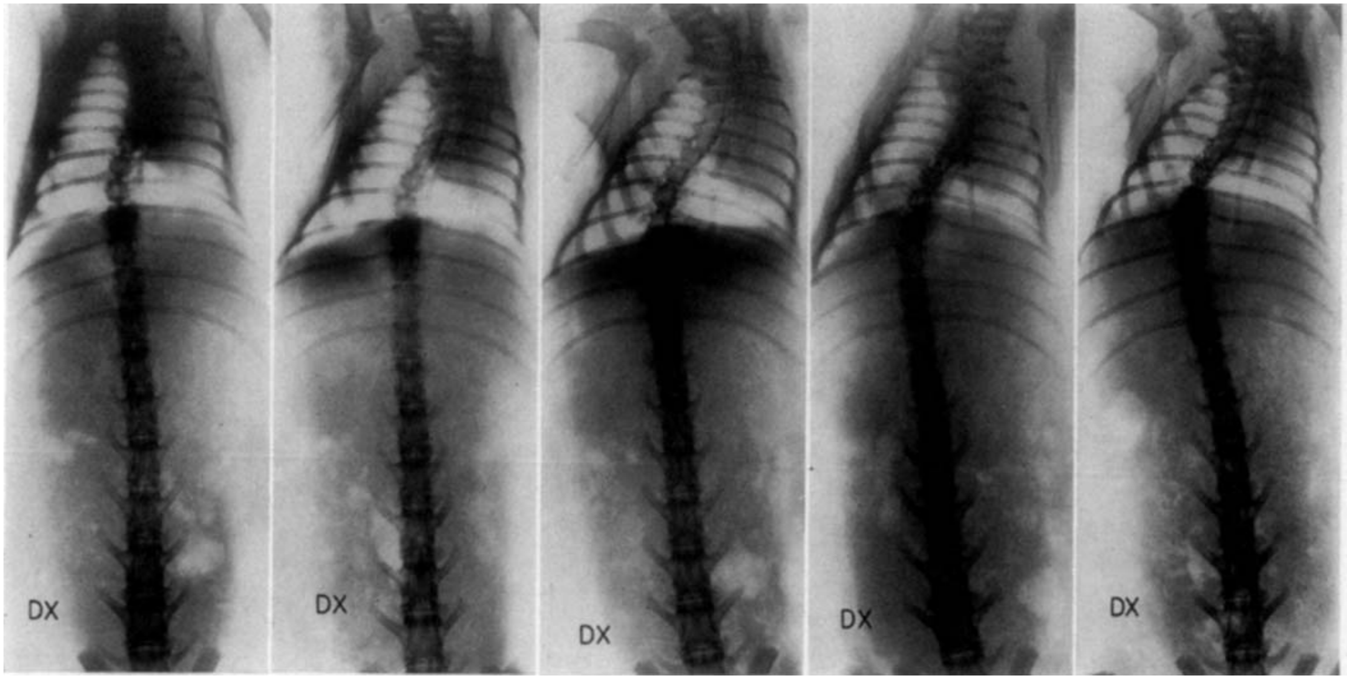
TABLE III. — *Immediate results of transection of the costotransverse ligaments performed unilaterally at different numbers of levels in 5 rabbits of the same litter.*

Rabbit no.	Location of operation	Scoliosis in degrees
518	Th 6	7
519	Th 6 — Th 7	20
520	Th 6 — Th 8	35
521	Th 6 — Th 9	42
524	Th 6 — Th 10	50

The same operation was performed step by step on 3 rabbits from the sixth to tenth thoracic vertebrae. The results are seen in Table IV and are illustrated in Fig. 2.

TABLE IV. — *Immediate results in 3 rabbits of transection of the costotransverse ligaments performed unilaterally step by step in one sequence at different numbers of levels.*

Location of operation	Average scoliosis in degrees
Th 6	12
Th 6 — Th 7	19
Th 6 — Th 8	28
Th 6 — Th 9	32
Th 6 — Th 10	40



a b c d e

Fig. 2. Rabbit. Transection of the costotransverse ligaments on the right side step by step in one sequence. The position of the spine recorded radiographically immediately after each operative phase. Transection performed by: *a* Th 6, *b* Th 6—7, *c* Th 6—8, *d* Th 6—9, and *e* Th 6—10.

Transection of the costotransverse ligaments led to slight scoliosis even when it was done at one intercostal space. The larger the number of levels involved, the severer was the scoliosis induced.

Similar results were also obtained when other operations provoking scoliosis were performed at different numbers of levels.

The material was small, but the same tendency was discernible in all experiments: *The greater the number of levels involved in an operation provoking scoliosis, the severer was the resulting scoliosis.*

The immediate effect of transection of different portions of intercostal muscles on the position of the spine

In order to clarify the influence of different portions of the intercostal muscles on the position of the spine, the following operations were performed unilaterally step by step in one sequence at five intercostal spaces, one third of the muscles involved being cut in each phase of the operation. The position of the spine was radiologically recorded immediately after each phase.

1. Transection of the external intercostal muscles alone was done on 3 rabbits. The operation was begun from the dorsal aspect. The results are shown in Table V.

TABLE V. — *Immediate results in 3 rabbits of transection of the external intercostal muscles in five intercostal spaces, performed unilaterally step by step in one sequence, beginning from the dorsal aspect.*

Portions of external intercostal muscles transected	Scoliosis in degrees		
	Rabbit 1	Rabbit 2	Rabbit 3
Dorsal thirds	30	27	40
Dorsal and medial thirds	40	27	45
All	35	30	45

2. Transection of the external intercostal muscles alone was done on 3 rabbits. The operation was begun from the ventral aspect. The results are shown in Table VI.

TABLE VI. — *Immediate results in 3 rabbits of transection of the external intercostal muscles in five intercostal spaces, performed unilaterally step by step in one sequence, beginning from the ventral aspect.*

Portions of external intercostal muscles transected	Scoliosis in degrees		
	Rabbit 1	Rabbit 2	Rabbit 3
Ventral thirds	0	0	0
Ventral and medial thirds	5	15	10
All	35	40	30

3. Transection of both the external and the internal intercostal muscles was carried out on 3 rabbits. The operation was begun from the dorsal aspect. The results are seen in Table VII.

TABLE VII. — *Immediate results in 3 rabbits of transection of all intercostal muscles in five intercostal spaces, performed unilaterally step by step in one sequence, beginning from the dorsal aspect.*

Portions of external and internal intercostal muscles transected	Scoliosis in degrees		
	Rabbit 1	Rabbit 2	Rabbit 3
Dorsal thirds	40	38	35
Dorsal and medial thirds	50	55	40
All	55	60	45

4. Transection of both the external and the internal intercostal muscles was carried out on 3 rabbits. The operation was begun from the ventral aspect. The results are seen in Table VIII.

TABLE VIII. — *Immediate results in 3 rabbits of transection of all intercostal muscles in five intercostal spaces, performed unilaterally step by step in one sequence, beginning from the ventral aspect.*

Portions of external and internal intercostal muscles transected	Scoliosis in degrees		
	Rabbit 1	Rabbit 2	Rabbit 3
Ventral thirds	0	0	0
Ventral and medial thirds	0	10	10
All	40	40	55

The following observations were made:

Transection of both external and internal intercostal muscles led to rather severe initial scoliosis.

Transection of external intercostal muscles alone resulted in scoliosis, which was only somewhat slighter than that resulting when both the external and internal intercostal muscles were cut.

Transection of the dorsal parts of intercostal muscles led to rather severe scoliosis, which became only slightly aggravated when the medial and ventral parts of these muscles were subsequently cut.

Transection of the ventral and medial parts of intercostal muscles resulted in only slight or no scoliosis.

The immediate effect of two or three different procedures involving various stabilizing structures on the same side

On 26 rabbits two or three of the procedures which had previously provoked initial scoliosis were carried out unilaterally at five levels in one sequence. In these experiments either the first, second or third operation consisted in the transection of intercostal muscles or nerves or costotransverse ligaments, or in rib resection. Immediately after the various procedures the position of the spine was radiologically recorded. The results are compiled in Table IX.

In all these experiments an increase of the scoliosis averaging 7—30 degrees was observable after the second or third operation. It is obvious that *the greater the number of scoliosis-provoking procedures carried out on the same side, the severer was the initial scoliosis induced.*

The immediate effect of procedures on the same or different structures carried out bilaterally

In order to study the effect of different operations on functional scoliosis, this condition was first provoked by one or more procedures on one (the right) side in 9 rabbits, and then one or more procedures were carried out at the same levels on the opposite (left) side. All surgical procedures were carried out step by step in one sequence, and immediately after each operative phase the position of the spine was radiologically recorded. The results of these experiments are compiled in Table X and are illustrated in Fig. 3. The following observations were made:

TABLE IX. — *Immediate results in rabbits of procedures provoking scoliosis as carried out in combination with each other unilaterally at the same five levels in one sequence.*

Procedure I	Procedure II	Procedure III	Average scoliosis in degrees					No. of animals
			After proc. I	After proc. II	Increase	After proc. III	Increase	
Transection of the intercostal muscles	Transection of the costotransverse ligaments		46	63	17			5
Transection of the ext. intercostal muscles	Transection of the costotransverse ligaments		34	54	20			4
Transection of the costotransverse ligaments	Transection of the intercostal muscles		44	65	21			2
Transection of the costotransverse ligaments	Transection of the ext. intercostal muscles		44	62	18			2
Transection of the costotransverse ligaments	Transection of the intercostal nerves		42	58	16			7
Transection of the intercostal nerves	Transection of the costotransverse ligaments		27	57	30			4
Transection of the costotransverse ligaments	Resection of the ribs laterally of their tubercles	Resection of the dorsal ends of the ribs	42	55	13	65	10	1
Resection of the ribs laterally of their tubercles	Transection of the costotransverse ligaments	Resection of the dorsal ends of the ribs	35	42	7	60	18	1

Table X. — *Immediate results in rabbits of bilateral procedures carried out in one sequence at the same levels (sixth to tenth thoracic vertebrae).*

After each operative phase the position of the spine was radiologically recorded.
+ primary curve right convex
— primary curve left convex

(See page 28).

Procedures carried out in the order indicated by the arrow

	Procedure	Scoliosis in degrees								
	Rabbit no.	710	630	660	760	779	761	662	772	773
Procedures on the *right* side	Resection of the sacrospinalis			0	0					
	Resection of the multifidus			0	0					
	Transection of the costotransverse ligaments	+60	+47	+40	+40	+40	+30			
	Transection of the ext. and int. intercostal muscles							+55	+35	+40
Procedures on the *left* side	Resection of the sacrospinalis			+40	+40					
	Resection of the multifidus			+40	+40			+55		
	Transection of the costotransverse ligaments	—10		+ 4	—5			+30	+22	
	Transection of the dorsal thirds of the ext. intercostal muscles								0	
	Transection of the medial and dorsal thirds of the ext. intercostal muscles								—20	
	Transection of the dorsal thirds of the ext. and int. intercostal muscles		+12							
	Transection of the medial thirds of the ext. and int. intercostal muscles		0	—35		—5	0	—25		
	Transection of the ventral thirds of the ext. and int. intercostal muscles									
	Transection of the costotransverse ligaments					—25	—12			
	Resection of ribs laterally of their tubercles						—31			—20
	Resection of the dorsal ends of the ribs			—30			—41			—45

Note: on the printed page, curly brackets join some of these values to more than one row. For rabbits 760 (—35) and 761 (0), the bracket spans the dorsal-thirds and medial-thirds rows. For rabbits 779 (—5) and 662 (—25), it spans the dorsal-thirds, medial-thirds and ventral-thirds rows.

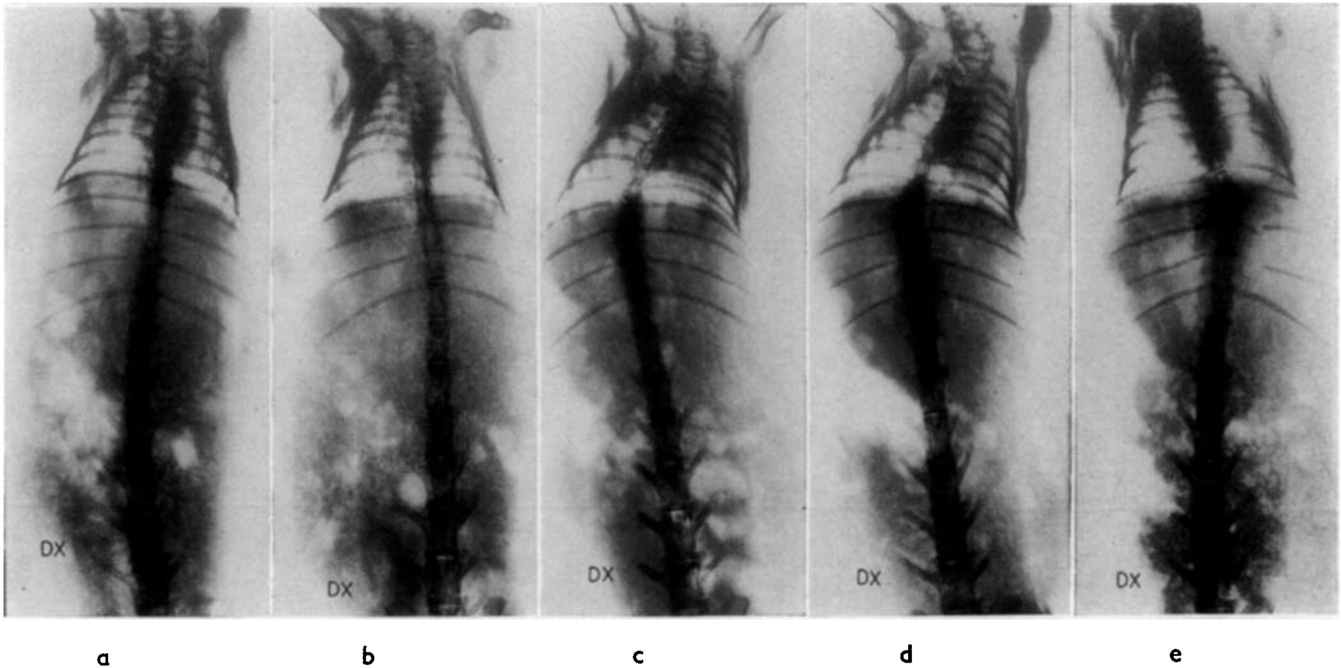


Fig. 3. Rabbit. Several different procedures were carried out in one sequence at the seventh to eleventh ribs at the age of 80 days. Radiographs were taken immediately after each operative phase. *a.* No scoliosis resulting after resection of the sacrospinalis performed on the right side nor after resection of the deeper back muscles, *b. c.* Transection of the costotransverse ligaments on the right side subsequently performed resulted in scoliosis. *d.* The position of the spine was not changed after resection of the deep back muscles on the left side. *e.* By resection of the dorsal ends of the ribs performed on the left side immediately afterwards the scoliosis was transferred to the left side.

A previous functional scoliosis was not appreciably influenced by resection of the deep back muscles on the concave (intact) side.

If the operation by which the functional scoliosis had been provoked was performed at the same levels on the concave (intact) side, the scoliosis as a rule completely straightened.

Scoliosis induced by the transection of costotransverse ligaments was usually transferred to the other side when intercostal muscles were cut at the same levels on the concave (intact) side. It appears therefore that the transection of intercostal muscles provokes scoliosis somewhat more effectively than the transection of costotransverse ligaments.

When costotransverse ligaments and/or intercostal muscles were cut on one side and rib resection was performed on the other (concave) side, the convexity of the primary curve always developed towards that side on which the ribs had been resected.

These experiments show that *certain operations which had failed to provoke functional scoliosis, also failed to counteract this condition when performed contralaterally to an operation which had led to this result.* Furthermore, it emerged that *functional scoliosis could be straightened or transferred to the other side by a second operation performed contralaterally to the first.*

The provocation of functional scoliosis in pigs

In the pigs, the position of the spine was only occasionally radiologically recorded immediately after operation, but on inspection a definite initial scoliosis was observable after the majority of operations, at least after transection of intercostal muscles and/or costotransverse ligaments, transection of all ligaments attaching the dorsal ends of the ribs to the spine, and rib resection. As in the case of the rabbits, the convexity of the primary curve was always directed towards the side operated upon. Operations which provoked scoliosis in the rabbits, also invariably induced this condition in the pigs. As a rule, the initial scoliosis was somewhat slighter in the pigs than in the rabbits.

The general features of functional scoliosis

Functional scoliosis developed immediately after operation (Figs. 1—3). Twenty-four hours later it was usually almost unchanged (Fig. 15).

The primary curve. The convexity was always directed towards the side of the operation, and its apex was usually situated in the middle of the operated region of the spine.

The secondary curves. Immediately after operation the animal as a rule was imbalanced, particularly when the scoliosis was severe. Initially, the primary curve was often incompletely compensated by one or more secondary curves, usually one cranial and one caudal to the primary curve.

Kyphosis or lordosis of the region of the spine operated upon was sometimes observed, but in the functional stage of scoliosis the change in position in the sagittal plane was never marked.

Rotation of vertebrae was not observed in functional scoliosis.

Drooping of the ribs on the side of the operation was an almost constant finding after the various thoracic operations provoking scoliosis.

Tension of the spine in the longitudinal direction led to decrease of the scoliosis (Figs. 4 a and b).

When the animal was killed or kept in deep anaesthesia, the scoliosis was always completely straightened (Fig. 4 e).

Changes in lateral flexibility developed immediately after the operations resulting in functional scoliosis (Figs. 4 c and d). On forcible lateral flexion towards the intact side, an abnormally increased curve of the spine was observed in the region operated upon, and apparently rigid secondary curves were sometimes seen both cranially and caudally of this region. On forcible lateral flexion of the spine towards the side of the operation, a marked decrease in lateral flexibility was discernible at the primary curve, which was thus seemingly »fixed». The decrease in flexibility was dependent on the force with which the animal was bent: The greater the force, the less was the local limitation of lateral flexibility. This was affected after all operations provoking scoliosis, and also after resection of the deep back muscles (which failed to induce functional scoliosis), but not after resection of the sacrospinalis alone. Post mortem the changes in lateral flexibility disappeared almost completely (Figs. 4 f and g).

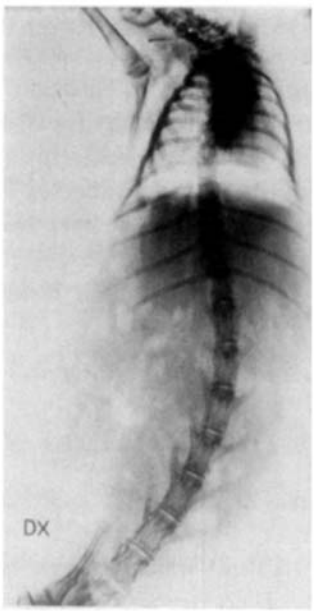
All the phenomena here described were discernible in functional scoliosis in both rabbits and pigs.

The further course of functional scoliosis

The cases of functional scoliosis ran various courses. Some of them soon showed complete regression, while others developed into persistent structural scoliosis. Complete regression of the condition occurred in some cases after all

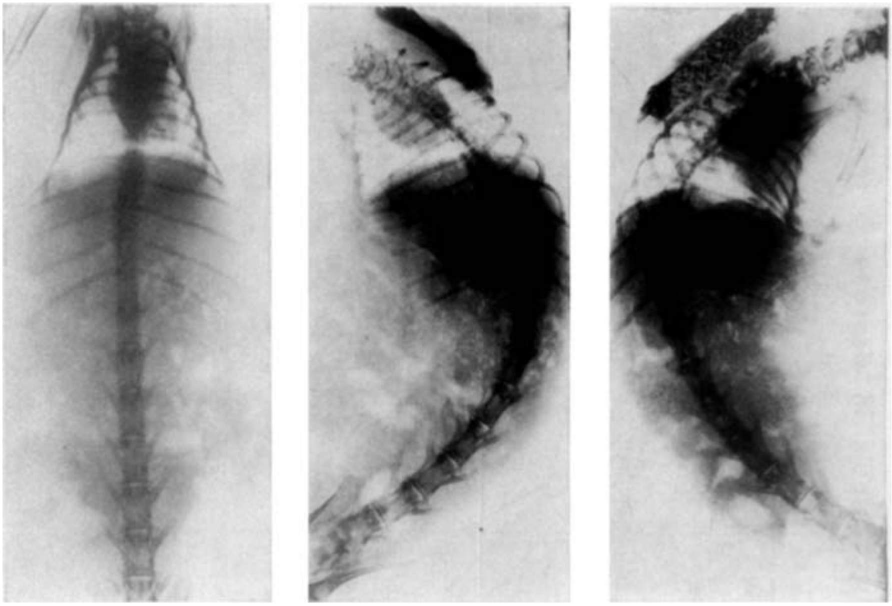
a

b



c

d



e f g

Fig. 4. Rabbit. Transection of the costotransverse ligaments and the dorsal portions of the intercostal muscles at the sixth to tenth intercostal spaces on the right side at the age of two months. *a—d.* Alive immediately after operation. *a.* In resting position. *b.* By tension in longitudinal direction. Straightening of the spine. *c.* In forcible lateral flexion towards the right side: The primary curve is rigid. *d.* In forcible lateral flexion towards the left side. *e—g.* Killed immediately afterwards. *e.* In resting position: Complete straightening of the scoliosis. *f* and *g.* In lateral flexion the rigidity of the primary curve has disappeared.

thoracic operations resulting in scoliosis, except resection of the dorsal ends of ribs and transection of both the costotransverse ligaments and intercostal muscles (Tables XI and XII). As a rule, regression occurred during the first six weeks after the development of scoliosis (Fig. 5). Regression was a particularly common finding after operations followed by marked cicatrization and after operations which only slightly affected the contact between the ribs and the vertebrae. The diagrams in Figs. 5 and 6 illustrate some typical courses.

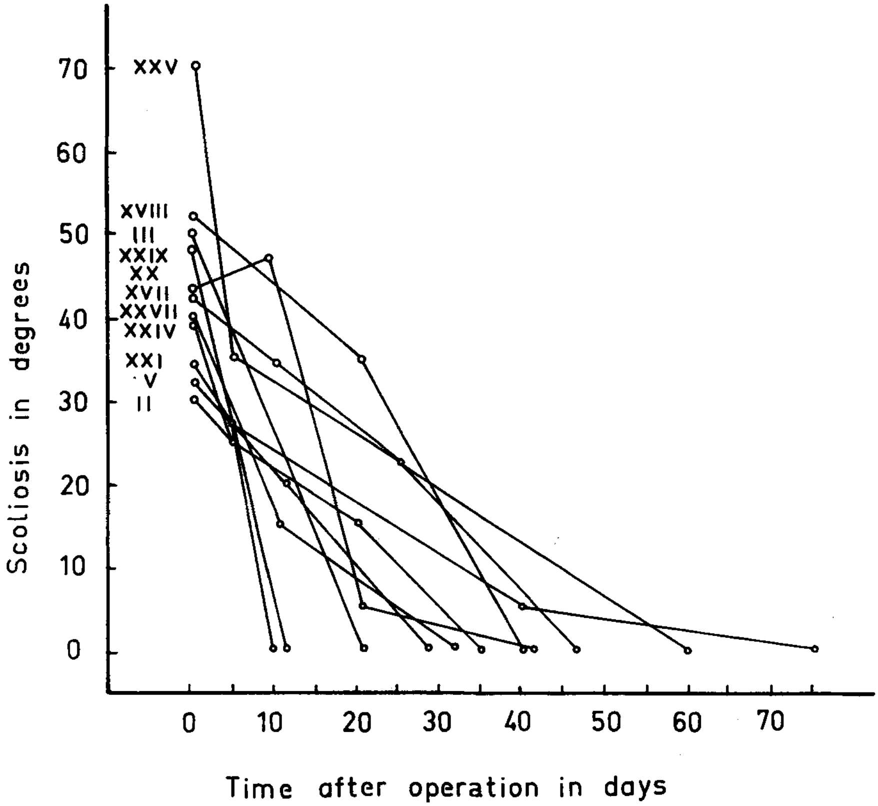


Fig. 5. Examples of regressive scoliosis in rabbits provoked by eleven different operations found to produce this condition. The Roman numerals indicate the kind of operation (see Table I). As a rule, regression occurred within six to eight weeks after operation.

C. Structural scoliosis

The provocation and course of structural scoliosis

Structural scoliosis resulted either from the operations which had caused initial, functional scoliosis, or from certain fixative operations. Those operations, consisting of resection, transection, transposition or electrocoagulation of various structures, which did not lead to functional scoliosis, did not result in later structural scoliosis, either. See Table I, page 16.

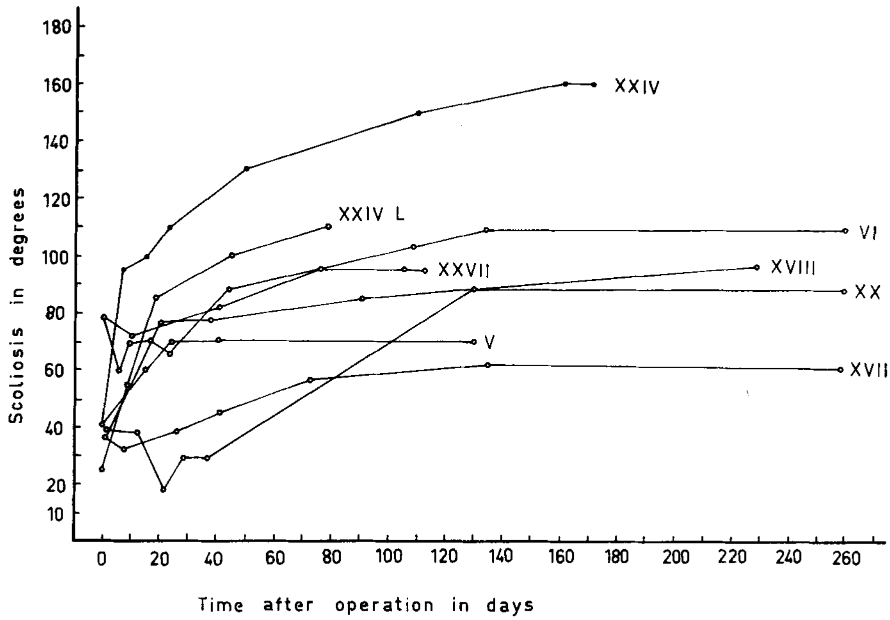


Fig. 6. Examples of the course of progressive scoliosis. The 8 rabbits were operated upon by different methods found to produce this condition. The Roman numerals indicate the kind of operation (see Table I). Progression mainly occurred during the first six to eight weeks after operation.

From the standpoint of lateral deviation, the functional scoliosis ran different courses. In some animals the scoliosis exhibited a steady regression, or alternating progression and regression, while in a large number of cases a steady progression occurred.

Examples of both increase and decrease of the scoliosis were seen throughout the period of growth, but in both rabbits and pigs regression as well as progression mainly occurred during the first two months after the development of scoliosis. See Figs. 5 and 6.

The development of structural scoliosis from functional scoliosis in rabbits

After all those operations involving the resection or transection of various structures which led to functional scoliosis, a permanent structural scoliosis

TABLE XI. — *Structural scoliosis in rabbits resulting from resection or transection of different structures in the spine or its vicinity.*

All operations were performed unilaterally at five levels. The position of the spine was radiologically recorded a minimum of two months after operation.

Operation	Scoliosis in degrees			No. of rabbits
	Average	Min.	Max.	
Simple thoracic operations				
Resection of the dorsal ends of the ribs..	86	25	170	35
Hemilaminectomy....................	58	0	180	35
Transection of the ligaments of the heads of the ribs	55	0	127	14
Transection of the ligaments attached to the dorsal ends of the ribs	49	0	106	12
Resection of the ribs laterally of their tubercles	41	0	110	21
Resection of the heads of the ribs	34	0	62	5
Transection of the costotransverse ligaments	22	0	90	12
Transection of the thoracic wall	21	0	60	8
Transversectomy	17	0	45	5
Transection of the intercostal muscles ..	16	0	48	3
Transection of the intercostal nerves....	16	0	85	13
Provoked epiphysiolysis of the heads or transection of the necks of the ribs ..	13	0	44	12
Combined thoracic operations				
Transection of the costotransverse ligaments and the intercostal muscles ..	63	55	75	3
Transection of the costotransverse ligaments and the intercostal nerves	34	0	90	8
Lumbar operations				
Hemilaminectomy....................	49	15	110	8
Transection of all muscles and ligaments attached to the transverse processes and the arches	28	17	35	6
Transversectomy	23	20	26	2
			Total	202

developed in some animals. The results in the rabbits after a minimum of two months are compiled in Tables XI and XII.

With regard to degree, no definite correlation was discernible between functional scoliosis and the subsequent, structural condition (Table XIII). All animals on which the dorsal ends of ribs had been resected, or both costo-transverse ligaments and intercostal muscles had been cut, developed permanent structural scoliosis, but after all other thoracic operations provoking scoliosis complete regression occurred in some cases. After one and the same operation, too, wide variations in the degree of the scoliosis were seen.

Summary of the effect on rabbits of different operations provoking scoliosis

For the sake of comparison, Table XIII has been compiled to illustrate the functional and structural scoliosis induced by different operations involving the resection or transection of various structures in the spine or its vicinity. The table shows the average degree of scoliosis resulting from the different operations and their relative efficacy. The results of the operations described in the foregoing may be summarized as follows:

Simple thoracic operations

Resection of the dorsal ends of ribs led to the severest average functional and structural scoliosis. In no case was complete regression of the scoliosis observed, but wide variations in degree occurred.

Resection of ribs laterally of their tubercles resulted in functional and structural scoliosis which was much slighter than in the foregoing case. The farther laterally of the tubercle the resection was performed, and the smaller the piece resected, the slighter was the resulting scoliosis. Only one out of 21 cases showed complete regression.

Transection of ribs and the corresponding intercostal nerves and vessels led to slight functional scoliosis. Of 8 rabbits, 5 developed structural scoliosis up to 60 degrees.

Resection of the heads of ribs resulted in severe functional scoliosis and much slighter structural scoliosis. Of 5 cases one showed complete regression.

Provoked epiphysiolysis of the heads or transection of the necks of ribs induced severe functional scoliosis, which in all cases regressed. In 5 cases

TABLE XII. — *Structural scoliosis in rabbits resulting from resection or transection of different structures in the spine or its vicinity.*

The same animals as appear in Table XI. The position of the spine was radiologically recorded a minimum of two months after operation.

Operation	No. of rabbits						
	Scoliosis in degrees						
	0	1—9	10—19	20—29	30—39	40—49	50—59
Simple thoracic operations							
Resection of the dorsal ends of the ribs				2	1	2	4
Hemilaminectomy..........................	4		3	2	4	3	3
Transection of the ligaments of the heads of the ribs	3			1	2		1
Transection of the ligaments attached to the dorsal ends of the ribs	1		1	1	2	2	2
Resection of the ribs laterally of their tubercles	1		4	3	4	2	1
Resection of the heads of the ribs	1			1	1		
Transection of the costotransverse ligaments ..	5		2	2		1	1
Transection of the thoracic wall	3	1	1		1	1	
Transversectomy	3					2	
Transection of the intercostal muscles	2					1	
Transection of the intercostal nerves..........	8		2				2
Provoked epiphysiolysis of the heads or transection of the necks of the ribs	5	1	3	1		2	
Combined thoracic operations							
Transection of the costotransverse ligaments and the intercostal muscles							1
Transection of the costotransverse ligaments and the intercostal nerves	2		1	1		2	
Lumbar operations							
Hemilaminectomy..........................			2		1	2	1
Transection of all muscles and ligaments attached to the transverse processes and the arches			1	2	3		
Transversectomy				2			

No. of rabbits													
Scoliosis in degrees													Total
60–69	70–79	80–89	90–99	100–109	110–119	120–129	130–139	140–149	150–159	160–169	170–179	180	
1	4	5	5		6	2	2				1		35
4	1	3	2	1	1	2				1		1	35
1	2	1	1	1		1							14
		1	1	1									12
1	2	1	1		1								21
2													5
			1										12
1													8
													5
													3
		1											13
													12
1	1												3
1			1										8
			1		1								8
													6
													2

Table XIII. — *Comparison of functional and structural scoliosis in rabbits resulting from resection or transection of different structures in the spine or its vicinity.*

The same animals as appear in Tables II and XI.

The numbers 1—12 indicate the order of the operations in regard to efficacy in producing scoliosis.

Operation	Funct. scoliosis		Struct. scoliosis	
	Order of efficacy	Average scoliosis in degrees	Order of efficacy	Average scoliosis in degrees
Simple thoracic operations				
Resection of the dorsal ends of the ribs..	1	51	1	86
Resection of the heads of the ribs	2	51	6	34
Provoked epiphysiolysis of the heads or transection of the necks of the ribs ..	3	51	12	13
Transection of the ligaments of the heads of the ribs	4	49	3	55
Transection of the intercostal muscles ..	5	49	10	16
Transection of the costotransverse ligaments	6	44	7	22
Hemilaminectomy....................	7	44	2	58
Transection of the ligaments attached to the dorsal ends of the ribs	8	38	4	49
Transection of the intercostal nerves....	9	37	11	16
Resection of the ribs laterally of their tubercles	10	35	5	41
Transection of the thoracic wall	11	21	8	21
Transversectomy	12	18	9	17
Combined thoracic operations				
Transection of the costotransverse ligaments and the intercostal muscles ..	1	73	1	63
Transection of the costotransverse ligaments and the intercostal nerves	2	61	2	34
Lumbar operations				
Transection of the muscles and ligaments attached to the transverse processes and the arches	1	40	2	28
Transversectomy	2	23	3	23
Hemilaminectomy....................	3	17	1	49

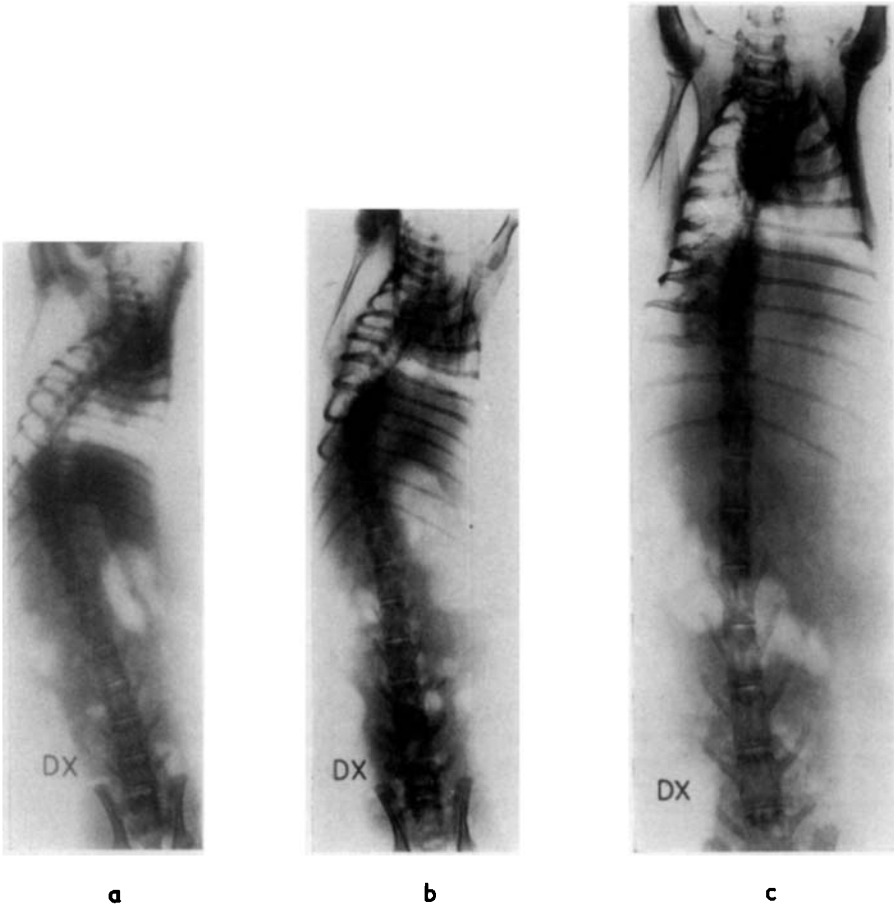
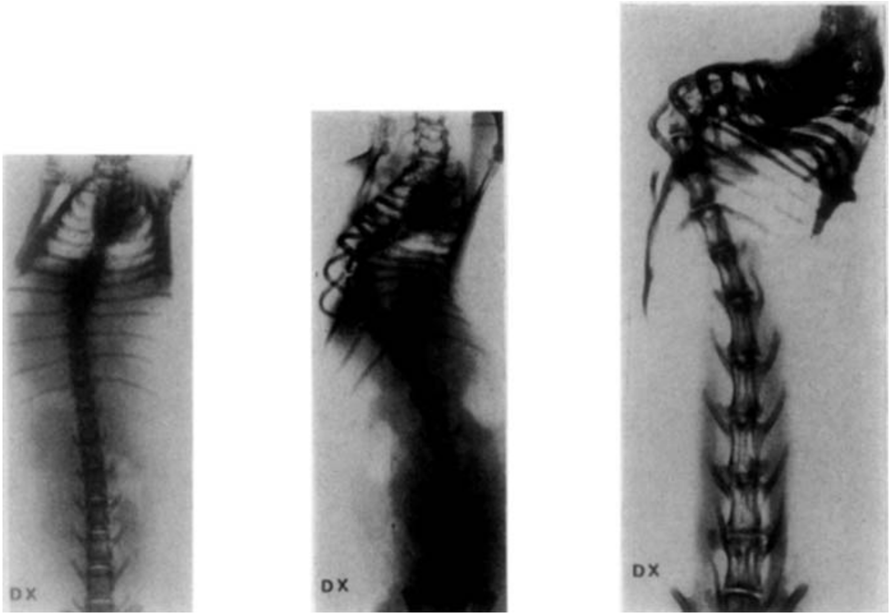


Fig. 7. **Rabbit. Transection of the necks of the sixth to tenth ribs on the right side performed at the age of 20 days.** ***a.*** **Immediately after operation scoliosis of 60 degrees.** ***b.*** **Ten days after operation scoliosis of 45 degrees.** ***c.*** **Forty-five days after operation only slight scoliosis. Abundant cicatrization in the area of the operation.**

out of 12 regression was complete. After these operations marked cicatrization was often observable. See Fig. 7.

Transection of the ligaments of the heads of ribs led to relatively severe functional and structural scoliosis. Complete regression occurred in 3 out of 14 cases. There were wide variations in the degree of the scoliosis.



a b c

Fig. 8. Rabbit. Hemilaminectomy of the sixth to tenth thoracic vertebrae on the right side performed at the age of 30 days. *a.* Immediately after operation. *b.* Two weeks after operation. *c.* Half a year after operation scoliosis of 140 degrees.

Transection of intercostal muscles provoked relatively severe functional scoliosis, but of 3 rabbits only one developed structural scoliosis (of 48 degrees). Cicatrization was marked.

Transection of costotransverse ligaments induced relatively severe functional scoliosis, but complete regression occurred in 5 out of 12 cases. In the remainder, structural scoliosis up to 90 degrees developed.

Hemilaminectomy led to relatively severe functional, and still severer structural scoliosis. Complete regression was seen in only 4 out of 35 cases, while the remainder of the animals developed scoliosis varying in degree, the maximum being 180 degrees. The more radical the operation, the severer was the functional and structural scoliosis resulting. See Fig. 8.

Transection of all ligaments attaching the dorsal ends of ribs to the spine produced relatively severe functional and structural scoliosis. Complete regression occurred in only one out of 12 cases.

Transection of intercostal nerves resulted in moderate functional scoliosis, but of 13 animals only 5 developed structural scoliosis (up to 85 degrees).

Transversectomy in the thoracic region led to only slight functional and structural scoliosis.

Combined thoracic operations

Transection of both costotransverse ligaments and intercostal muscles resulted in severe functional and structural scoliosis in all rabbits. It should be noted that when carried out alone, the different procedures led to structural scoliosis which was on the average slight.

Transection of costotransverse ligaments and intercostal nerves produced severe functional scoliosis. Of 8 rabbits 2 showed complete regression, while the remainder developed structural scoliosis up to 90 degrees.

After all the above-mentioned thoracic operations the primary curve was convex to the side of the operation in both functional and structural scoliosis.

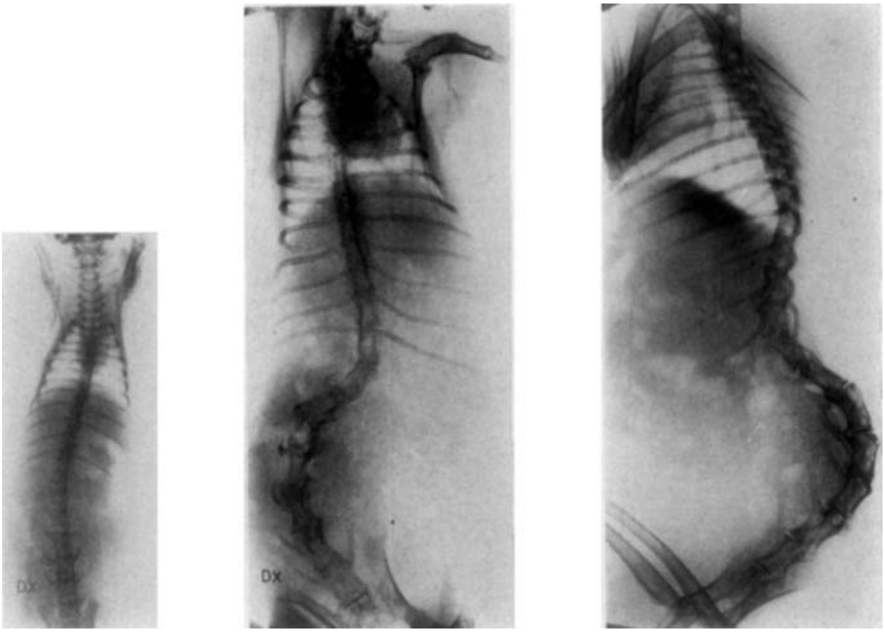
Lumbar operations

Transection of the muscles and ligaments between the transverse processes and between these and the arches resulted in relatively severe functional scoliosis, which was convex towards the operated side. The resultant structural scoliosis was slight. In one case it was directed towards the side of the operation, in 5 cases towards the intact side. Furthermore, 2 rabbits showed severe apparent kyphosis.

Transversectomy in the lumbar region led to only slight functional scoliosis, which was convex towards the side of the operation. The subsequent structural scoliosis was associated with slight lordosis. In one of 2 animals the scoliosis was directed towards the operated side, while in the other it was convex to the intact side.

Hemilaminectomy provoked slight functional scoliosis directed towards the side of the operation. All animals developed permanent structural scoliosis. The convexity was in 6 cases directed towards the operated side, in 2 cases towards the intact side. In addition, 4 rabbits developed kyphosis up to 90 degrees. See Fig. 9.

After all the above-mentioned lumbar operations the primary curve of the functional scoliosis was invariably convex to the side of the operation. While the condition developed into the structural form, the scoliosis was in some cases gradually transferred to the other side.



a b c

Fig. 9. Rabbit. Hemilaminectomy of the first to fifth lumbar vertebrae on the right side performed at the age of 30 days. *a*. Immediately after operation. *b* and *c*. Fourteen months after operation scoliosis of 90 degrees and kyphosis of 100 degrees.

The development of structural scoliosis from functional scoliosis in pigs

Just as in the rabbits, structural scoliosis resulted in the pigs after all those operations involving the transection or resection of various structures in the spine or its vicinity which had led to functional scoliosis. After the different operations, structural scoliosis was mostly somewhat slighter in the pigs than in the rabbits. The results in the pigs a minimum of two months after operation are compiled in Table XIV.

Resection of the dorsal ends of ribs including both costal joint surfaces in 19 pigs resulted in structural scoliosis of an average of 34 degrees, the minimum being 18 degrees and the maximum 77 degrees.

Hemilaminectomy and transversectomy were performed on one pig, which developed structural scoliosis of 30 degrees. *Incomplete hemilaminectomy*

TABLE XIV. — *Structural scoliosis in pigs resulting from resection or transection of different structures in the spine or its vicinity.*

All operations were performed unilaterally at five levels. The position of the spine was radiologically recorded a minimum of two months after operation.

Operation	No. of pigs									
	Scoliosis in degrees									
	0	1—9	10—19	20—29	30—39	40—49	50—59	60—69	70—79	Total
Transection of the intercostal muscles and the costotransverse ligaments						1				1
Transection of the intercostal muscles........					2	1				3
Transection of the costotransverse ligaments..			1	1	1	1				4
Resection of the dorsal ends of the ribs			2	8	6	1	1		1	19
Resection of the heads of the ribs					1					1
Hemilaminectomy and transversectomy......					1					1
Transection of the ligaments attached to the dorsal ends of the ribs			1							1

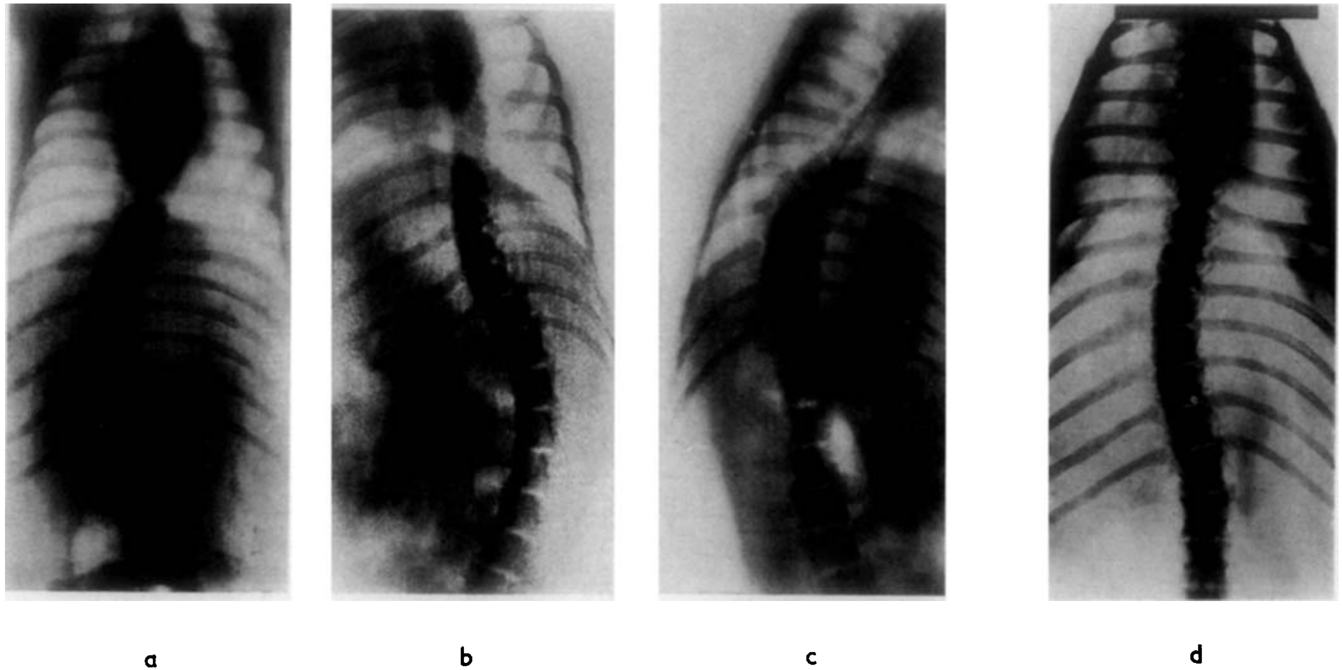


Fig. 10. Pig. Transection of the costotransverse ligaments at the seventh to eleventh intercostal spaces on the right side performed at the age of two months. *a–c.* Radiographs taken one month after operation. *a.* Resting position. *b.* Lateral flexion towards the side of the operation. Primary curve is rigid. *c.* Lateral flexion towards the intact side. Secondary curves are rigid. *d.* Animal killed and dissected two months after operation. Scoliosis of 30 degrees. Note rotation of vertebrae and drooping of ribs on the operated side.

(not including the articular processes) was done on one pig without any scoliosis resulting.

Resection of the heads of ribs was performed on one pig. Structural scoliosis of 30 degrees resulted.

Transection of all ligaments attaching the dorsal ends of ribs to the spine was carried out on one pig, which developed structural scoliosis of 15 degrees.

Transection of intercostal muscles in 3 pigs resulted in structural scoliosis averaging 37 degrees, the minimum being 35 and the maximum 40 degrees.

Transection of costotransverse ligaments led in 4 cases to structural scoliosis of an average of 31 degrees, the minimum being 17 and the maximum 46 degrees. See Fig. 10.

Transection of both intercostal muscles and costotransverse ligaments was carried out on one pig, which developed structural scoliosis of 40 degrees.

The effect of fixation of different skeletal parts to each other in rabbits and pigs

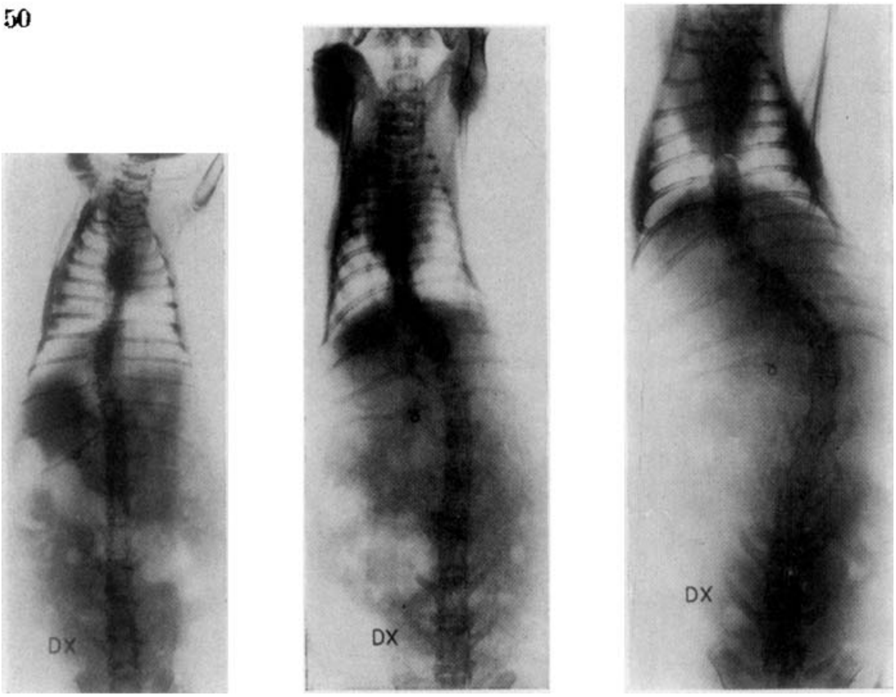
On growing rabbits and pigs the following fixative operations were done with nylon thread:

1. *Fixation of five to six transverse processes* in the thoracic region to each other was performed on 28 rabbits, 14 of which developed scoliosis up to 90 degrees.

2. *Fixation of three to seven ribs* to each other was performed on 20 rabbits. In 7 cases scoliosis up to 90 degrees developed. The result was dependent on the site of fixation. In those animals in which scoliosis developed, the nylon thread was tied around the ribs near their tubercles. On 2 rabbits *fixation of five ribs was done on one side in association with transection of the costotransverse ligaments at the same levels on the contralateral side.* Both animals developed structural scoliosis of 50 degrees and, in addition, apparent kyphosis.

3. *Fixation of spinous processes to ribs* was carried out in various ways on 9 rabbits and 8 pigs. Marked scoliosis resulted only when the spinous processes were fixed to ribs situated several levels cranially or caudally of them and the thread was tied around the ribs near their tubercles. Figs. 11 and 12 show the scoliosis thus produced in rabbits and pigs.

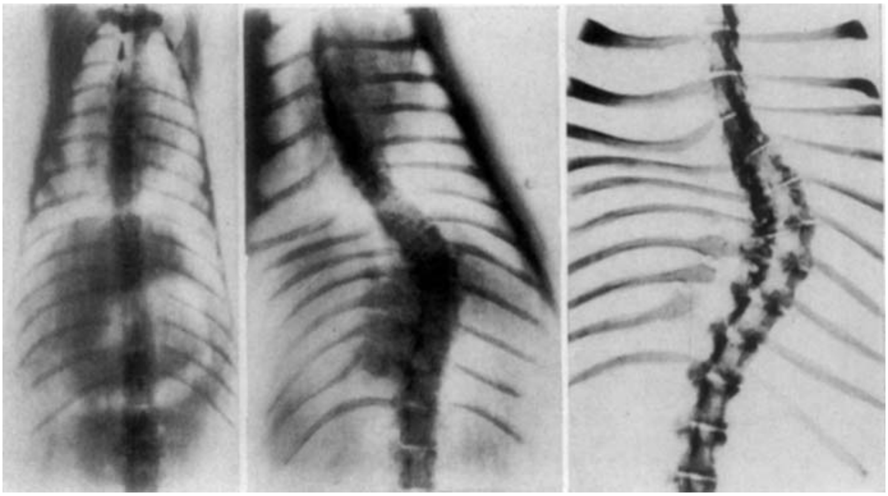
Immediately after fixation no appreciable changes in the position of the spine were observable. The structural scoliosis provoked by these operations developed gradually, and as a rule steadily progressed throughout the whole



a b c

d

Fig. 11. Rabbit. Fixation with nylon thread of the spinous processes of the ninth to eleventh thoracic vertebrae and the tenth to twelfth ribs to the spinous processes of the second to fourth lumbar vertebrae on the right side performed at the age of one and a half months. The site of fixation of the most caudally situated thread to the rib and the lumbar spinous process was marked with metal thread. *a.* Immediately after operation. *b.* One month after operation. *c* and *d.* Seven months after operation scoliosis of 70 degrees towards the intact side and lordosis.



a b c

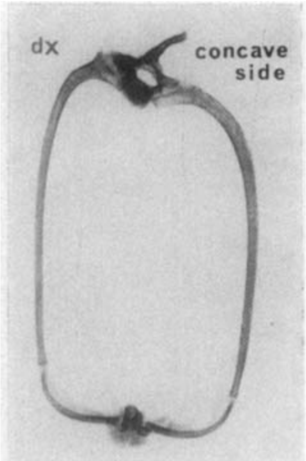
Fig. 12. Pig. Fixation with nylon threads of the spinous processes of the seventh to ninth thoracic vertebrae to the ninth to thirteenth ribs on the right side performed at the age of two months. *a.* Two weeks after operation. *b.* Two and a half months after operation. *c.* Specimen half a year after operation.

period of longitudinal growth. This form of scoliosis was always convex to the intact side, and it was often associated with lordosis or kyphosis of the region involved in fixation.

The general features of structural scoliosis

A primary curve and one or more secondary curves always occurred in structural scoliosis. The convexity of the primary curve was directed towards the side of the operation after all procedures except the fixations and some lumbar operations.

Rigidity of both the primary and the secondary curves was a constant phenomenon, and usually the rigidity steadily increased (Figs.10, 15 and 16). As a rule, the scoliosis was somewhat straightened by tension of the spine in the longitudinal direction (Fig. 15), immediately post mortem (Figs. 15 and 16), and in deep anaesthesia, but it never became completely straight, as was the case in functional scoliosis immediately after operation.



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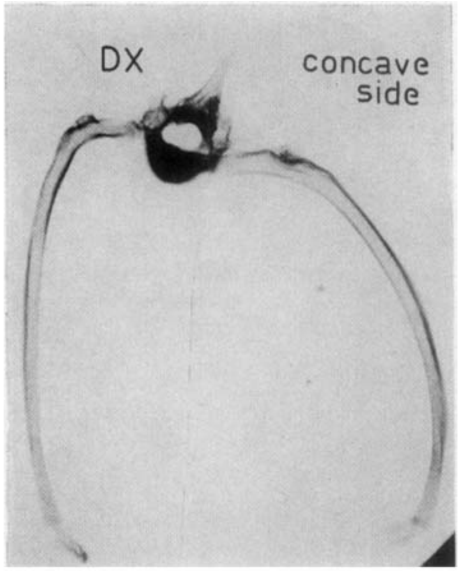


14

Fig. 13. Rabbit. The vertebra and ribs at the apex of a scoliosis of 85 degrees provoked by transection of five intercostal nerves on the right side. Note rotation of the vertebra and distortion of the ribs.

Fig. 14. Pig. The vertebra and ribs at the apex of a scoliosis of 40 degrees provoked by transection of the intercostal muscles on the right side in seven intercostal spaces. Note rotation of the vertebra and distortion of the ribs.

Lordosis or kyphosis of the spine at the primary curve frequently developed simultaneously with lateral deviation. Owing to rotation and structural changes of the vertebrae it was often difficult to decide whether kyphosis or lordosis was involved. Rib humps frequently gave an erroneous impression of kyphosis (as in man). In thoracic scoliosis, true lordosis was commoner than kyphosis, while in lumbar scoliosis kyphosis was commoner, although lordosis also occurred (Fig. 9).

The lateral flexibility of the spine was abnormally changed. The curves were rigid. In all phases of scoliosis the flexibility was markedly decreased towards the convex side of the curves in particular (Figs. 10, 15 and 16).

Rotation of certain vertebrae at the curves was a constant finding in structural scoliosis. The vertebral bodies were rotated towards the convex side (Figs. 10, 13 and 14). As a rule, rotation increased as long as the scoliosis progressed, but no correlation was discernible between the degree of rotation and lateral deviation.

Drooping of the ribs on the convex side of the primary curve was a frequent finding.

Rib humps, usually a dorsal hump on the convex side and a ventral hump on the concave side, occurred in thoracic scoliosis.

All the above-mentioned phenomena and many other adaptational changes of the spine and its surrounding structures were observable in structural scoliosis in both rabbits and pigs. Similar changes occur in man (KLEINBERG, LINDEMANN, LORENZ, LOVETT, v. NICOLADONI, SCHULTHESS).

Initial adaptive structural changes of the spine and its surrounding parts

In order to study the initial changes of various soft parts occurring in experimental scoliosis, 10 growing rabbits were investigated more closely for a period of time after scoliosis had been provoked.

Fig. 15 illustrates an experiment in which scoliosis was provoked in a rabbit by transection of the ligaments of the heads of five ribs. The animal was radiologically studied one day after operation both alive and post mortem after dissection step by step. Fig. 16 illustrates an experiment in which a rabbit was operated upon and investigated in the same way five days after operation.

The results of these studies showed the following:

Immediately after operation scoliosis developed which began to progress.

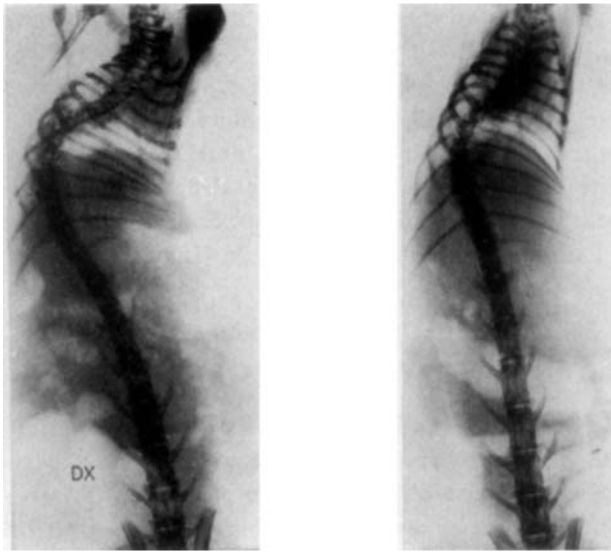
The scoliosis was somewhat straightened by tension in the longitudinal direction of the spine twenty-four hours after operation (Fig. 15 b).

At the primary curve the lateral flexibility of the spine was abnormally increased towards the intact (concave) side and decreased towards the operated (convex) side. Both the primary and the secondary curves were more or less rigid (Figs. 15 d and e, and 16 b and c).

Post mortem only partial straightening of the spine occurred in both the sagittal and the frontal plane, not complete straightening as in functional scoliosis (Figs. 15 f and 16 d), and the changes in lateral flexibility were less striking (Figs. 15 g and h, and 16 e and f).

When the thoracic wall and the back muscles had been removed from the specimen, the scoliosis showed a further decrease (Figs. 15 i and 16 g) but the curves were still definitely rigid (Figs. 15 j and k, and 16 h and i).

After removal of the surrounding structures, the curves of both the bodies and arches of the vertebral column were still found to be somewhat rigid (Figs. 15 l—o, and 16 j—m).



a b

Fig. 15. Rabbit. Transection of the ligaments attached to the heads of the sixth to tenth ribs was performed on the right side at the age of 75 days. Radiographs taken immediately after operation, *a*, and *one day after operation*, *b—p*.

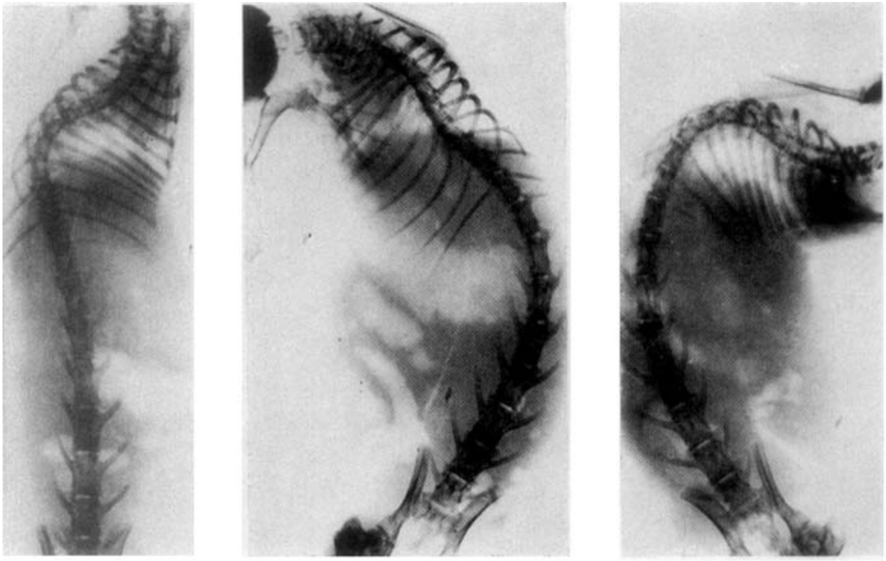
a. In resting position immediately after operation. *b*. One day after operation in tension in the longitudinal direction: Slight straightening of the scoliosis (cf. Fig. 15 c).

Alive in resting position, *c*, in flexion towards the right side, *d*, and towards the left side, *e*. The curves are rigid.

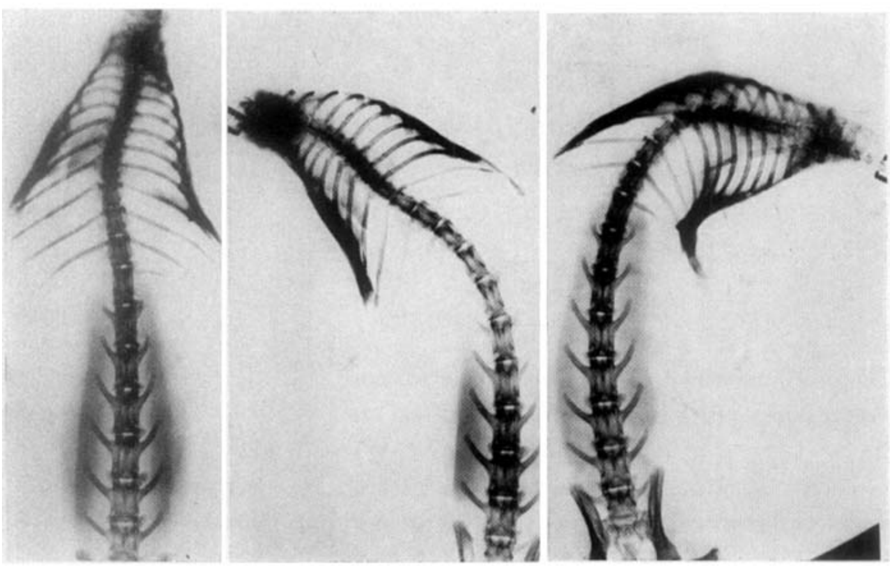
Specimen kept freely, *f*, in lateral flexion towards the right side, *g*, and towards the left side, *h*. The curves are less rigid than *in vivo*.

The spine kept freely, *i*, in lateral flexion towards the right side, *j*, and towards the left side, *k*. The curves are still moderately rigid.

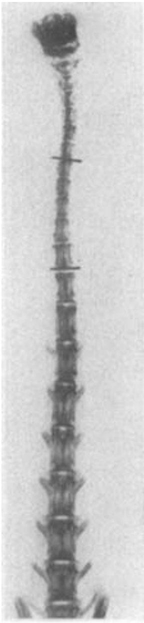
The bodies and arches of the vertebral column kept freely, *l* and *m*, in lateral flexion towards the right side, *n*, and towards the left side, *o*. The primary curve is moderately rigid, *p*. The thoracic wall spread out: The half on the convex side is markedly broader than the half on the concave side.



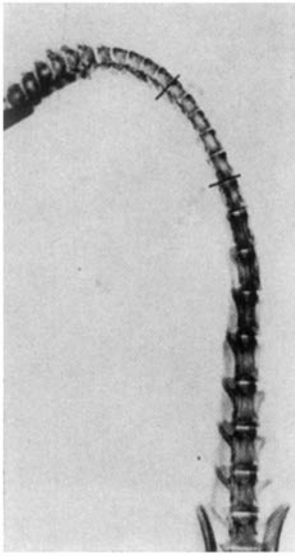
c d e



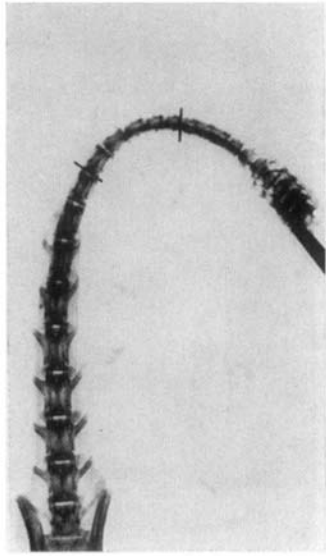
f g h



i



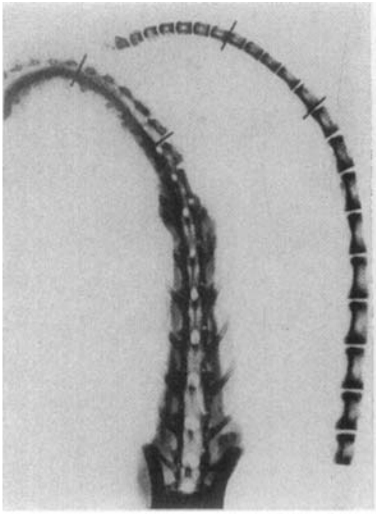
j



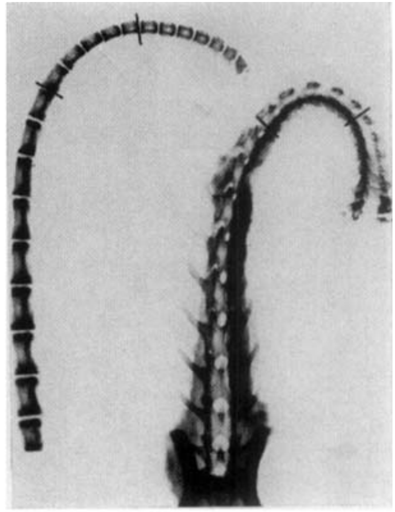
k

l

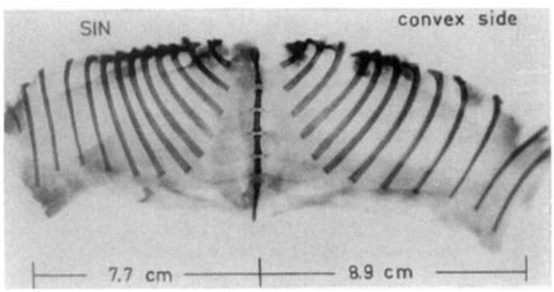
m



n



o



p

When dissected out, the thoracic wall was found to be definitely asymmetric, the concave side being markedly narrower than the convex side (Figs. 15 p and 16 n).

As early as one day after the development of functional scoliosis, structural changes had developed simultaneously in the spine and its surrounding structures. After five days the changes had progressed. These phenomena were verified in all the above-mentioned experiments.

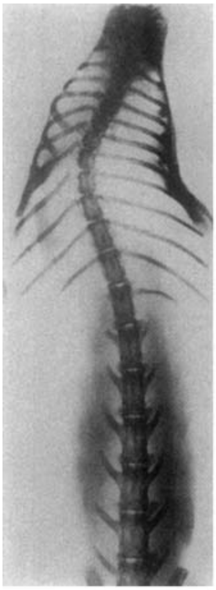
a b c

Fig. 16. Rabbit. Transection of the ligaments attached to the heads of the sixth to tenth ribs performed on the right side at the age of 75 days. All radiographs were taken *five days after operation.* Alive in resting position, *a*, in lateral flexion towards the right side, *b*, and towards the left side, *c*. The curves are rigid.

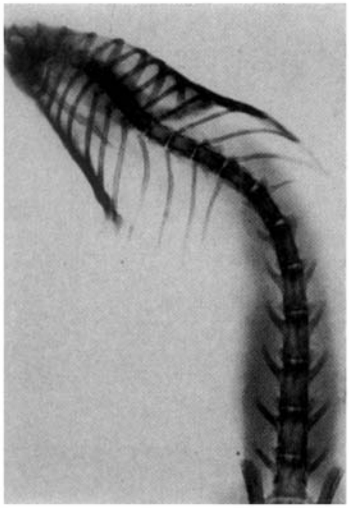
Specimen kept freely, *d*, in lateral flexion towards the right side, *e*, and towards the left side, *f*. The curves are rigid, but less so than *in vivo.*

The spine kept freely, *g*, in lateral flexion towards the right side, *h*, and towards the left side, *i*. The curves are still clearly rigid. The bodies and the arches of the vertebral column kept freely, *j* and *k*, in lateral flexion towards the right side, *l*, and towards the left side, *m*. The curves are somewhat rigid.

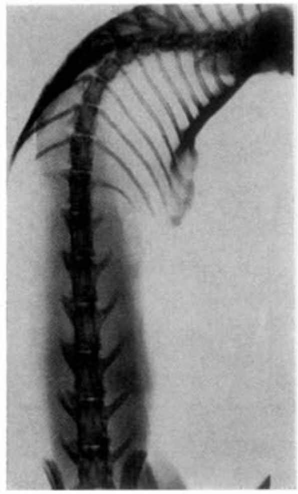
n. The thoracic wall spread out: The half of the convex side is markedly broader than the half of the concave side.



d

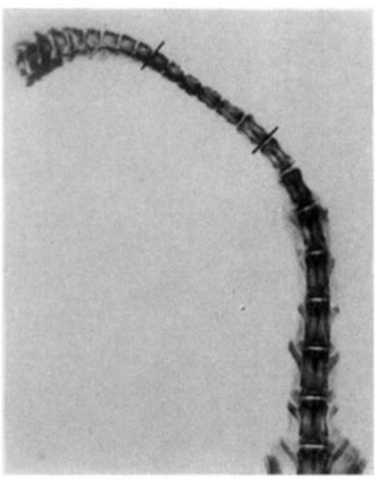


e

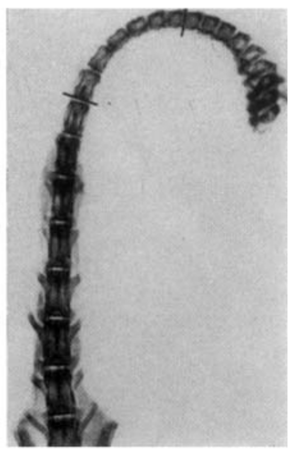


f

g



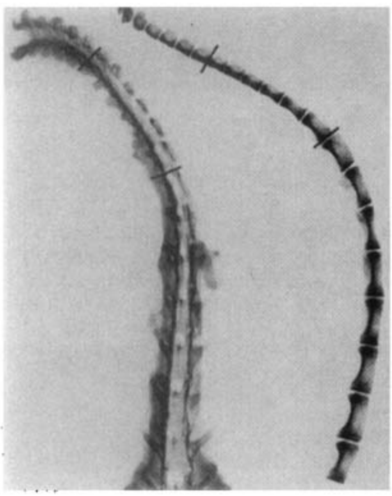
h



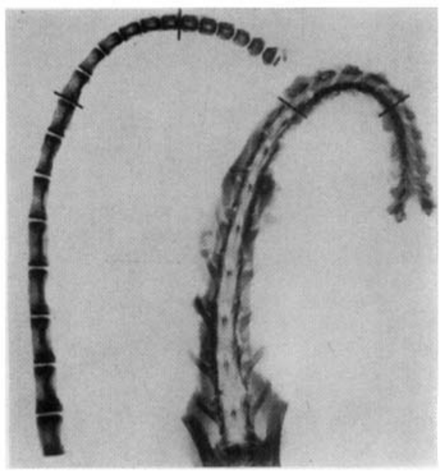
i

j

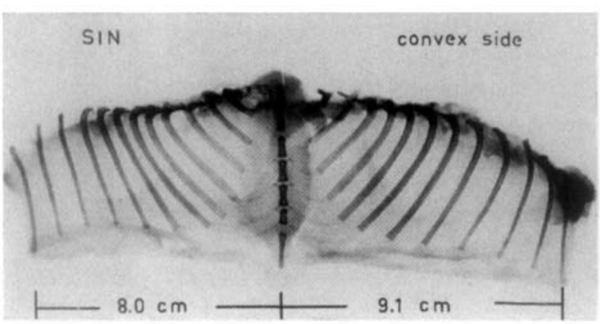
k



l



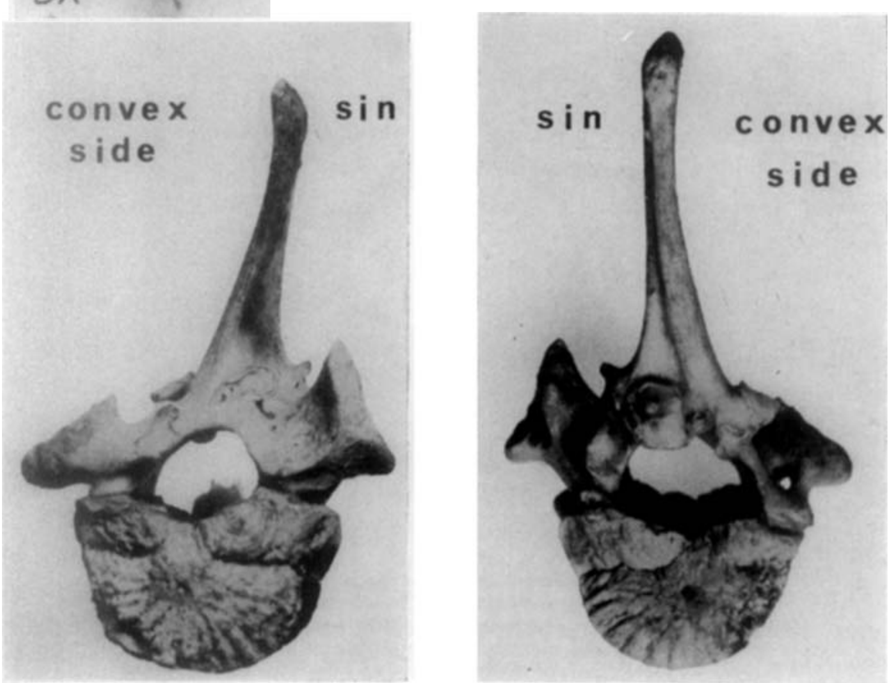
m



n

Fig. 17. Pig. Bodies of a scoliotic spine of 77 degrees provoked by rib resection. The animal was killed and dissected half a year after operation. Note the wedge shape of the bodies at the apex of the curve.

Fig. 18. Pig. The vertebra at the apex of a scoliosis of 39 degrees provoked by rib resection. The animal was killed half a year after operation. *a*. Cranial view without epiphysis. *b*. Caudal view without epiphysis. Note the distortion and asymmetry of all parts of the vertebra.



a b

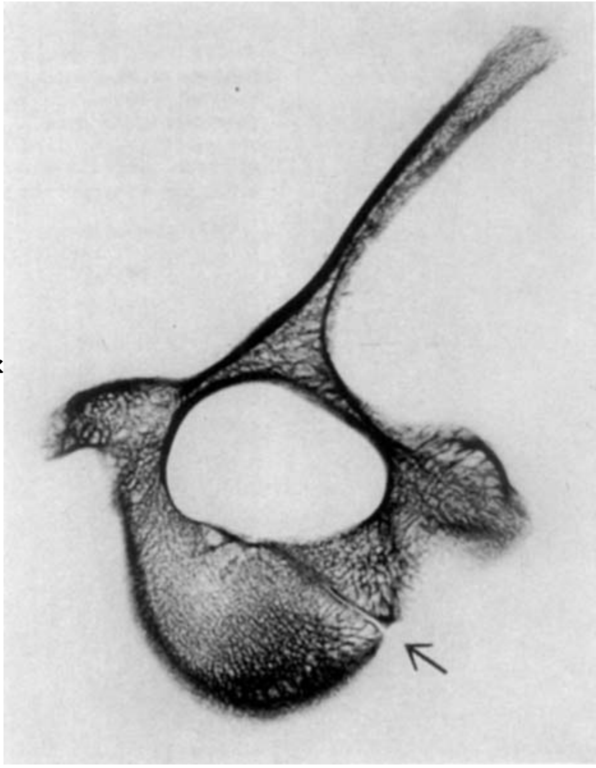
The macroscopic changes of the vertebrae

Eight scoliotic pig spines were dissected in order to enable closer study of the vertebrae. Almost all vertebrae exhibited changes, the greatest changes being found in the vertebrae situated at the apices of the curves, the slightest in those outside the curves (Figs. 17 and 20).

In the most deformed vertebrae the following changes were observed (Fig. 18):

The vertebral body was wedge-shaped, being much higher on the convex side of the curve. The most pronounced changes were seen at the cranial epiphysis on the concave side. In the transverse projection the vertebral body was somewhat egg-shaped, with the larger pole towards the concave

Convex side



Left side

Fig. 19. Pig. Transverse section of the vertebra at the apex of a scoliosis of 40 degrees provoked by rib resection on the right side, at the age of seven weeks. The animal was killed at the age of seven months. The neurocentral junction is fused on the convex side of the curve and open on the concave side.

side. On this side, the vertebral body and the neurocentral junction were much broader than on the convex side. In some animals the neurocentral junctions of certain vertebrae were fused on the convex side, while they were still open on the concave side (Fig. 19).

The vertebral foramen was mostly oval and displaced towards the concave side of the curve in relation to the vertebral body.

The arch was much lower and thicker on the concave side, and both halves of the arch were oblique and displaced towards the concave side.

The articular processes were usually broader and thicker on the concave side.

The transverse process was as a rule descendent, short and thick on the convex side of the curve, and ascendent, long and narrow on the concave side.

The base of the spinous process was shorter and thicker on the concave side. Its basal parts were displaced towards the concave side, its dorsal parts towards the convex side.

In experimental scoliosis all parts of the vertebrae thus showed deformation. The changes were the same as are typical of human idiopathic scoliosis, according to KLEINBERG, LORENZ *and* LOVETT.

Studies on the growth changes of the vertebrae

In order to study the growth changes of the vertebrae in scoliosis, different parts of scoliotic vertebrae were measured. Furthermore, in spines in which structural scoliosis was to be provoked, certain vertebrae were marked with vitallium screws.

1. *Studies on the longitudinal growth of the vertebrae*

The vertebrae of 2 scoliotic pig spines were dissected, and the height of the vertebral bodies and the pedicles of the arches were measured with calipers on both the convex and the concave side of the curve. In addition, the corresponding parts of normal vertebrae of pigs of the same age were measured. The results of these measurements are shown in Fig. 20.

The vertebrae at the apex of the primary curve showed the greatest deformation, those outside the curves the slightest. The vertebral bodies were higher than normal on the convex side, lower than normal on the concave side. The arches were much lower than normal on the concave side, while on the convex side they were sometimes equally high, sometimes

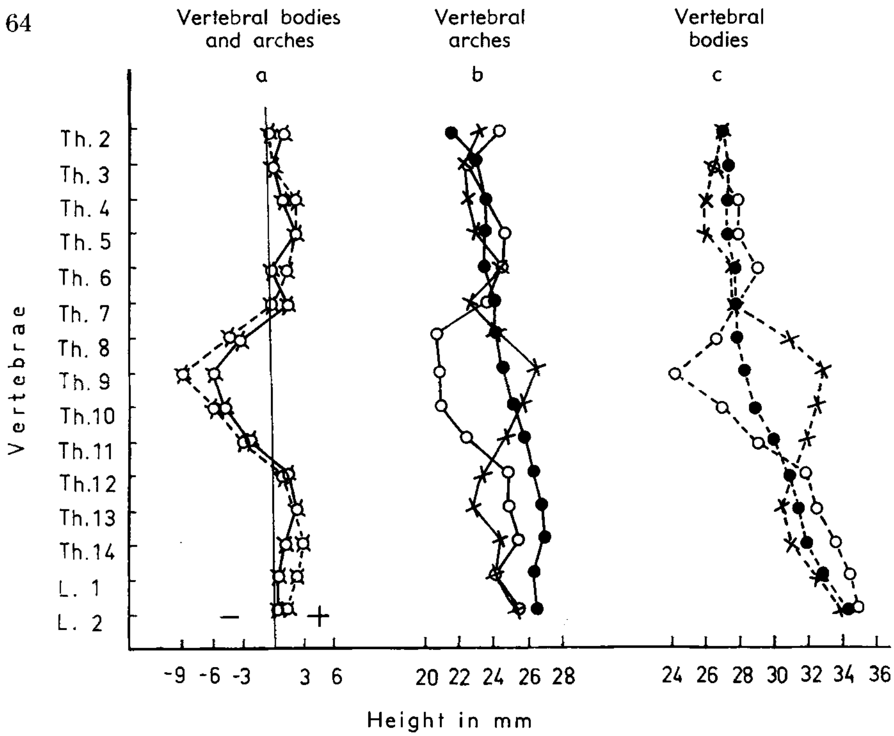


Fig. 20. Diagrammatic representation of the longitudinal growth changes of the vertebrae in scoliosis. The height of the pedicles of the vertebral arches and of the vertebral bodies was measured at corresponding points on the right and left sides in a scoliotic and a normal pig of the same age. Scoliosis was induced by resection of the dorsal ends of the seventh to eleventh ribs on the right side. On dissection four months after operation there was scoliosis of 40 degrees with the apex of the primary curve at the ninth thoracic vertebra.

a. The differences in height between the right and left sides of the bodies and of the pedicles of the arches of the scoliotic pig. Note that the differences are much greater at the primary curve than at the secondary curves.

¤- - ¤- - ¤ Differences in height of the vertebral bodies on the right and left sides.

¤——¤——¤ Differences in height of the pedicles of the arches on the right and left sides.

— The right side higher.

+ The left side higher.

b. Height of the right and left sides of the pedicles of the arches of the scoliotic and the normal pig.

×——×——× Height of the pedicles of the arches of the scoliotic pig on the right side.

○——○——○ Height of the pedicles of the arches of the scoliotic pig on the left side.

●——●——● Height of the pedicles of the arches of the normal pig (the same on both sides).

c. Height of the right and left sides of the vertebral bodies of the scoliotic and the normal pig.

×- - -×- - -× Height of the vertebral bodies of the scoliotic pig on the right side.

○- - -○- - -○ Height of the vertebral bodies of the scoliotic pig on the left side.

●- - ●- - -● Height of the vertebral bodies of the normal pig (the same on both sides).

The arches and bodies of the scoliotic spine are higher than normal on the convex side and lower than normal on the concave side at the apex of the primary curve.

somewhat higher and sometimes somewhat lower than normal, depending on the deviation of the spine in the sagittal plane.

These studies show that the longitudinal growth of the vertebral body, and often of the arch, too, had been increased on the convex side while retardation of the longitudinal growth of both the vertebral body and the arch had occurred on the concave side of the curve.

2. *Studies on the lateral growth of the vertebrae*

In cooperation with A. LANGENSKIÖLD some preliminary studies on the incorporation of alizarin in the vertebrae of rabbits during progression of experimental scoliosis were carried out. These studies indicated that the madder dye was especially accumulated on the concave side of the vertebral bodies.

In 5 growing pigs certain vertebrae were marked with vitallium screws, and simultaneously an operation producing scoliosis was performed in such a way that the marked vertebra came to be situated in the middle of the primary curve.

Fig. 21 illustrates one of these experiments. In a seven-week-old pig two screws were symmetrically applied, one to each side of the basal part of the spinous process of a vertebra, and at the same time rib resection was unilaterally performed. The pig was killed half a year later, showing scoliosis of 36 degrees. The screws were still situated at the base of the spinous process, but on the convex side of the curve the screw lay much nearer the lateral surface than the screw on the concave side.

Furthermore, screws were symmetrically applied to the body of a vertebra in a two-month-old pig, one to each side immediately ventrally of the neurocentral junction, and at the same time transection of intercostal muscles was unilaterally performed. Scoliosis of 35 degrees had developed when the animal was killed half a year later. On the concave side the screw was found to be situated much deeper in the vertebral body, *i.e.* farther from both the lateral and the ventral surfaces of the latter, than the screw on the convex side (Fig. 22).

These experiments show that increased lateral growth (apposition) had occurred in both the vertebral body and the arch on the concave side of the curve, while the apposition was much slighter on the convex side. Thus, the scoliotic vertebrae had grown in the lateral direction much more towards the concave than towards the convex side. The regular occurrence of these phenomena in experimental scoliosis has later been confirmed by KARAHARJU in experiments with tetracycline.

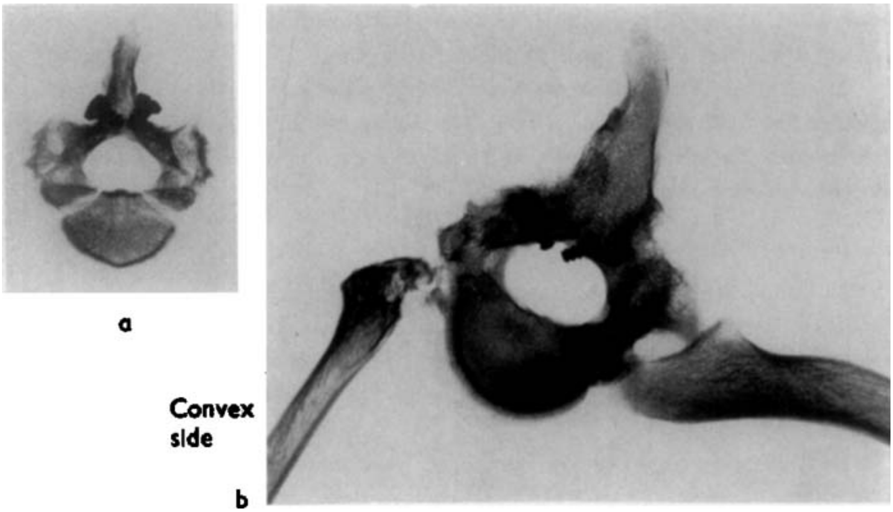


Fig. 21. Pig. At the age of seven weeks screws were symmetrically applied to both sides of the basal part of the spinous process of the ninth thoracic vertebra, as shown in *a*. Simultaneously, the seventh to eleventh ribs were resected on the right side. Scoliosis of 36 degrees developed, with the ninth thoracic vertebra situated at the apex. The animal was killed half a year after operation. Note that the screws are situated further towards the convex side than towards the concave side of the curve, *b*.

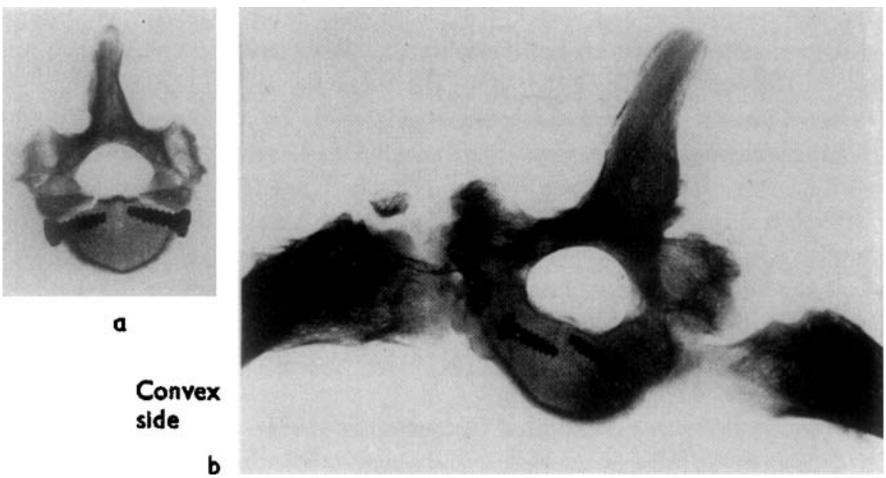


Fig. 22. Pig. At the age of two months screws were applied as symmetrically as possible one to each side of the body of the ninth thoracic vertebra, as in *a*. Simultaneously, transection of the intercostal muscles of the seventh to eleventh intercostal spaces was performed on the right side. Scoliosis of 35 degrees developed with the ninth thoracic vertebra situated at the apex. The animal was killed half a year after operation. The screw on the concave side is seen much deeper in the vertebral body than the screw on the convex side, *b*.

Histological findings

Thirty-three scoliotic rabbit spines were histologically examined at various points of time after the operation by which scoliosis had been provoked (Figs. 23—28).

Summary of the histological studies

The *intervertebral discs* exhibited definite changes as early as one day after scoliosis had been provoked. The nuclei pulposi were displaced towards the convex side, the fibres of the annuli fibrosi were extended on the convex side and compressed on the concave side. These changes of the discs were seen at all stages of scoliosis in the animals investigated.

The epiphyseal bony nuclei of the vertebral bodies changed gradually. The greatest changes were observable in the cranial bony nuclei, which steadily atrophied on the concave side, while the corresponding parts of the caudal bony nuclei as a rule became hypertrophied. On the convex side the bony nuclei were of about equal thickness.

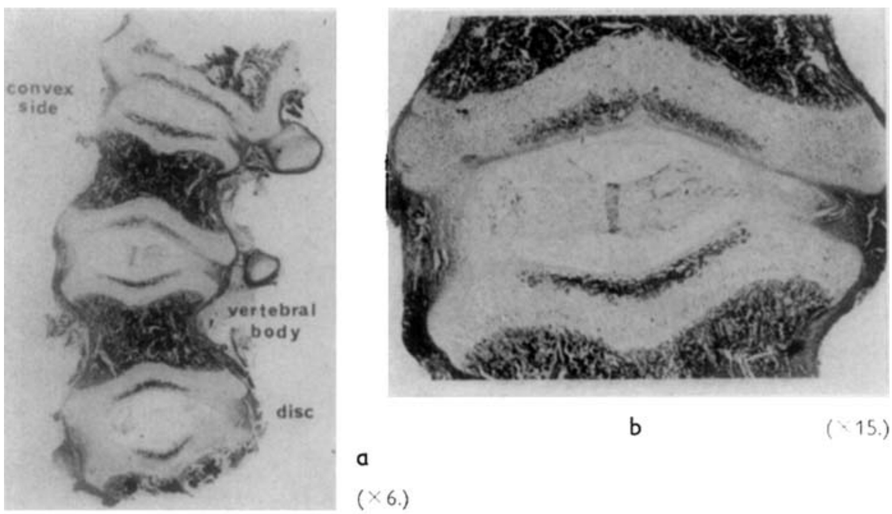


Fig. 23. Rabbit. Scoliosis was provoked by rib resection at the age of ten days and the animal was killed *one day after operation*. *a*. Section of vertebrae from apex of the primary curve. *b*. Magnification of the medial disc in *a*. The nucleus pulposus is displaced towards the convex side of the curve. The annulus fibrosus is extended on the convex side and compressed on the concave side. Somewhat increased sclerosis is seen on the concave side of the bodies.

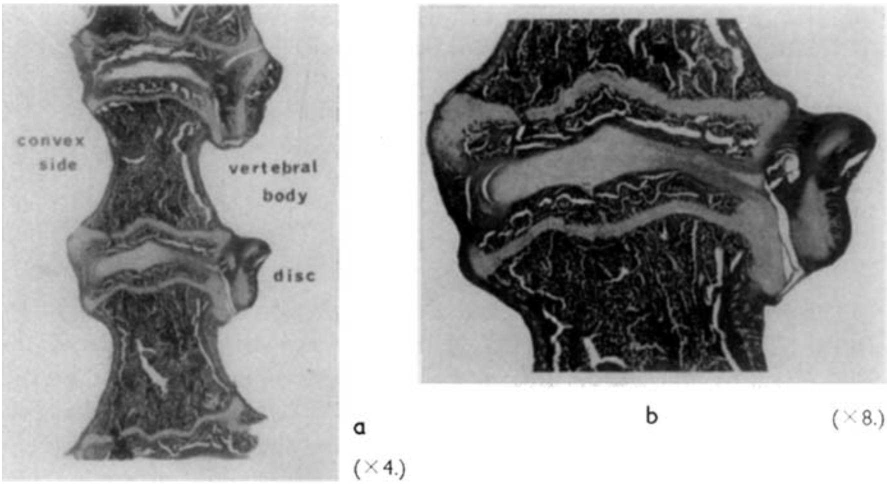


Fig. 24. Rabbit. Scoliosis was provoked by transection of costotransverse ligaments at the age of 40 days, and the animal was killed *10 days after operation*. *a*. Section of vertebrae from the primary curve. *b*. Magnification of the medial disc in *a*. Displacement of the nucleus pulposus towards the convex side and increased sclerosis of the bodies on the concave side. The annulus fibrosus is extended on the convex side and compressed on the concave side.

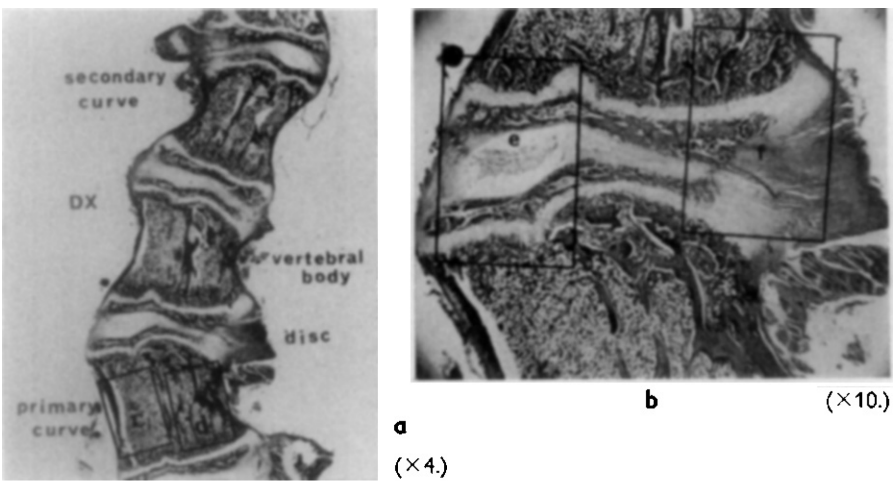
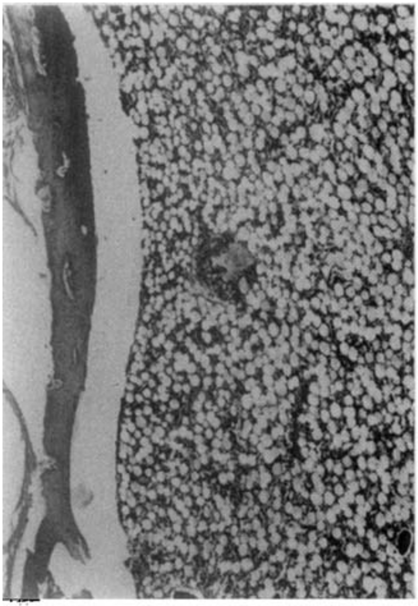


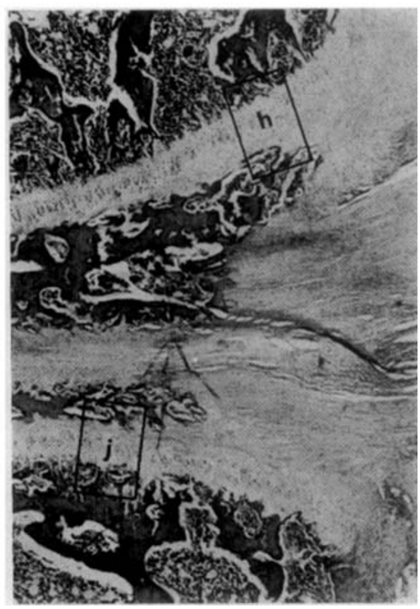
Fig. 25. Rabbit. Scoliosis was provoked by rib resection at the age of eight days. The animal was killed *two months after operation*. *a*. Section of vertebrae from the cranial secondary curve and the primary curve. *b*. Magnification of a disc of the primary curve in *a*. *c* and *d*. Magnifications of the areas marked in *a*. *e*—*f*. Magnifications of the areas marked in *b*. *g*—*j*. Magnifications of the areas marked in *e* and *f*. The changes in the primary and the secondary curves are of the same type. The nucleus pulposus is displaced towards the convex side. Increased sclerosis is seen on the concave side. The annulus fibrosus is extended on the convex side and compressed on the concave side. Narrowing of the cranial epiphyseal nucleus is seen on the concave side. The cartilage columns are disarranged on the concave side and regular on the convex side.



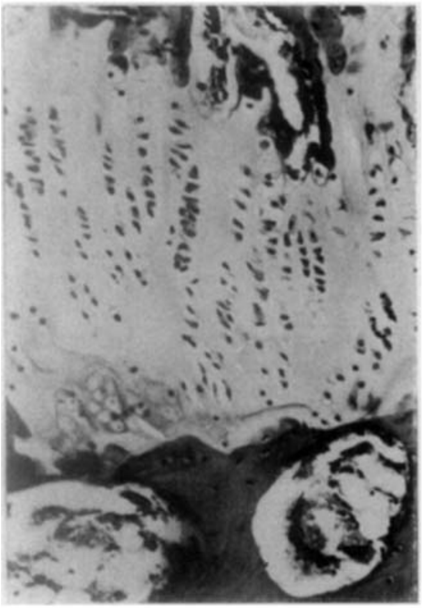
c (×30.)

d (×30.)

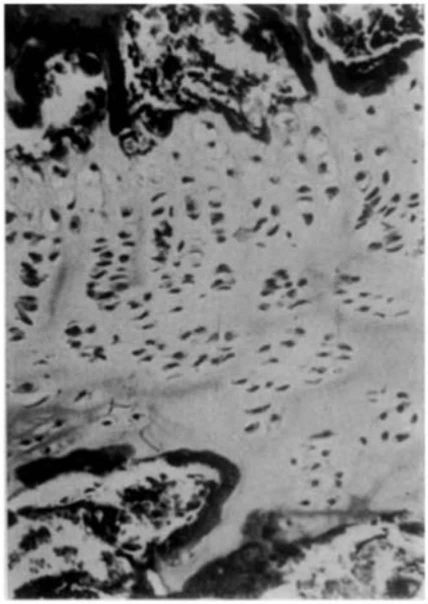
e (×30.)



f (×30.)



g (×185.)



h (×185.)

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The endochondral growth zones of the vertebral bodies underwent a gradual, steady change. On the concave side the cranial growth zones, in particular, were reduced and their cartilage columns were uneven and irregular. On the convex side the cartilage columns of the growth zones were much higher and showed a more regular arrangement than on the concave side.

In the *diaphyses of the vertebral bodies* gradually increasing sclerosis on the concave side and porosis on the convex side were observable as early as one day after scoliosis had been induced. The difference in height between the concave and convex sides steadily increased. In severe scoliosis inter-body fusion gradually developed in some cases. As a rule, the changes of the vertebral bodies were most conspicuous at the cranial epiphyses on the concave side.

The *neurocentral junctions* were narrower and fused much earlier on the convex than on the concave side.

The *vertebral arches* exhibited changes resembling those seen in the vertebral bodies, inasmuch as they were lower and more sclerotic on the concave side of the curve.

All these changes of the vertebral bodies and arches were observable in both the primary and secondary curves in the animals investigated.

The histological changes constitute evidence in favour of the view that the vertebrae had been exposed to increased pressure on the concave side and decreased pressure or increased tension on the convex side of the curves, with increased lateral apposition on the concave side and other adaptional changes resulting. See page 81.

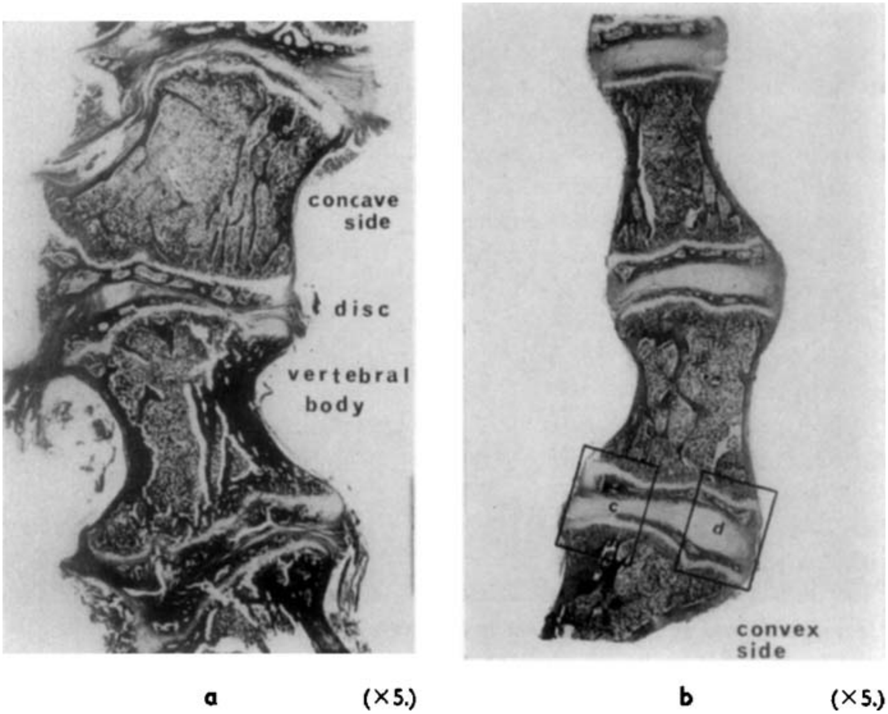
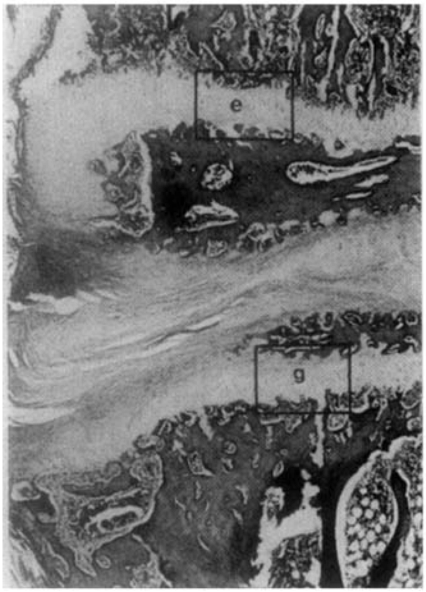
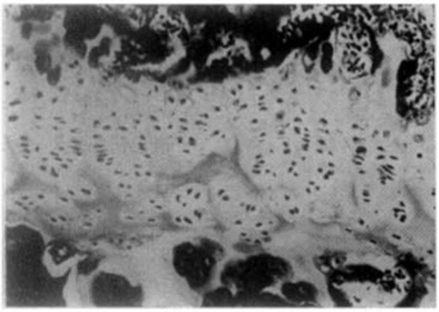


Fig. 26. Rabbit. Scoliosis was provoked by rib resection at the age of six days. The animal was killed *three months after operation. a.* Section of vertebrae from the primary curve. *b.* Vertebrae from the cranial secondary curve. *c* and *d.* Magnifications of the areas marked in *b. e–h.* Magnifications of the areas marked in *c* and *d.* The changes in the secondary curve are the same as seen in the primary curve (cf. Fig. 25).

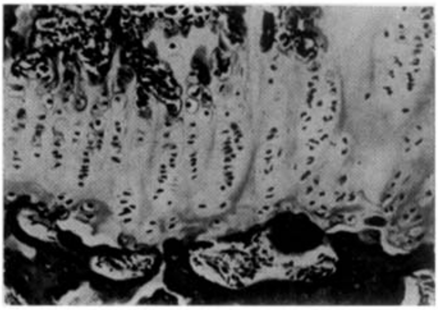


c (×25.)

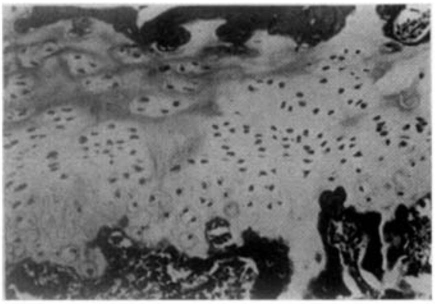
d (×25.)



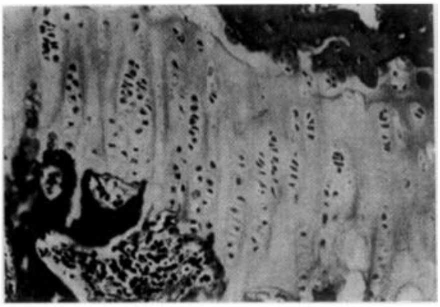
e (×110.)



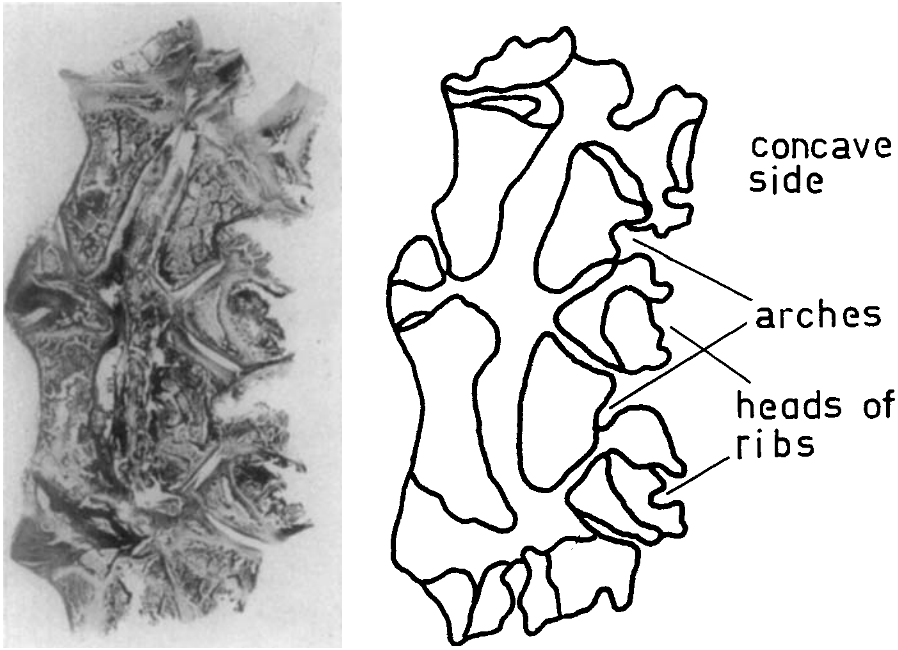
f (×110.)



g (×110.)



h (×110.)



a (×5.) b

Fig. 27. Rabbit. Scoliosis was provoked by rib resection at the age of six days. The animal was killed *four months after operation.* Section of *arches* from the primary curve. The arches are markedly lower and more sclerotic on the concave side than on the convex side.

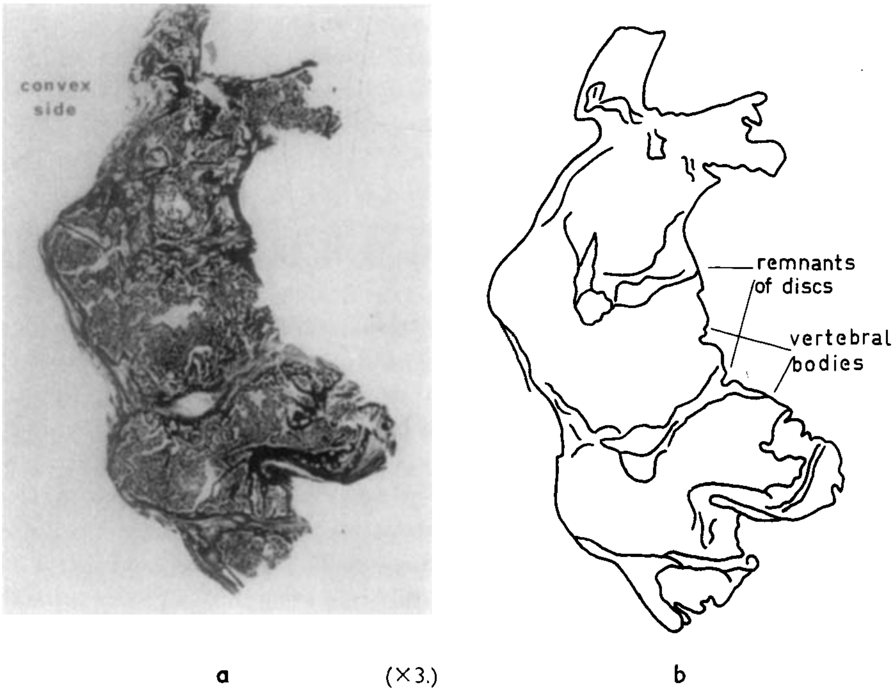


Fig. 28. Rabbit. Scoliosis was provoked by rib resection at the age of nine days. The animal was killed *one year after operation.* Section of the vertebrae from apex of the primary curve. The borderlines between the vertebrae are uneven and in some sites interbody fusion has taken place. The nucleus pulposus is seen on the convex side. Sclerosis is more marked on the concave side than on the convex side.

V. DISCUSSION AND CONCLUSIONS

Many investigations have been performed in order to clarify the aetiology and pathogenesis of idiopathic scoliosis, but according to CAREY, »most of the evidence presented has consisted of end-results of pathologic processes, the courses and starting point of which have been obscure or obliterated in the majority of patients with scoliosis.»

Hence, there seemed to be reason for undertaking experimental studies on scoliosis in animals, although the static and dynamic conditions of the spine are different in man and quadrupeds. It is known, however, that scoliosis may develop in man during continuous recumbency. This seems to indicate that the erect position of the spine cannot always play an essential part in the development of scoliosis. Thus it appears that not only static, but also dynamic factors cause this condition. The numerous reports on scoliosis in quadrupeds (BAYER, CHLUMSKY, ECKHARDT, HÄRTEL, LINDEMANN, OTTENDORFF, SCHMIDT, SCHULTHESS) seem to constitute further evidence in the same direction.

The development of functional scoliosis. In the experiments described many operations immediately led to functional scoliosis, which always disappeared if the animal was killed or subjected to deep anaesthesia within a few hours after operation. This shows that the functional scoliosis was sustained by active muscular forces.

Normally, the spine is in a state of dynamic equilibrium. It is almost continuously exposed to the action of dynamic forces (MICHELE, STEINDLER), and consequently the spine and its surrounding structures continuously act upon each other. The dynamic forces are often much stronger than the static ones (CAREY, STEINDLER).

In all operations resulting in initial scoliosis the dynamic equilibrium must have been disturbed in some way or other by the transection or resection of various structures. Owing to the nature of the operation, a weakening of active forces must have taken place on the side of the operation while the corresponding forces were still effective on the intact side. Consequently, it appears that a unilateral reduction of muscular forces which stabilize the spine in the frontal plane may lead to scoliosis towards the side of the operation, unless there are sufficient compensatory forces to prevent this outcome.

Of the operations leading to initial scoliosis there were only a few, however, by which dynamic forces (muscles) were directly affected. To facilitate understanding of the results of the different operations, the spine may be regarded as an elastic mast of a ship, with ribs for yards and muscles and ligaments for stays (BENNINGHOFF, LOB).

The operations which provoked scoliosis either affected active muscular forces directly (resection, transection or denervation of muscles), or were structures operated upon which transfer the action of muscles to the spine (ribs, transverse processes, laminae, ligaments, other muscles).

None of the thoracic operations involving only the deep back muscles led to scoliosis. *It was a common feature in most of the thoracic operations resulting in initial scoliosis that the dorsal ends of ribs, or ligaments attaching the ribs to the spine, were in some way or other attacked.*

The rib is attached to the spine by several ligaments in such a way that movement of the dorsal end of the rib is markedly limited in both the cranial and the caudal direction. Hence, the dorsal end of the rib constitutes a lever for the forces acting on the spine via the rib in the frontal plane, for instance. By various operations, ribs (levers) were attacked at, or near, their main points of support, *i.e.* at the articulation between the head of the rib and the adjacent vertebral bodies or at the costotransverse joint. This affected the attachment of the rib to the spine and altered its position. Consequently, some of the forces acting via the ribs were reduced, while the corresponding forces on the intact side were still effective. These operations frequently resulted in scoliosis towards the side of the operation.

One of the few thoracic operations resulting in scoliosis by which the dorsal ends of ribs or adjacent parts were not directly affected was the transection of intercostal muscles, which usually provoked severe initial scoliosis. The muscles involved act upon the spine via the dorsal ends of the ribs. The different operations on intercostal muscles show that the external and dorsal parts of the muscles, in particular, have a considerable stabilizing effect on the spine in the frontal plane. Denervation of intercostal muscles (transection of intercostal nerves) invariably led to scoliosis, the average degree of which was slighter, however, than in the scoliosis resulting from transection of the same muscles. This may, perhaps, be accounted for by the fact that transection of intercostal nerves only led to a weakening of active muscular forces, while both active and passive forces were reduced by the transection of intercostal muscles.

Of the hemilaminectomies performed, only those led to marked scoliosis which were sufficiently radical, *i.e.* included the portion of the arch situated between the base of the spinous process and the transverse process. By these operations the function of the posterior costotransverse ligament was suspended. Since transection of the anterior and posterior costotransverse ligaments usually resulted in rather severe initial scoliosis, it may be assumed that when the condition developed after hemilaminectomy, one cause must have been the imbalance of the active forces influencing the spine which was due to the loss of function of the posterior costotransverse ligament.

Only a few operations were performed on the lumbar spine. The results seem to indicate that the muscles attached to the transverse processes in the lumbar region of the spine have a marked effect on the position of the latter. Initial scoliosis was mostly milder in degree in the lumbar spine than in the thoracic spine, probably owing to the differences in anatomical conditions. The transverse processes are much more strongly developed and have a different direction in the lumbar spine than in the thoracic spine. In the lumbar region they correspond to some extent to the levers constituted by the ribs in the thoracic spine.

The course of the experimental scoliosis varied even after the same kind of operation.

Comparative studies revealed no definite correlation with regard to degree between functional scoliosis and subsequent structural scoliosis.

It may be stated that the differences in course may be accounted for by compensatory phenomena due to reflexes, by regeneration or healing of the affected tissues and by cicatrization. How the compensatory phenomena due to reflexes arise is not clear. Intense regeneration of affected tissues was observed in the youngest animals, in particular, and sometimes resulted in almost complete restoration of the anatomical conditions. Postoperative cicatrization was often abundant, particularly after operations by which periostal tissue had been injured. *In many cases the scar tissue completely compensated for weakened or removed structures, and occasionally it even caused transition of the scoliosis to the other side.* It is known that in man, too, scars may affect the position of the spine and cause scoliosis (KLEINBERG, LANGENSKIÖLD & MICHELSSON 1962, LINDEMANN).

Even if no absolutely certain conclusions can be drawn, it appears that regression of the scoliosis mainly occurred after such operations provoking this condition where rapid regeneration or healing of the affected tissues was possible, or where abundant cicatrization occurred and the scars in conjunction with compensatory forces due to reflexes had anatomical possibilities for acting on the spine, either directly or indirectly via other structures.

On the other hand severe progressive structural scoliosis developed after those operations inducing this condition where regeneration or healing of the cut or removed structures was inconsiderable or did not occur, where cicatrization was slight, or the scars and the compensatory forces had fewer anatomical possibilities of influencing the position of the spine.

Experimental scoliosis showed the same general features, in the main, as are typical of human idiopathic scoliosis.

Lateral flexibility. In man, a change in the lateral flexibility of the spine often constitutes the first sign of incipient scoliosis. In our laboratory animals the lateral flexibility of the spine exhibited changes immediately after the operations by which scoliosis had been induced (Fig. 4, page 34). The apparent rigidity of the primary curve observable immediately after operation may, at first sight, seem to be a puzzling finding, since it was obviously not due to adaptional changes of soft parts or bones. The fact that the change in lateral flexibility disappeared almost completely when the animal was killed within a few hours after the development of initial scoliosis seems to indicate that this change was mainly dependent on active forces. That identical changes in lateral flexibility were caused by different operations *i.e.* by operations on either muscles, nerves or bones, is more easily understood if the spine is regarded as an elastic mast, stayed by forces which in part act via the ribs. These forces are derived in part from active structures (muscles), in part from passive structures (ligaments or muscles). The operative procedures influenced the complicated staying system of the spine, in which the different structures are dependent on each other. Equal flexions to both sides were again achieved only when the corresponding structures on the intact side were subjected to the same kind of treatment as had initially produced scoliosis. When adaptive structural changes in the spine and its vicinity had developed, the changes in lateral flexibility were in part due to contraction of soft parts and structural changes of vertebrae, but probably those (dynamic) factors, too, which were responsible for the altered lateral flexibility in functional scoliosis still played a part.

Rotation of vertebrae. No rotation of vertebrae was observable in functional scoliosis. This change developed only gradually. The rotation of the bodies of the vertebrae was always directed towards the convex side of the curve, and it increased in some cases throughout the period of growth, but no definite correlation was discernible between the degree of rotation and lateral deviation. Because of the complexity of the system of forces influencing the spine, the causes of rotation cannot easily be understood. Owing to the structure of the vertebrae and their fixation on each other and to the ribs by soft parts their normal rotational movements are relatively slight. It may be assumed that in scoliosis rotation, too, is to a considerable extent due to the forces acting on the spine via the ribs. Operations which produce scoliosis probably cause imbalance also of the forces acting on the vertebrae in the transverse plane, and this is likely to result in rotational movements between the different vertebrae. When adaptive changes of the soft parts have developed rotation is likely to increase, and this may lead to subluxation between the vertebrae. Furthermore, rotation may be influenced by the adaptational structural changes of the vertebrae which gradually develop. Simultaneously with rotation of the vertebrae, adaptive changes of the ribs, *e.g.* humps, obviously arise.

The effect of different fixative operations. Fixation caused imbalance of the forces acting on the spine by the introduction of new forces, while by the other operations resulting in scoliosis forces were suspended. The fixative operations were performed on the basis of the experience gained from the other procedures. The new forces were thus applied to the dorsal ends of certain ribs and vertebrae. The results (page 49) show that *fixation led to scoliosis only in those cases where the anatomical conditions were suitable for such an operation, where the growth potency of the region of the spine lying between the fixed skeletal parts was high, and where the fixation of ribs was done near their tubercles.* The growth potency of the region involved by fixation was of essential significance. The effect of this kind of operation depends on the fact that the growth of the vertebrae increases the tension in the threads used for fixation and thereby also the compression to which the vertebrae on the side of the operation are exposed. This accounts for the results obtained: *The younger the animal and the greater the number of vertebrae involved by the fixative operation, the severer was the scoliosis resulting.* That fixation of ribs done far laterally of their tubercles as a rule did not lead to scoliosis, while the same procedure when performed at the tubercles usually resulted in progressive scoliosis, may be due to the different mobility of the different parts of the ribs, and to the elasticity and adaptional capacity of the ribs. In addition to lateral deviation, fixation usually also caused curves in the sagittal plane, either kyphosis or lordosis, depending on how the new forces were applied.

The development of structural changes in experimental scoliosis may be ascribed to the altered balance of forces caused by the surgical procedures. In this connexion certain facts relating to the transformation of soft parts and bones should be recalled. Soft parts are shortened when the distance between their points of attachment is shortened for a sufficient length of time and extended when the opposite is the case (LANGE). According to STEINDLER, both muscles, fasciae and ligaments may undergo structural changes if their loading is altered for a sufficiently long time or sufficiently radically. These rules afford an explanation for the development of the contractures seen in the present material.

According to WOLFF's law, both the structure and the shape of bones are influenced by the forces to which they are exposed and in this process both static and dynamic (muscular) forces play a part (CAREY, GEISER & TRUETA, JANSEN). Opinions concerning the effect of changes in compression and tension on bone growth are controversial, but it is generally believed that at least a markedly increased pressure usually leads to retardation (BLOUNT & CLARKE, GELBKE, HAAS, HUETER, NACHLAS & BORDEN, STROBINO & al., VOLKMANN) and reduced pressure to acceleration of growth (ARKIN & KATZ, GHILLINI, HUETER, MÜLLER, VOLKMANN). Increased distension, too, may result in accelerated growth (RING, SMITH & CUNNINGHAM). Decreased loading may cause osteoporosis, increased loading osteosclerosis (WEINMANN & SICHER). From the changes observable in the present study it may be concluded that the operations resulting in scoliosis caused increased pressure on the concave side of the spine and decreased pressure, or distension, on the convex side.

On the basis of what has been stated above, it may be assumed that the forms of experimental scoliosis described in this paper developed in the following way:

By various operations imbalance of the forces acting on the spine was caused either by the reduction of forces on one side (transection or resection of structures) or by the introduction of new forces (fixative operations). The imbalance immediately led to the development of scoliosis (except after fixative operations), resulting in increased pressure on the vertebrae and decreased loading on the soft parts on the concave side of the curve, and reduced pressure or distension of the vertebrae and extension of the soft parts on the convex side. The altered *loading soon brought about simultaneous adaptational changes of different bones and soft structures in the spine and its vicinity, clearly demonstrable as early as one day after operation. Owing to the altered position of the spine and the altered loading, contractures of the soft parts on the concave side of the curve and extension and, as a rule, gradual compensatory hypertrophy of the soft parts on the convex side ensued. Increased pressure on the vertebrae led to retardation of the longitudinal growth, atrophy of the cranial epiphyseal nuclei and cartilage plates, in particular, and increased sclerosis and increased lateral apposition (a compensatory phenomenon) of the vertebrae on the concave side of the curve, while reduced pressure or increased tension on the convex side led to increased longitudinal growth, porosis and increased resorption of the vertebrae. The further development of the condition depended on the interaction between the factors resulting in scoliosis, the compensatory phenomena due to reflexes and the secondary structural changes.*

VI. SUMMARY

The purpose of the present study was to throw light on the mechanism of development of experimental scoliosis.

The results are based on observations made after different operations on a total of 800 rabbits and 66 pigs.

In order to study the influence of different structures on the position of the spine, various operations were unilaterally performed on different skeletal parts, muscles, ligaments and nerves in the spine and its vicinity (Table I, page 16).

Initial, functional scoliosis resulted after some of these operations involving the dorsal ends of ribs, lumbar transverse processes, muscles and/or ligaments attached to them, or intercostal muscles (Table II, page 21). The primary curve in functional scoliosis was invariably convex towards the side of operation.

Transection of the external and dorsal portions of the intercostal muscles was found to be much more effective a procedure in provoking scoliosis than transection of any other portions of these muscles (Tables V—VIII, pages 26 and 27).

The functional scoliosis provoked by the different operations always disappeared completely if the animal was subjected to deep anaesthesia or was killed within a few hours after operation. This shows that it was due to active muscular forces.

The greater the number of structures unilaterally removed or cut, the loss of function of which had been found to provoke functional scoliosis, the severer was the scoliosis resulting (Table IX, page 29).

Functional scoliosis provoked by one of the different operations could be straightened or transferred to the other side when one or more of the procedures found to produce scoliosis was carried out contralaterally to the first operation (Table X, page 30).

Thus the position of the spine could be influenced by surgical procedures both qualitatively and quantitatively.

The forms of functional scoliosis in the present material exhibited one or more compensatory, secondary curves. No definite rotation of vertebrae occurred, and after thoracic operations drooping of the ribs was a common finding on the convex side of the curve (Fig. 1, page 22).

Lateral flexibility of the spine showed immediate changes after all operations provoking functional scoliosis (Fig. 4, page 34). On flexion towards the intact side the primary curve exhibited greater flexibility than normal but the curve was rigid and became only incompletely straightened by flexion towards the side of the operation. Post mortem the changes in lateral flexibility disappeared almost completely, which shows that they were mainly due to active forces.

When scoliosis was produced in growing animals, the condition usually changed throughout the period of growth. Sometimes it showed complete regression, while in other cases permanent structural scoliosis developed (Figs. 5 and 6, pages 36 and 37). The course was found to depend on various factors, *e.g.* healing and regeneration of the injured tissues and postoperative cicatrization. Cicatrization, in particular, seemed to play an essential part, inasmuch as it often completely compensated for removed or cut structures. The development of structural scoliosis was not directly related to the degree of the initial scoliosis produced by operation. Complete regression of the condition occurred in some cases after all thoracic operations, except resection of the dorsal ends of ribs and transection of both costotransverse ligaments and intercostal muscles (Table XII, page 40).

After all those operations which induced functional scoliosis, structural scoliosis certainly resulted in some cases (Tables XI and XII, pages 38 and 40).

Various fixative operations using nylon thread resulted in structural scoliosis. Fixation of ribs to each other, and of transverse processes to each other, led to scoliosis in some cases. Severe progressive scoliosis developed only when spinous processes were fixed to ribs situated several levels cranially or caudally of them and the threads were applied to the ribs near their tubercles (Figs. 11 and 12, pages 50 and 51). The greater the growth potency of the region involved by fixation, the severer was the scoliosis resulting.

The forms of functional scoliosis resulting from the operations here described were sustained by active muscular forces. Even when the position of the spine had been changed for one day only, structural changes of both vertebrae, discs, muscles and ligaments were observable (Figs. 15 and 23, pages 54 and 67). The soft parts were compressed on the concave side and extended on the convex side of the curve. In the spine, shortening of the annuli fibrosi and somewhat increased sclerosis of the vertebral bodies were discernible on the concave side of the curve, while on the convex side the annuli fibrosi were somewhat extended. The nuclei pulposi were displaced towards the convex side of the curve.

The changes increased steadily and simultaneously in both the soft parts, bones and cartilage and the following results were usually recorded:

The scoliosis became gradually more and more rigid, with interbody fusion of vertebrae sometimes resulting.

Rotation of the vertebrae as a rule increased steadily as long as the scoliosis progressed, and was always directed towards the convex side of the curve. No definite correlation was observable between the degree of lateral deviation of the spine and rotation. The rotation is influenced by appositional and resorptional processes building the vertebrae back towards the midline.

Lordosis or kyphosis of the spine was a common finding at the primary curve. If the rotation of the vertebrae is taken into account, lordosis was more frequent in the thoracic spine, while kyphosis occurred more often in the lumbar spine.

In thoracic scoliosis rib humps occurred as a result of adaptional changes, mostly a dorsal hump on the convex side of the curve and a ventral hump on the concave side (Figs. 13 and 14, page 52).

The extent of deformation of the different vertebrae was found to be dependent on their situation in relation to the scoliosis. The greatest changes were seen at the apex of the primary curve.

Increased longitudinal growth and porosis of the vertebrae were observable on the convex side of the curve, impaired osteogenesis and chondrogenesis on the concave side (Figs. 20 and 23—28, pages 64—75).

Marked atrophy of the vertebral bodies was seen on the concave side of the curve, particularly in the cranial epiphyses. The neurocentral junctions were narrower and fused earlier on the convex side than on the concave side of the curve (Figs. 18 and 19, pages 61 and 62).

Both macroscopic inspection, measurement and marking of growing vertebrae and histological studies showed that the vertebrae — body as well as arch — exhibited markedly accelerated lateral growth (increased apposition) on the concave side of the curve, and decreased lateral growth or increased resorption on the convex side (Figs. 18—22, pages 61—66).

The changes observable on the soft parts may be accounted for by the rules relating to the transformation of soft parts after altered loading, and the bone changes are explainable by WOLFF's and HUETER—VOLKMANN's laws.

The patho-anatomical skeletal changes observable in the forms of scoliosis provoked in laboratory animals by selective operations on soft parts in the vicinity of the spine corresponded completely to the changes observable in human idiopathic scoliosis. Since in the present experiments these typical changes occurred simultaneously in all skeletal parts involved, and obviously were due to extra-skeletal factors, the results obtained do not support the view that the cause of idiopathic scoliosis in man lies within the spine itself.

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