

From the Orthopaedic Hospital of the Invalid Foundation,
Helsinki, Finland (Head: Professor A. Langenskiöld, M.D.)

DEFORMATION OF VERTEBRAE IN EXPERIMENTAL SCOLIOSIS

THE COURSE OF BONE ADAPTATION AND
MODELLING IN SCOLIOSIS WITH REFERENCE TO
THE NORMAL GROWTH OF THE VERTEBRA.

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I INTRODUCTION

Few, if any, orthopaedic diseases have received so much attention from investigators as scoliosis. Despite several decades of clinical and experimental research work, the cause of idiopathic scoliosis still remains unknown. Bone changes occurring in connection with scoliosis have been described, but the pathomechanism of the changes has escaped definite explanation.

Bone is hard, rigid tissue and these properties impose certain conditions on its growth. Bone formation cannot occur interstitially because it is unyielding tissue. "Remodelling" is a fundamental process in the growth of bone, indicating continuous change of form during its growth. It is a normal, dual process of growth, encompassing both apposition and resorption of bone. Remodelling changes are complicated by a process called osseous drift. Local formation of bone is associated with apposition to one surface and resorption from the opposite one. This in a way causes drifting of the bone.

External factors also influence the growth and modelling of bone. Especially during the growth period bone is sensitive to these influences. Many deformities of bone arise under the influence of external pressure. It is obvious that, at least to a certain degree, this is also the case in scoliosis.

In the Orthopaedic Hospital of the Invalid Foundation, problems associated with scoliosis have been studied for several years under the leadership of Professor *Anders Langenskiöld*. The present study forms a part of this wider series of investigations. The object of the study was to elucidate structural changes occurring in experimentally induced scoliosis and to investigate the pathomechanics of these changes. The so-called tetracycline method that has been generally accepted during recent years provided the prerequisites for following the structural changes of scoliosis as a dynamic event.

II REVIEW OF LITERATURE

1. Growth of the normal vertebra

The growth of vertebrae and long bones is considered to be mainly similar. The vertebral body grows in length by means of the plates of epiphyseal cartilage on the cephalic and caudal surfaces. On the margin of the human vertebra there is a so-called ring-apophysis which does not participate in longitudinal growth (*Bick, Bick and Copel, Bisgard and Musselman, Carpenter, Ehrenhaft, Haas, Hanson, Hollinshead, MacGowan, Roaf, Scmorl and Jung-hanns*).

The rate of growth in length of the back remains almost equal over the entire period of growth with the exception of the period of prepuberty during which it is accelerated. Between the ages of three and fifteen a thoracic vertebra grows about one millimeter a year (*Anderson et al., Duthie, Takkunen*). When the ossification in the iliac apophysis is completed, vertebral growth is completed. Ossification of these apophyses occurs in girls at about 14 years of age, in boys at about the age of 16 (*Calvo, Risser*). The growth in length of the vertebrae has been quantitatively studied by means of radioactive isotopes (*Jee, Lee*). In the epiphyseal plates of pigs and rabbits, the growth is stronger anteriorly (*Ponlot, Sielig*). Such epiphyseal plates do not exist in humans.

According to *Larsen* and *Nordentoft* no apposition occurs in the posterior part of the body after five years of age. By analogy with the growth of the cranium the vertebral arch grows rapidly between the ages of 3 and 5, but by the age of one year the parts of the arch have already been united by bone tissue in the thoracal spine (*Ottander*). The neural arch does not become enlarged in all directions; while enlarging it migrates away from an "imaginary point" which would be located in the dorsal part of the vertebral body (*Lacroix, Ponlot*).

The vertebral body and the arch are joined together by the so-called neuro-central epiphysis which closes at the age of 3 to 6 years. The cartilaginous pillars of this epiphysis are bipolar, and the growth thus occurs in two directions, towards both the body and the arch (*Knutsson, Mineiro, Pacher, Rowe and Roche*).

2. Modelling of bone under pressure

The fact that pressure may influence the growth of bone has been known for centuries. As a rule, growth in length occurs in the epiphyseal line. The increased length is attained through the multiplication of cartilage cells which are later converted into bone by enchondral ossification (*Siffert*). Growth in thickness, on the other hand, occurs through the addition of new bone to bone surfaces.

The generally accepted view of the nature of the external form and of the internal architecture of bone is expressed in *Wolff's law*, usually stated in the following form: "Every change in the form and function of a bone, or in function alone, is followed by a certain change in the external conformation and in the internal architecture in accordance with mathematical laws." (*Carey, Geiser and Trueta, Jansen, Townsley, Weinmann and Sicher*).

Pressure has an effect on the growth in both length and thickness of the bone.

Pressure stimulates appositional bone growth. Thus, for instance, increased weight-bearing of the tibia will result in increased thickness and density in the middle of the shaft. Fractures healed in faulty positions have a tendency to straighten. This straightening is effected by the deposition of appositional new bone along the concavity while bone is being resorbed from the convex side (*Arkin, Bell, Carey, Evans, Frost, Gelbke, Ghillini*).

Pressure parallel to the axis of the epiphyseal growth affects the rate of such growth. Increased pressure in this direction will inhibit growth while decreased pressure will to some extent accelerate it. This relationship was recognized in 1862 by *Hueter and Volkmann*, and it is called the *Hueter-Volkmann law*. Pressure acting obliquely to the direction of growth results in deflection of the direction of such growth, with lateral or spiral displacement of the newly laid-down bone as the consequence (*Alexander, Arkin and Katz*).

According to *Maass*, pressure effects the entire bone so that the intensity of growth will not change. If pressure inhibits the growth in a certain direction, the bone will compensatorily grow without quantitative alternations in a direction that is free from pressure.

Several experimental studies have been performed on the effect of pressure on epiphyseal growth. It has been shown that compression by means of a wire loop or staples will entirely arrest epiphyseal growth. Quantitative measurements as to the magnitude of the pressure necessary for this have been made (*Arkin and Katz, Blount and Clarke, Blount and Zeier, Gelbke, Ghillini, Haas, Nachlas and Borden, Siffert, Smith and Cunningham, Strobino et al.*).

While studying juvenile vertebral osteochondrosis, *Edgren and Vainio* concluded: "It is possibly linked up with the static reconstruction phenomena of

the growing vertebra. We may assume that this increased weight on the ventral part of the vertebral body is the stimulus which induces the constructive material available to collect at this part of the vertebra: when the sagittal diameter of the vertebra increases, the supporting points approach the load-line and static improves." This statement pertains the vertebral growth in the ventral direction.

In their experimental study on the effect of pressure on the tibia, *Arkin* and *Katz* were able to demonstrate interesting changes both in the epiphysis and in the diaphyseal area. After six weeks of immobilization in a plaster cast it was found that growth was retarded on the side under pressure. On the opposite side growth was accelerated. On the side that had been under pressure, trabeculation was found to have increased in the shaft of the tibia. This was an illustration of a paradox between *Wolff's* and *Hueter-Volkman's* laws. Increased pressure in the direction of growth in length results in increased growth in thickness but reduced growth in length.

3. Structural changes caused by scoliosis

Idiopathic scoliosis is not a bending of the spine in the frontal plane due to irregular growth, but rather a most complex deformity involving lateral displacement of the vertebra, rotation and multiform thoracic deformities (*Cobb*, *McCarroll* and *Costen*).

Scoliotic structural changes have been described in rather great detail in the literature for over a century. Several experiments on animals have resulted in deformities resembling scoliosis in man, lending support to concepts of structural changes.

The following structural changes in the scoliotic vertebra have been observed:

- the vertebra is lower on the concave side and higher on the convex side
- the vertebral body is deformed
- the bone structure of the vertebral body is denser on the concave side, and usually resorption is observed on the convex side
- in the intervertebral disc the nucleus pulposus is displaced towards the convex side
- the arch on the concave side is short and clumsy, whereas on the convex side it is longer
- the spinous process has turned towards the concave side
- the neuro-central epiphysis is open on the concave side and its growth is disturbed on the convex side
- the neural canal is "narrowed" on the concave side
- there is atrophy of the epiphyseal plates on the concave side

- on the concave side, proliferation of the epiphyseal cartilage is reduced or absent and the cartilage bar formation is deformed
- on the convex side, the growth of the epiphyseal cartilage is accelerated; irregularities have also been found in this area.

(*Bade, Beadle, Deutschländer, Imhäuser, Jaroschy, Kleinberg, Lange, Lorenz, Lovett, Michelsson, Miles, Müller, Nicoladoni, Ottendorff, Pacher, Reiner and Werdorff, Roaf, Schanz, Schulthess, Stilwell, Unger*)

Mèry (1707) was the first to draw attention to the rotation and torsion of the vertebrae observed in a scoliotic back (*Valentin*). Rotation means that the vertebrae in the area of scoliosis are rotated in relation to each other so that the body turns towards the convex side. Torsion, especially in German literature, indicates a vertebral asymmetry that is formed in association with, and as a consequence of, rotation. On the basis of studies with cadavers, mechanical models and mathematical deductions, the conclusion has been reached that the lateral bending in extension of the spine is associated with rotation of the vertebrae towards the concave side, and lateral bending in flexion with rotation directed towards the convex side. Since lateral bending is as a rule associated with rotation, no rotation will occur without lateral deviation (*v. Lesser, Lovett, Reiner and Werdorff, Steindler*).

Rotation in apical vertebra (the most laterally displaced) is an integral part of scoliosis that becomes aggravated when the curve increases. The joints of the articular processes are located laterally and posteriorly in relation to the centre of the vertebra. Therefore the spinal column cannot yield in the direction of the joints without wheeling partially around with the result that the vertebra turns obliquely towards the convex side. The more posteriorly the articular processes are situated, the more severe is the rotation of the apical vertebra, and the earlier it appears. This is the case, e.g., in scoliosis of the lumbar spine. Rotation reduces pressure on the vertebral end plates on the concave side. Therefore, the effect of pressure on the end plates is less in the lumbar area where rotation appears early. If the articular processes are situated less posteriorly, as in the thoracic spine, rotation of the apical vertebra appears later. It has been supposed that the wedged vertebra that forms in a scoliotic back increases the tendency towards rotation (*Arkin, Carey, Lovett, Ponseti and Friedman, Risser, Steindler*).

When a healthy trunk is turned maximally, rotation from 1° to 4° occurs between each two adjacent vertebrae (*Lindahl and Raeder*). The greatest changes have been considered to occur in the disc (*Jentschura, Somerville*), the centre of the rotation being at the site of neurocentral epiphysis (*Ottander*).

At the limit of rotatory excursion the rotary force affects the vertebral body and causes structural changes, or torsion.

4. Pathomechanism of scoliotic structural changes

The normal spine tends to return as closely as possible to the mid-line over the sacrum. This is called the straightening tendency of an angulated vertebral column. A scoliotic spine, i.e. the involved vertebrae, straightens to the extent permitted by the soft tissues on the concave side. As the scoliosis progresses, and if no other forces are involved, the curve will eventually reach the point where the lateral soft tissues on the convex side are maximally stretched and the compression on the concave side cannot increase any more. In this situation, other forces are also at work, among them the growth of the vertebra (*Risser*).

Since the beginning of the 19th century, the pathomechanism of the structural changes caused by scoliosis has been studied. In 1824 *Bamphfield* observed that scoliosis appeared only during the growth period of the spine. He expressed the view that scoliosis is due to increased growth on one side of the vertebral bodies concurrently with resorption caused by pressure on the opposite side. It is generally agreed that scoliosis becomes aggravated only during growth (*Calvo, Duthie*).

Of the many structural changes caused by scoliosis referred to previously, the *wedge-formed* vertebrae have engaged the attention of investigators most. In considering the development of wedged vertebrae, the fundamental view has been that when the spine is bent laterally, pressure has increased on the concave side and correspondingly decreased on the convex side. A wedged vertebra in scoliosis does not develop in an adult; the process of wedge-forming stops when the growth of the spine ceases. These facts would suggest that a deformity which appears and becomes aggravated only during the period of growth must be related to growth.

In the section "Modelling of bone under pressure", the laws according to which modelling occurs were surveyed. In the case of a scoliotic wedged vertebra, attention has almost always been paid to effects consistent with *Hueter-Volkmann's* law. According to this, increased pressure on the concave side and decreased pressure on the convex side result in retardation of growth on the concave side and, on the other hand, in its acceleration on the convex side of the epiphyses (*Arkin, Bick, Bisgard and Musselman, Blount and Clarke, Haas, Lindemann, Michelsson, Moser, Müller, Rathke*).

Maass has presented a concept of the mechanism of development of the wedged vertebra that deviates somewhat from that presented above. According to him, quantitative growth has not changed but it occurs on the concave side in a direction devoid of pressure. This results in increased density of the bone structure on the concave side and the development of a wedged vertebra.

The increased density of the bone structure on the concave side has generally been explained by *Wolff's* law that pressure augments bone growth (*Arkin, Deutschländer, Müller, Schanz*). *Stilwell* has given as his opinion that the thickening is due to the fact that, on the concave side, the periosteum draws away from the compact bone like a taut bow-string, and new bone formation occurs in and along the elevated Sharpey fibers of the periosteum.

In the same way, the decreased trabeculation found to occur on the convex side, has been said to be caused by reduced pressure, according to *Wolff's* law. In *Stilwell's* view, however, the periosteum is involved even here, being stretched and tense at the convexity, and, due to pressure, bone and cartilage tissues are resorbed.

Less attention has generally been paid to the pathomechanism of vertebral rotation. Opinions about the origin and direction of torsion differ. Some of the rotation has been said to occur by means of vertebral torsion. In the scoliotic apical vertebra the body is squeezed over or deflected to the convex side. The opinion has been expressed that muscles are not involved in the appearance of torsion and that this passive plastic deformation is due to the wedged vertebra (*Arkin, Müller*). According to work done by *Appleton*, muscle section results in torsional deformation, but this mechanism has not been explored. *Arkin* has found experimentally that pressure applied obliquely to the axis of epiphyseal growth will change the direction of such growth, as has already been mentioned above. Thus the torsional deformation in scoliotic vertebrae is caused by the deflection of growing epiphyseal cartilages in a manner analogous to "the deflection of water entering a flowing stream" — as *Arkin* says.

The neurocentral epiphyses have also been considered to be implicated in the development of torsional deformity, owing to the asymmetric growth of these paired epiphyses in a scoliotic vertebra (*Knutsson, Mineiro, Schulthess*).

Changes in the intervertebral discs have been largely regarded as mechanical. As a result of the lateral deviation in the spine, the intervertebral spaces have become narrowed on the side of the concavity and widened at the convexity, a consequence of this being that the elastic nucleus moves over to the convex side (*Bick et al.*).

The structural changes in scoliotic vertebrae have, as a rule, been considered secondary (*Bick et al., Lovett, Michelsson, Stilwell*), although views as to their primary nature have also been presented (*Knutsson, McCarroll and Costen, Mineiro, Ottander, Roaf*).

Numerous attempts have been made to solve the problems involved in scoliosis by means of animal experiments. The majority of animal experiments have been directed towards elucidating the etiology of scoliosis; *Michelsson* has given a thorough review of these experiments in his work.

Scoliosis has been effected by resecting the epiphyses and preventing growth by means of stapling the end plates (*Bisgard and Musselman, Ghillini, Haas, Moser, Nachlas and Borden*). The destruction of the neurocentral epiphysis on one side has resulted in the development of scoliosis (*Ottander*). *Pacher* was able to produce scoliosis by simultaneously resecting the neurocentral epiphyses and the end epiphyses. Scoliosis has also been effected by preventing epiphyseal growth experimentally by means of X-ray treatment or radioisotopes (*Arkin et al., Arkin and Simon, Engel*).

5. Use of tetracycline in bone studies

The fixation of tetracycline in living tissues has been known for years (*Bottinger, Helander and Bottinger*). The observation by such investigators as *Milch, Rall and Tobie* that tetracycline is deposited in mineralizing bone, has stimulated the use of this phenomenon in studying bone physiology (*Frost*).

Tetracycline labelling of bone possesses the following characteristics: any currently available tetracycline administered in vivo by any route will be deposited in newly formed and mineralizing bone, cartilage and teeth. Most tissues will be stained as a result of tetracycline administration. Within 48 hours of the withdrawal of the drug, "adventitious" tetracycline disappears from the bone, and the remaining tetracycline is present only in the labelled bone and calcified cartilage. Tetracycline so deposited will appear as yellow fluorescence in proper sections under ultraviolet light (*Bailey and Levin, Bottinger, Frost, Frost et al., McLeay and Walske, Plaza-Roca, Tubaro*).

Tetracycline labelling is comparable to the use of isotopes and alizarin but possesses none of the drawbacks of these agents. The tetracycline label is permanent in that it remains in situ until the labelled bone is resorbed. Although some fading occurs, there is no diffusion of the agent into the surrounding tissues (*Frost, Frost et al., Kelly et al., McLeay and Walske, Milch et al., Owen*).

Tetracycline has been found to pass through the placenta and to become deposited in the growth zones in the foetal skeleton. Administered during the early period of growth it has been found to cause growth and developmental disturbances in bones, especially in teeth. This was verified by tests in vitro. (*Bevelander et al., Carter and Wilson, Cohlan et al., Filippi and Mela, Hakala and Mäkelä, Saxén, Wallman and Hilton*) During later periods of growth, however, the drug exerts no adverse effects on bone formation and mineralization (*Frost, Frost et al., Ibsen and Urist*). Several examples of the affinity of tetracyc-

line to tissues undergoing necrobiotic changes have also been published (*Kornamo and Niemi, Milch et al., Mustakallio, Rall et al., Tapp et al., Whitmore et al.*).

The exact nature of tetracycline fluorescence and fixation is not known. Several investigators have, however, reached the conclusion that the process involved is the binding of structurally unaltered tetracycline with calcium, probably by means of a peptide bond (*Finerman and Milch, Häkkinen, Ibsen and Urist, Kohn, Plaza-Roca, Shils, Urist and McLean*).

III MATERIAL AND METHODS

1. Experimental animals

The vertebrae of both pigs and rabbits differ little in fundamental structure from those of man (*England, Weaver and McKean*). On the cranial and caudal surfaces of the vertebrae the animals mentioned have epiphyseal plates. In the rabbit and pig vertebral growth occurs in the same way as in man (*Amato and Bombelli, Beadle, Ellenberger and Baum, Krause, Smith and Walmsley*).

Rabbits and pigs were used as test animals. They were selected for the study mainly from the age groups in which growth was most rapid, because scoliosis is particularly a disease of the growth period. Some older animals were used as controls. No attention was paid to their sex. The diet and management was uniform. A total of 168 test animals were used, 121 rabbits and 47 pigs. As is seen from table 1, a scoliosis-provoking operation was performed

TABLE 1. — *Material used and investigations performed.*

	Number of animals	Investigations			
		X-ray examination	Histological examination	Tetracycline examination	Study on rotation
Rabbits					
Study on normal growth	31	121	24	27	
Study on scoliosis	78	254	62	62	
Died during operation	12				
	---	---	---	---	
Totals	(121)	(375)	(86)	(89)	
Pigs					
Study on normal growth	15	82	7	15	2
Study on scoliosis	30	201	15	30	6
Died during operation	2				
	---	---	---	---	---
Totals	(47)	(283)	(22)	(45)	(8)
Totals	168	658	108	134	8

upon 78 rabbits and 30 pigs. Thirty-one rabbits and 15 pigs served as a control series and the normal vertebral growth was also studied from them. Because the rabbit is small as a test object and especially because its vertebral body is filled with a very coarsely porous spongiosa, analyses of the results was difficult. This difficulty became especially evident in the tetracycline technique to be reported later. It was for this reason that pigs were used as experimental animals in the later part of the study.

2. Surgical procedures

Anaesthesia: The rabbits were operated on under local anaesthesia with 0.25 % Xylocain exadrine®. The pigs were anaesthetized by means of open mask using trilene.

Types of operation: Because human scoliosis is mostly convex to the right, all scoliosis-provoking operations were performed on the right. Resection of 5 ribs was performed on all rabbits. The intercostal nerves were cut simultaneously. Four different kinds of surgical procedures were performed on the pigs (Table 4). Costal resection was performed on 18 pigs. The number of resected ribs ranged from 5 to 8. Costal resection supplemented with fixation by a dacron thread on the left was carried out on eight pigs. Costal resection and hemilaminectomy was performed on one pig. Dorsal ligaments of the 8th to 12th ribs were severed in three pigs.

Technique of operation: A longitudinal dorsal skin incision was made over the operative area. The right side of the spinous processes and arches was freed in the midline and the ribs to be removed were freed subperiosteally. The costae were resected so that about 1.5 cm in the rabbits and about 8 cm in the pigs were removed from the dorsal end of the ribs. The most dorsal part of the resected costae was carefully freed and removed entirely. The intercostal nerves were identified and a piece of about one cm was removed from them. In fixation procedures the left side of the spinous processes and vertebral arches as well as of the dorsal ends of the ribs was also freed. The fixation was effected by attaching the costa and spinous process to each other so that a dacron thread was threaded first under the rib and then in a figure-of-eight suture through a hole drilled in the spinous process. The thread was tied at a moderate tension. The precise level of fixation will be seen from table 4. In one of the pigs in which costal resection was carried out, the right side vertebral arches were also removed from the area shown in table 4. In three operations, all the ligaments attached to the dorsal ends of the costae listed in table 4 were severed.

Operative complications: Pneumothorax was produced in almost all the operations on rabbits. In spite of this, operative mortality was comparatively low, 12 rabbits dying during surgery. In the operations on pigs, cardiac arrest caused apparently by trilene was the cause of operative death in two cases. Pneumothorax did not develop in pigs.

Antibiotic prophylaxis: The test animals which were examined by means of the teracycline method received no other antibiotic protection. Those in whom this examination was not performed received 100.000 units of procain penicillin intramuscularly. Streptomycine powder was applied to the wound in all operations.

3. Methods of study

All examined spines were prepared and examined visually before any other studies were undertaken.

X-ray examination

X-ray films were taken of all the animals employed in the series. Antero-posterior roentgenograms with back against the cassette were taken of both rabbits and pigs, and lateral exposures were taken when the animal was lying on its right side. The films were taken without anaesthesia by holding the animals by their limbs. The first X-ray was taken immediately after operation. The degree of scoliosis was measured from the X-ray films by determining the curvature in accordance with the direction of the vertebral end plates. In all, 658 X-ray examinations were made.

Histological examination

Histological examination was performed on 86 rabbits and 22 pigs. Of the animals, 62 rabbits and 15 pigs were scoliotic, the rest were normal. A different number of slices were taken from each animal. The preparations were fixed in 10 per cent solution of formalin and decalcified in 32 per cent solution of EDTA whose pH was between 7.2 and 7.4. Following decalcification they were dehydrated in a rising series of alcohols. The specimens were mounted in paraffin and cut in the ordinary way using the Leitz sliding microtome No. 1300. The slices were taken in frontal, sagittal and cross planes and stained with Van Gieson haematoxyline eosine. The histological preparations were photographed on Adox black-and-white film, using the Leitz Ortolux microscope.

Tetracycline examination

As mentioned above, the use of tetracycline in investigations is based on the fact that when injected into an animal it is deposited in newly-formed bone labelling the bone structure at that particular moment. On the basis of growth that had occurred in relation to this labelled area it was possible to follow normal growth as well as the development of scoliotic structural changes. The use of tetracycline limited the time of observation of the objects of study, because the bone labelled by it becomes resorbed later. The post-operative survival time had, therefore, to be limited so that the labelled bone structure was still visible in the preparation.

The spongiosa of the vertebral body of the rabbit is very large-celled. Therefore, when as a result of growth the tetracycline line has moved from the area of the compact bone to that of the spongiosa, it is hardly visible — at least it is not possible to obtain satisfactory registrations on films. It was mainly because of this that the study which was started with rabbits was completed with pigs.

Tetracycline (Oxytetracycline, Terramycin®, Pfizer*) was administered intramuscularly immediately prior to operation in doses of 500 mg on three successive days to pigs and in doses of 100 mg on two successive days to rabbits. In a few cases the tetracycline injection was repeated once or several times after the pre-operative injection. The specimens were thoroughly cleaned by removing all soft tissues. They were either examined immediately or preserved at 0°C. In the case of pigs the tetracycline preparations were made by means of an ordinary close-toothed saw, and of rabbits by means of a rotating blade mounted on a Reko-Dental drill. The specimens were cut in frontal, sagittal and cross planes. The cross slice was sawn in the cross plane in relation to the vertebra concerned. The surfaces that were to be examined were ground smooth by means of emery paper. The preparations were examined by using two OPTON-fluorescence lamps with Osram HPO 75 mercury high-pressure bulb equipped with a UG 1 filter as the source of light. The photographs of the preparations were taken by means of a Leitz Aristofot apparatus in reflected light using the same lamps and a Wratten 2B and CC20 R filter in the objective. The photographs were taken on Agfa ct 18 film, and the copies of the diapositives were made by Kuvasampo Oy.

Rotatory study was performed on 8 scoliotic pig preparations. The method of study is given in connection with the results.

*) The author is much indebted to Pfizer for kindly supplying the Terramycin used in this study.

IV RESULTS

1. Normal growth of the vertebra

Histological examination

The vertebrae of rabbits and pigs resemble each other both in their macroscopic and microscopic structure. Figures 1 to 4 show histological slices made in frontal and cross planes of normal thoracic vertebrae of growing rabbits and pigs.

In the frontal plane sections 1 and 2, it can be seen that there is an epiphyseal plate at both ends of the rabbit and pig vertebrae. These epiphyseal plates border on one side upon the intervertebral disc and on the other upon the epiphyseal line. In close-ups taken from epiphyseal lines (Figs. 1 b and 2 b) it can be seen that the cartilaginous cells mature towards the diaphysis. The diaphyseal part of the rabbit vertebra consists of relatively coarse spongiosa.

In cross-sections, figures 3 to 4, the rabbit and pig vertebrae are seen largely to resemble each other. Compact bone forms the outer surface of the vertebra and surrounds the neural canal. On the border between the body and arch, symmetrically on both sides, lie the neurocentral epiphyses. In close-ups taken of them (Figs. 3 b and 4 b) it can be seen that this epiphysis in both rabbits and pigs consists of centrally situated mother cells which mature in two directions. Growth in this epiphysis, therefore, occurs towards both the body and the arch. As in frontal sections, the distinct difference in density between the spongiosa of rabbit and pig vertebrae can also be observed in cross-sections.

Tetracycline examination

In all normal vertebrae examined by means of tetracycline, similar changes during growth were found in both rabbits and pigs. The growth of a pig vertebra is seen in figure 5. Tetracycline was injected into the animal 65 days prior to killing. Cross, frontal and sagittal sections were prepared from the vertebrae.

In pictures taken in ultraviolet light the bone labelled by tetracycline appears as yellow fluorescence. In the corresponding drawing, this is illustrated by the blue line. The area labelled by tetracycline thus indicates the shape of the vertebra at the moment of injection. The non-fluorescent bone around it has grown later.

In cross-sections it will be seen that growth on the outer surface of the vertebra has occurred almost symmetrically. In the neurocentral epiphysis, growth proceeds symmetrically towards both the body and the arch.

Sagittal and frontal sections reveal that the vertebra has grown to an equal extent in both the cranial and caudal epiphysis. In the lateral and ventral directions the growth has occurred appositionally. The epiphyseal plates have grown symmetrically with the rest of the vertebra in the cross plane, but no growth worth mentioning has occurred in the craniocaudal direction.

The observations obtained lend support to previous views of growth of the vertebra. The vertebrae of rabbits and pigs grow mainly in the same way as those of human beings.

Growth mechanism of the neural canal

The neural canal forms a specific independent component of the vertebra. As was mentioned above, its growth ceases considerably earlier than the growth of the rest of the vertebra, i.e., simultaneously with the cessation of growth of the skull. It became apparent in the present study that the growth of the neural canal occurs in a slightly different way depending on whether the neurocentral epiphysis is closed or not.

Twenty-one rabbits were used. Tetracycline was injected into the animals. They were killed at different intervals. The vertebrae to be examined were cut in cross plane from the middle of the diaphysis, and the preparations were examined under UV light.

The observations were similar in all the preparations examined. Immediately following the injection tetracycline was incorporated in the lateral side of the compact part of the neural canal.

The way of growth before closure of the neurocentral epiphysis is shown in figure 6 a. The tetracycline line may be seen located asymmetrically in the compact part of the neural canal. Apposition and resorption have occurred asymmetrically. Some growth has occurred in the neurocentral epiphyses.

Figure 6 b reflects the way of growth following closure of the epiphysis mentioned above. The tetracycline line is situated symmetrically in the compact part of the neural canal, a fact that would suggest that apposition and resorption have occurred symmetrically.

Figure 7 demonstrates schematically the growth mechanism of the neural canal. Thicker lines, corresponding to the tetracycline line in the preparation, indicate the shape of the neural canal at the moment of injection.

The neurocentral epiphyses are symmetrical. Together they form a blunt angle opening in the ventral direction. Maturation of the cartilaginous cells in this epiphysis does not always occur perpendicularly to the epiphyseal line (Figs. 3 b and 4 b).

Because of the bony structure of the area, it is difficult to examine the dorsal part of the vertebral body in the rabbit. On the other hand in the vertebrae of pigs (Fig. 5) it is possible to observe apposition in the dorsal part of the body, proportional to the growth that has occurred in the neurocentral epiphyses. This may allow the conclusion that the neural canal does not become enlarged in the ventral direction to any degree worth mentioning.

2. Studies on scoliotic rabbits

Development of scoliosis in rabbits

The development of scoliotic curvature in rabbits is seen in table 2 as a function of the post-operative time. A total of 254 X-ray examinations were performed. The scoliotic curvature was measured from the ends of the scoliotic area on the basis of the angle formed by the end plates of the vertebrae.

As may be seen from the table, immediately following the operation a rather severe scoliosis was often noticed, the most common range of the scoliotic

TABLE 2. — *Extent of scoliosis in rabbits.*

Time after operation in days	Scoliosis in degrees							
	0—19	20—29	30—39	40—49	50—59	60—69	70—79	Over 80
Immediately after operation		2	13	18	28	11	6	
Under 9	2	2	4	2	11	4	3	
10—19	1	3	3	5	18	7	4	3
20—29	1	4	5	6	11	3	2	7
30—39	1	2	2	7	1	2	1	6
40—49		1	2	1	4	2	3	7
50—69				1	1	2	1	5
70—100		1	1	1	2	2	3	3

curvature being 55° – 59° . A part of these later straightened to some extent. The majority of the scolioses investigated, however, either remained unchanged or progressed regularly. The scoliotic curvature progress as a function of time.

Structural changes caused by scoliosis

Scoliotic structural changes were examined histologically in 62 rabbits and 15 pigs. On account of the large series and variations in observation time, the histological changes found in rabbits were subjected to closer scrutiny.

Figure 23 shows that by means of tetracycline and histological sections taken from the same scoliotic vertebra, the newly formed bone on the concave side was found to be structurally different from normal. The word trabeculation is used to illustrate this altered bone structure (*Arkin and Katz*). The compact bony layer of the trabeculated area is more thick and porous in comparison with normal compact bone and that on the convex side.

Figure 18 gives a schematic description of the areas in which the histological alterations which eventually occurred were systematically surveyed. These include: trabeculated bone structure (1, 2, 3), changes in the neurocentral epiphysis on the side of the convexity (4), asymmetry of the neural canal (5) and alterations in the end epiphyses (6).

It was found that structural alterations in scoliotic vertebrae appeared quite rapidly after operation. The intervertebral disc had already been displaced towards the convexity a few days following the operation. This is not, however, considered an actual structural change, but on the basis of other studies it is rather regarded as a mechanical phenomenon due to lateral deviation of the spine (*Bick et al.*). Figure 8 shows thickened bone structure on the concave side of the vertebral body even 5 days after the operation. Nine days post-operatively (Fig. 9) the trabeculation on the concave side of the vertebral body is clearly visible. Asymmetry of neurocentral epiphyses appears in a mild form — this epiphysis is broader on the concave than on the convex side. 15 days after operation (Fig. 10) the changes are already clearly visible. Alterations may be observed in the vertebral body and neurocentral epiphyses, and trabeculation has also appeared in the area of the arch. Changes in the most severely deformed vertebrae are shown in figures 11 and 12.

The scoliosis-provoking operation performed on the oldest rabbits also resulted in structural changes. As was mentioned above, all the animals subjected to histological scrutiny were operated on during the growth period. Figure 13 presents a vertebra deformed by scoliosis, taken from a rabbit operated on at the age of 76 days. At the time of operation the neurocentral epiphyses were

closed. Nevertheless definite changes may be observed in this section of the vertebral body.

Histological alterations in scoliotic vertebrae are most pronounced in the area of the apex. The radiological status and cross-sections of various vertebrae of the scoliotic area are presented in figure 14. It will be seen that in the apical vertebra, the neurocentral epiphyses are closed on both sides. Strong trabeculation both in the body and in the arch may be observed at the concavity. The neural canal is asymmetric and there is trabeculation on the convex side of the neural canal. These changes become milder as the normal vertebra is approached. In the last section of the series of pictures the vertebral structure is almost normal.

Figure 15 illustrates the radiological development of the scoliosis of rabbit No. 81 as well as the scoliotic changes found in the cross section specified at the apex. Definitely increased trabeculation may be observed on the concave side in both body and arch. The neurocentral epiphysis is partly closed on the convex side. The neural canal is clearly deformed towards the concavity. Trabeculation is increased on the convex side of the neural canal.

In figures 16 and 17, scoliotic changes are illustrated as frontal sections. Definitely increased trabeculation on the concave side may be seen in all preparations. Figures 16 c and 17 c demonstrate the changes in the end epiphysis on the concave side. The cartilaginous structure is irregular and the normal palisade formation is disturbed in comparison with the epiphyseal structure on the convex side (Figs. 16 b and 17 b). There are irregularities in the cartilaginous cells of the end epiphyses on the concave side and, as may be seen from figure 17 c, the cartilaginous cellular layer is thicker on the concave side. There are more cells in this area and indistinct palisade formation is more than normally directed towards the concavity. This change is most distinctly apparent in figures 22 f to h, which show a vertebra from a scoliotic pig.

Figure 18 depicts those areas where changes were found in the scoliotic vertebra of a rabbit. These changes are classified in table 3. The changes were observed in both cross and frontal sections in 62 rabbits. The severity of the changes was assessed on the basis of the following criteria. The numbers refer to the diagram in figure 18.

- (1) Changes in the vertebral body at the side of concavity.

0 = No changes.

I = Moderate trabeculation. (Fig. 10)

II = Severe trabeculation. (Fig. 14 c)

- (2) Changes in the concave side of arch, laterally.
 - 0 = No changes.
 - I = Moderate trabeculation. (Fig. 14 c)
 - II = Severe trabeculation. (Fig. 12)
- (3) Changes in the convex side of arch, medially.
 - 0 = No changes.
 - I = Moderate trabeculation. (Fig. 14 d)
 - II = Severe trabeculation. (Fig. 14 e)
- (4) Changes in the neurocentral epiphysis on the convex side.
 - 0 = No changes.
 - I = Epiphysis narrowed and cartilaginous cells irregularly placed.
(Fig. 14 f)
 - II = Epiphysis partly or totally closed. (Fig. 15)
- (5) Deformation of the neural canal.
 - 0 = No changes.
 - I = Neural canal slightly asymmetric towards the concavity. (Fig. 12)
 - II = Neural canal severely asymmetric towards the concavity. (Fig. 15)
- (6) Changes in the end epiphysis on the concave side.
 - 0 = No changes.
 - I = Cartilaginous cells irregularly placed and cartilaginous palisade formation disturbed. (Fig. 17 c)
 - II = Cartilaginous cells very irregularly placed and cartilaginous palisade formation disturbed. (Fig. 16 c)

From table 3 it can be seen that in the vertebral body, changes on the concave side, i.e. increased trabeculation, appear most generally and are the first to be observed. It has been possible to establish this even a few days after operation. The next common alteration is increased trabeculation in the lateral part of the concave side of arch. Almost simultaneously, changes appear in the neurocentral epiphysis on the convex side, with disarrangement of the cellular structure. This is followed by additional trabeculation on the medial part of the convex side of arch, and the neural canal becomes asymmetric. The changes occurring in the end epiphyses also appear rather early in the form of irregular cellular structure on the concave side. These changes are, however, comparatively slight in the early stages and they do not progress so severely as the other alterations observed. In none of the sections examined was the cellular structure on the concave side of end epiphysis totally destroyed.

As can be seen from the table, changes occurred somewhat more rapidly and clearly if the operation was performed at an earlier age. Definite histological

TABLE 3. — *Histological changes in rabbits associated with scoliosis.*
(Explanation of the signs in text).

Age at the time of operation in days	Post-operative time in days	Areas and severity of the histological changes — Fig. 18								
		(1)			(2)			(3)		
		0	I	II	0	I	II	0	I	II
Under 29	0—19	1	2	2	3	1		2	2	
	20—39		2	2	2	2		3	1	
	Over 40			3		1	2		2	2
30—39	0—19	2	3		2	3		4		
	20—39		3	3	5	1		5	1	
	Over 40		2	5	1	5	1	1	5	1
40—49	0—19	4	3	3	3	5	2	5	5	
	20—39		2	3	1	3	1	1	4	
	Over 40		1	4		3	2	2	3	1
50—69	0—19	1	1		1	1		1	1	
	20—39	1	1	1	1	1	1		2	
	Over 40			1		1			1	
Over 70	0—19		1			1			1	
	20—39		2			1	1		2	
	Over 40		1	1		2		1	1	

changes were also found in older rabbits. The changes progress as a function of the post-operative time.

A casuistic table of the series of rabbits operated upon is presented before the illustrated appendix on page 53. (Table 7)

3. Studies on scoliotic pigs

Development of scoliosis in pigs

The series of pigs operated upon is presented in table 4. The animals were arranged according to the greatest measured scoliotic curvature and according to operative technique.

The severest scolioses occurred in the group in which both costal resection and fixation were performed. In this group, the maximum curvature was almost always attained towards the end of the observation period; at worst it was 102°.

TABLE 4. — *Scoliosis-provoking operations in pigs.*

Pig No.	Operative technique		Least and greatest scoliosis in degrees			
			Least	Post-operative time in days	Greatest	Post-operative time in days
	Resection of the dorsal ends of the ribs on the right					
16	8—13 (6)		5	24	5	94
14	8—14 (7)		0	104	9	36
8	7—11 (5)		5	78	11	57
4	7—11 (5)		5	84	12	10
15	8—12 (5)		13	24	13	94
6	7—12 (6)		0	78	13	57
10	6—12 (7)		3	35	15	51
9	7—11 (5)		13	74	16	15
9	6—11 (6)		13	35	17	117
1	7—11 (5)		11	49	18	69
7	8—12 (5)		5	83	19	67
13	7—13 (7)		16	104	20	79
21	8—13 (6)		15	65	21	98
2	6—10 (5)		11	49	21	69
18	5—12 (8)		13	23	23	81
11	8—13 (6)		15	43	25	119
5	8—12 (5)		20	67	29	83
17	6—11 (6)		13	35	35	81
	Resection of the dorsal ends of the ribs on the right and fixation with dacron thread Th-Th and Th-Th on the left					
	costa—spinosus process	costa—spinosus process				
22	8—12 (5)	7—10	35	85	37	118
19	8—12 (5)	7—8	31	111	37	65
26	6—11 (6)	5—9	38	15	47	109
24	7—12 (6)	6—9	37	47	48	137
25	8—13 (6)	7—10	39	50	50	72
23	8—12 (5)	6—8	42	82	53	82
27	8—12 (5)	6—9	83	58	84	115
28	7—12 (6)	5—10	90	58	102	115
	Resection of the dorsal ends of the ribs on the right and hemilaminectomy on the right, Th 7 to 11					
20	7—11 (5)		11	39	31	111
	Transection of the ligaments attached to the dorsal end of the ribs, Th 8 to 12					
30					12	51
31					14	51
29					35	61

In the group in which scoliosis was accomplished by means of costal resection only, the curvature was greater at the beginning than at the end of the observation period in a part of the animals.

The level of the costal resection and the number of ribs resected did not have linear influence on the amount of scoliosis. Similarly, the level of fixation was not in direct correlation to the curvature of the scoliosis.

Development of scoliotic structural changes

In pig scolioses effected by costal resection only the progression did not continue regularly as a function of time, but a decrease of the scoliotic curvature could be observed in several cases. A radiogram taken of the preparation of pig No. 4 is seen in figure 19. The spine is radiologically almost straight, and no structural changes worth mentioning are visible in the vertebrae of the resected area. Quite distinct changes, on the other hand, are seen in figures 19 b and c, illustrating tetracycline sections made from the scoliotic area. Figure 19 b shows a frontal section from the apical area of the scoliosis. The bone area stained yellow by tetracycline indicates the shape of the vertebra at the moment of operation. The growth from both the cranial and caudal epiphyseal lines has been symmetric. On the other hand, there is definitely new bone on the concave side laterally from the tetracycline area. The same growth may also be observed in the epiphyseal area. The part of the bone strongly stained by tetracycline on the convex side is, however, partly absent, thus indicating that resorption has occurred in this area. A corresponding cross-section is seen in figure 19 c. Growth in the neurocentral epiphyses is symmetric on both sides. In this section there is also new bone laterally from the tetracycline area towards the concavity, both in the body and the arch; it has grown towards the concavity after the operation. Here again, as in figure 19 b, the tetracycline line has partly disappeared from the convex side, thus indicating resorption from this area.

Changes slightly more marked than the above are shown in figures 20 a to c. As can be seen from figure 20 a, it is already possible to demonstrate roentgenologically a rather definite scoliosis with rotation. The vertebrae of the apical area have taken a somewhat wedged form. Quite distinct changes are visible in the tetracycline sections (Figs. 20 b and c). New bone on the concave side is again seen in both frontal and cross-sections. Figure 20 b shows that the epiphyseal line and the corresponding bone area labelled by tetracycline form a slight wedge in relation to each other, thus indicating that growth in the end epiphyses is somewhat retarded on the concave side.

Structural changes in pig No. 11 are shown in figures 21 a to c. The changes here also were verified radiologically, the apical vertebra being wedge-formed. Figure 21 b shows frontal section taken from the three apical vertebrae. It will be observed that the appositional changes already seen above are most distinctive in the apical vertebra and become less so in the cranial and caudal directions. A close-up of the apical vertebra is seen in figure 21 c. Definite retardation of growth is seen in the caudal epiphyseal line, illustrated by the more distinct wedge formation of the bone area labelled by tetracycline

and the epiphyseal line. In this preparation new bone formation, stronger than before, may be observed on the concave side in both the epiphyses and the diaphyseal area of the vertebra.

The development of the structural changes in pig No. 18 shown in figures 22 a to c. It can be seen from the X-ray films that scoliosis has developed rather regularly. In the radiogram taken from the preparation, distinct structural changes are visible in the apical area. Figure 22 d presents a frontal section of the spine. Above and below the scoliotic area the vertebral growth is symmetric, thus completely resembling the growth of a normal vertebra, as previously shown in figure 5. On the other hand there are fairly clear structural changes deviating from the normal in the vertebrae at the apex of the scoliosis, the most pronounced being apposition towards the concavity. A close-up of the apical vertebra is seen in figure 22 e. This shows more clearly than before the angle between the present epiphyseal line and the area labelled by tetracycline. This indicates that growth has been slower in the epiphyseal line on the concave side. The most distinct phenomenon, however, is apposition towards the concavity. A histological slide of the same preparation is seen in figure 22 f. Here again the histological changes established previously come to light: clearly increased trabeculation in the vertebral diaphysis on the concave side. Figure 22 h gives a close-up of the epiphyseal line on the concave side. It seems to be divided into two parts and the palisade formation of the cartilaginous cells has turned towards the concavity.

A series of pictures from pig No. 5 is presented in figures 23 a to d. The radiogram taken from the preparation showd fairly clear scoliotic changes. This pig received two injections of tetracycline, the first immediately prior to operation as usual, and the second just before killing. Figure 23 a presents a cross-section of the apical scoliotic vertebra. The inner tetracycline line indicates the form of the vertebra at the time of operation. The outer tetracycline line bordering on compact bone, on the other hand, gives its shape immediately prior to killing. The area remaining between these two tetracycline lines reveals the additional bone growth after operation. It will be seen from the picture that growth towards the concavity has been quite strong. While moving towards the convexity, on the other hand, the tetracycline lines coalesce and the inner line indicating the vertebral structure at the time of operation disappears. According to this, resorption has occurred on the convex side. A histological slide made from this preceding preparation is seen in figure 23 b. On the concave side in the area of newly formed bone the compact part is abnormally broad and filled with tiny bone lacunae, as shown in close-up 23 d. There is likewise, close-up 23 c, a dense compact zone on the convex side, as is normal. A comparison of these two series of pictures shows how clear a picture tetracycline section

gives of the development of deformity. The area remaining between the tetracycline lines indicates the site of additional bone growth. The conclusion that has been drawn from this is that the trabeculated bone structure, compact bone that is broader than normal and filled with lacunae, consists of new bone.

The figures presented above are from pigs on whom only costal resection was performed. As was shown in the table presented previously, the scoliosis accomplished by costal resection only was in most cases much milder than that effected by means of both costal resection and fixation. On the other hand, in the vertebrae of the pigs on which fixation was performed, new bone formation was less on the concave side. These changes are presented numerically in tables 4 and 5.

On the other hand, in the scolioses effected by costal resection and fixation, growth of new bone towards the concavity was remarkably less despite strong radiological alterations. An example of this is presented in figures 24 a and b where a scoliosis of 53° had been effected by costal resection and fixation. Radiological changes in the vertebrae of the scoliotic area are quite clear. On the other hand, the structural changes in figure 24 b, as demonstrated by tetracycline section, are less than was expected. It will be noted that in the bone area labelled by tetracycline, definite growth of new bone has occurred towards the concavity. However, the observed growth of additional bone is rather small in extent in comparison with the radiological scoliotic deformity. The regularity of this change emerges quite clearly from table 5. The preparation shows that growth in neurocentral epiphyses is somewhat more abundant on the concave side than on the convex side. In sections this becomes apparent from the way in which on both sides of the neurocentral epiphysis the distance between the bone areas labelled by tetracycline is definitely longer on the concave side than on the convex side.

In figures 25 a and b there is an 84° scoliosis effected by dacron fixation and costal resection. A cross section of the apical scoliotic vertebra is presented in figure 25 b. Again it will be seen that definite additional bone growth towards the concavity has occurred in the bone area labelled by tetracycline. The most distinct change in this preparation, however, is that growth in the neurocentral epiphysis is definitely stronger on the concavity than on the convex side.

A perspicuous view of the quantitative difference in epiphyseal growth between the concave and convex sides is provided by figures 26 and 27. These pairs of tetracycline pictures are of the same preparation, as is also the X-ray picture. The sections were made symmetrically from both sides in the direction of the longitudinal axis of the spine, from the centre of the neurocentral epiphysis and perpendicularly towards it.

Changes are milder in figures 26 and more severe in figures 27. Both groups of figures, however, show clearly that on the convex side, growth in the end epiphysis is stronger, and in the neurocentral epiphysis less, than on the concave side.

Percentile determination of apposition

The most distinct change observed in the present series was appositional bone growth towards the concavity in the vertebral body. These changes were subjected to mathematical analysis. Other changes observed included: resorption from the convex side, asymmetry of the growth in neurocentral epiphysis, and retardation of growth in the cranial and caudal epiphyseal lines; these changes, although regularly observed, are not of such a kind that any uniform series of measuring results could be drawn up from them.

Of each of the 30 scoliotic pigs one or several photographs in either cross or frontal plane were taken of the apical scoliotic vertebral area. Measurement was made from the photographs in the way shown in figure 28. The following measurements were taken of the section: thickness = a, distance from the tetracycline line to the edge on the concave side = b, distance from the tetracycline line to the edge on the convex side = c. The amount of apposition in percentages was obtained from the formula

$$\text{apposition \%} = \frac{100 (b - c)}{a}$$

The result of measurement gives only an approximate picture of the amount of apposition. Often and especially in the cases of the greatest changes, c, or distance from the tetracycline line to the edge on the convex side, was 0. In these cases, such strong resorption had occurred on the side of convexity that the vertebral structure labelled by tetracycline had entirely disappeared from the section. In these cases the absolute apposition in percentages is in reality greater than the result of measurement.

The results of measurement are shown in table 5. The animals were divided into 4 groups according to operative technique. In the table, attention was paid to the following variables: age at the time of operation, degree of scoliosis, observation period and apposition per cent.

Tetracycline injection was administered to the animals, as already indicated, immediately prior to operation. Thus the vertebral structure shown by tetracycline in the section corresponds to the shape at the time of operation. As is seen from the table, the greatest appositional percentages occurred in pigs subjected to costal resection only. The greatest measured apposition per cent is

TABLE 5. — *Percentile apposition towards the concavity in scoliotic pigs.*

Operative technique	Pig No.	Age at the time of operation in days	Greatest scoliosis	Post-operative time in days	Percentage of apposition
Resection of five ribs	5	56	29	83	15
	7	56	19	83	19
	17	59	35	81	37
	18	59	23	81	32
	13	59	20	104	34
	14	59	9	104	17
	6	66	13	78	6
	8	66	11	78	9
	21	67	21	98	15
	2	74	21	69	16
	1	74	18	69	25
	15	83	13	94	19
	16	83	5	94	12
	10	85	15	51	24
	11	90	25	119	24
	9	92	17	117	23
	4	93	12	84	14
	3	102	16	74	22
Resection of five ribs and fixation	22	55	37	118	6
	23	55	53	82	14
	24	55	48	137	10
	28	56	102	115	19
	27	56	84	115	23
	25	59	50	72	13
	26	59	47	109	12
	19	87	37	111	6
Resection of ribs and hemilaminectomy	20	87	31	111	12
Transection of the ligament	29	43	35	61	28
	31	43	14	51	12
	30	53	12	51	9

37. In this group the scoliotic curvatures are relatively small in comparison with the group where fixation was used. In animals upon whom in addition to costal resection fixation was performed, high apposition percentages were not observed despite big scoliotic angles. However, in all the preparations definitely significant apposition towards the concavity was seen. In the two last operative groups the apposition changes observed were relatively mild.

The amount of the apposition per cent is in relation to the scoliotic curvature. This correlation, however, is not absolute, as can be seen from the table. On the other hand, the time interval from operation to the moment of observation (killing) is not in any noteworthy degree in correlation to the amount of apposition per cent. The maximum values of apposition occur in the youngest age group operated upon.

Study of rotation

During the development of scoliosis, fairly severe structural changes occur in the vertebrae, as has been clearly shown above. If vertebral rotation is studied on the basis of scoliotic preparations, the result obtained is not correct because quite strong remodelling changes occur in the vertebrae following scoliosis-provoking operation. In the present study, rotation in scoliotic pig vertebrae was determined according to the vertebral structure at the moment of operation. This was made possible by utilizing the tetracycline-labelled vertebral area which depicts the vertebral structure at the moment of operation. Two methods were employed in rotational studies. The methods are presented schematically in figure 29.

In the first method, tetracycline was injected into the animal in the usual way immediately prior to operation. Following scoliosis-provoking operation, the animals were killed after a certain period. The vertebrae of the scoliotic area, bordering both cranially and caudally on neutral areas, were sawn off in the cross plane. Each cross-section surface was photographed in the normal way in ultraviolet light. This gave a series of preparations, an example of which is seen in figure 30. Next, tracks were drilled at the sites of the tetracycline lines, identified by means of ultraviolet light and so illustrated the vertebral structure at time of operation. A flexible wire was implanted in these tracks.

TABLE 6. — *Rotation in a scoliotic spine.*

Pig No.	Measuring technique	Scoliosis in degrees	Scoliotic area Th No.-Th No.	Number of intervertebral spaces	Rotation in degrees	Rotation per intervertebral space
21	I	21	8-12	4	10	5,0
25	II	50	5-13	8	23	5,7
7	I	19	8-12	4	7	3,5
9	II	17	6-11	5	6	2,3
23	II	53	7-13	6	20	6,8
20	II	31	7-12	5	10	4,0

Similarly, the sites of neurocentral epiphyses were marked by wires in each cross-cut surface. The vertebrae were then replaced in their former sites on top of each other, and radiograms were taken in the cranio-caudal direction. X-raying was then continued, the topmost vertebra being removed each time until the last one was X-rayed alone. In this way it was possible to identify each vertebra separately. Enlargements of the radiograms were prepared on photographic paper. Measurement of rotation was performed according to figure 29 a, in regard to the bone structure labelled by tetracycline and represented in the radiogram by the implanted wires. The line drawn runs against the vertebral body at the moment of operation in places of neurocentral epiphyses at that time. Thus it was possible to calculate rotation in the entire scoliotic area as well as the rotation of individual vertebrae in relation to the vertebral structure at the moment of operation.

In the second method, which is diagrammatically presented in figure 29 b, the scoliosis-provoking operation and tetracycline injections were performed in the ordinary way. By means of a radiogram taken of the preparation, the neutral vertebrae, i.e. those with no rotation or vertebral asymmetry, were identified in both the upper and lower ends of scoliosis. The preparation was cut off from above and below the neutral vertebrae. A hole for the leading wire was drilled through the middle of the neutral vertebrae in a sagittal direction. The apical scoliotic vertebra was identified from both the radiogram and the preparation. The sites of the neurocentral epiphyses were identified laterally in ultraviolet light. A leading wire was implanted through them in the frontal plane. A radiogram was taken of the preparation with the leading wires in the cranio-caudal direction so that the leading wires placed in the neutral vertebrae were in the same plane. The apical vertebra was sawn off at the level of the leading wire implanted in cross plane. The cross-cut surface where the site of the leading wire could be clearly identified, was photographed in ultraviolet light. In place of the leading wire implanted through the apical vertebra in the radiogram, a line was drawn according to a picture taken of the tetracycline preparation; this line ran in relation to the tetracycline labelled area as is shown in figure 29 b. From this line and the sites of the leading wires placed in the neutral vertebrae, it was thus possible to calculate the degree of rotation in degrees in the area of scoliosis.

By means of the methods described, rotation was studied in 6 pigs. The aim of the study was not to establish exactly the amount of rotation in regard to the scoliotic curvature. Since the tetracycline method has made it possible to study rotation in regard to the vertebral structure at the time of operation, the aim of the present study was to try to find out whether *rotation is a real change between various vertebrae*, or whether the changes are merely a consequence

of the remodelling of the bone during the development of scoliosis. The rotational changes are shown in table 6. Two pigs were studied by the first method and four by the second method. These different methods were considered to yield uniform results, although the second method is technically easier. The amount of rotation is given in degrees from the neutral vertebra to the apical vertebra. The amount of rotation for each two adjacent vertebrae is obtained directly in the first method and in the second by dividing the total rotation by the corresponding number of intervertebral spaces. As can be seen from table 6, rotation occurred even in milder scolioses, its amount growing as the scoliotic curvature increased. However, as the table shows, there is no direct linear correlation between scoliotic curvature and degree of rotation. Fairly definite rotation was found even in the smallest scolioses, of 17° . Nevertheless, even in the greatest, 53° , rotation between any two vertebrae did not rise higher than 6.8° .

The present study has shown that in scoliotic spine, rotation occurs between various vertebrae. This observation supports earlier findings. The amount of rotation is found to grow as the scoliotic curvature increases — but the correlation is not linear.

Alterations in spinous process

In the pig, the spinous processes point almost directly dorsally only in the middle parts of the thoracic spine. On the other hand, in the cranial part of the spine they deviate to caudal, and correspondingly in the caudal part to cranial directions. The study was therefore limited to the middle part of the thoracic spine. It is true, of course, that the scoliotic changes effected in the experiments were as a rule, located in this area.

The spinous process normally grows perpendicularly in a dorsal direction. The tetracycline method shows that the spinous process labelled by tetracycline is situated symmetrically inside the spinous process that had grown after the injection (Fig. 31 a).

Scoliotic spinous processes were examined in 16 pigs. Changes were studied in the middle of the thoracic spine which, as was mentioned before, forms the apical region of scoliotic changes. The changes observed in various preparations are mainly similar.

Figure 31 b shows the spinous process of pig No. 19. A scoliosis of 37° had been accomplished in this pig. As is seen from the picture, the area labelled by tetracycline, which thus depicts the position of the spinous process at the moment of operation, is pointing directly dorsally. On the other hand, during the postoperative period, as the scoliotic deformity progressed, the spinous process clearly grew towards the concavity.

In the same way figure 31 c illustrates pig No. 26 whose scoliosis was 47° . The changes described above are still more clearly visible in this preparation. The tetracycline-labelled spinous process is hardly visible at all, so strong has been the drift towards the concavity. Because of the diffuse nature of the changes, no measurements were taken.

V DISCUSSION

Previously, when scoliotic structural changes were studied it was generally concluded that structural changes are consequences of passive deformation. In the present study it has emerged that although changes caused by passive deformation do exist, structural changes are also influenced by the process of growth that compensates lateral deviation.

In order to obtain an adequate basis for studies on scoliosis, normal vertebral growth was also investigated.

Because it is safe and easy to use, tetracycline labelling has provided good facilities for following the structural changes caused by both normal growth and scoliosis, despite their rapid development.

The use of tetracycline is based on its property of becoming incorporated in newly formed bone. While it is true that, in other investigations, tetracycline has also been found to find its way to tissues undergoing necrobiotic changes, such changes did not occur in the area of scoliotic spine involved in this study.

In bone studies, the tetracycline method has proved as certain and reliable as the use of isotopes (*Kelly et al.*). The bone structure that becomes visible in ultraviolet light shows the form of the bone at the moment of injection. Thus it may be concluded that if the tetracycline line has disappeared from some area resorption has occurred in that particular place, and in the same way, if in relation to the tetracycline line bone without tetracycline is observed, it has grown after the injection.

The animals operated on in the present study were given injections of tetracycline immediately before operation. The changes that occurred in the area so labelled were postoperative. From them it has been possible to follow the development of scoliotic structural changes and to analyze them.

It was found that rabbit and pig vertebrae like human vertebrae, grow in the same way as long bones. Growth from the cranial and caudal end epiphyses is symmetric, although the view has sometimes been presented that the cranial zone of growth possesses a better capacity for proliferation (*Moser, Müller*). Growth in lateral directions is symmetric apposition. The epiphyseal plates at the ends of rabbit and pig vertebrae do not grow in the cranio-caudal direction

to any extent worth mentioning. Lateral growth occurs in relation to other vertebral growth (Fig. 5).

Comparatively little attention has previously been paid in the literature to the growth of the neural canal. The neurocentral epiphysis previously found in human vertebrae has also been observed in rabbits and pigs. It also grows in two directions. This was verified in the present study by means of the tetracycline method.

The neurocentral epiphysis has already been found to be definitely involved in the growth of the neural canal (*Knutsson*). In the present study it was revealed that growth occurs in different ways, depending on whether the neurocentral epiphysis is closed or not.

In the neurocentral epiphysis, maturation and growth of the cells do not always occur perpendicularly towards the epiphysis concerned. While the neurocentral epiphysis is open the neural canal expands through the growth of this epiphysis and also through resorption and apposition activities in a dorsal direction. After closure of this epiphysis the neural canal expands symmetrically (Figs. 6 and 7).

Along with the growth of neurocentral epiphysis, formation of new bone has been found in dorsal parts of the vertebral body (Fig. 5). The dorsal part of the vertebral body is the imaginary point which, as stated earlier by *Ponlot*, is the centre of vertebral growth.

Scoliosis was effected in laboratory animals by operating on the right of the central part of the thoracic spine, because scoliosis in man is usually convex to the right and located in the area of the thoracic spine (*Moe, Shands and Eisberg*). Costal resection has been found to be a sure procedure for provoking scoliosis (*Langenskiöld and Michelsson*). In the present study, the main emphasis was not put on the question as to what surgical procedure would produce which amount of scoliosis; the aim was to produce various degrees of scoliosis and to study the development of structural changes in them as a function of post-operative time and scoliotic curvature.

Histological changes found in rabbits were dealt with in greater detail as there was abundant material and observations were systematically timed. The results are shown in tables 3 and 7. In previous literature, scoliotic structural changes have been described in great detail, but larger series in which the nature of these changes could have been elucidated do not exist.

In dealing with scoliotic structural changes, attention has been paid to the areas indicated in figure 18. So-called trabeculated structure was regularly found in the areas of vertebral bodies and arches. This bone structure is compact bone that is thicker than usual and contains more than the normal number of lacunae. On the basis of observations made simultaneously with

tetracycline study, this bone structure may be considered as new bone that has developed since the scoliosis-provoking operation (Fig. 23).

Even very early, only 5 days after operation, structural changes were found (Fig. 8). These changes become distinctly more severe as a function of post-operative time. Moreover the greatest changes were found in the greatest scoliotic curvatures. The changes first appear on the concave side of the vertebral body and later in other areas (Table 3). Changes typical of scoliosis could also be accomplished in older rabbits who were, however, still growing. Scoliotic structural changes are greatest at the site of the apical vertebra and decrease gradually towards the neutral area (Fig. 14).

The role of the neurocentral epiphysis has been surveyed in the literature where it has been mentioned as an etiological factor in the development of scoliosis (*Roaf*). However, it was found in the present study that, almost as a rule, the growth of neurocentral epiphysis is disturbed on the convex side, this being, therefore, a secondary structural change associated with scoliosis caused by a paraspinal procedure.

In previous studies, most attention has been paid to histological changes in the end epiphyses. The conclusion has been reached that on the concave or pressure side, the epiphyseal cartilaginous cells are irregularly situated, the cartilaginous pillars are deformed and chondrocyte proliferation is decreased. Similar changes were also seen in the present study. It was further observed, however, that the epiphyseal line is in some preparations thicker on the concave side although irregular. It was found that the cartilaginous cells had definitely increased in number and had begun to grow towards the concavity (Figs. 17 c and 22 h).

In tetracycline studies performed on pigs it was found in numerous preparations that the growth in neurocentral epiphyses is strongest on the concave side that is under pressure. On the other hand, it clearly emerged that growth in the end epiphyses is retarded in this area. The quantitative difference in the growth of these epiphyses situated at different levels is most distinctly apparent in figures 26 and 27. While the above-mentioned changes in scoliotic pig vertebrae are clear, the most conspicuous change in all the preparations examined was strong appositional growth towards the concavity (Figs. 19 to 25 and 30).

As has been mentioned in several studies, rotation is an essential factor in scoliotic deformities. The degree of rotation has been determined by examining vertebrae deformed by scoliosis. In clinical studies, the degree of rotation has sometimes been determined from the top of the spinous process (*Casagrande* and *Frost*). However, by using the tetracycline method it has been possible to establish that when the scoliotic deformity progresses the spinous process is drift-

ed towards the concavity (Fig. 31). The cause of this, apparently, is a state of tension between interspinous ligaments and other soft tissues. Because of deformation of the spinous processes, the estimation of the site of the spinous process apex does not give a correct view of the amount of rotation, but greater than normal values are obtained.

In the present study, the rotation of the scoliotic vertebrae was determined in regard to the vertebral structure at the moment of operation. Post-operative remodelling changes associated with scoliosis were thus eliminated, and the true rotation could be observed. Rotation to a maximum of 6.8° per any two adjacent vertebrae was observed in all 6 of the preparations examined (Table 6). The rotation was found to increase as the scoliosis progressed, although there is no linear correlation between scoliotic curvature and degree of rotation.

Many of the remodelling changes observed seemingly influence rotation. These include apposition towards the concavity and differences in growth between the neurocentral epiphyses (Fig. 29). Apposition towards the concavity apparently diminishes rotation. On the other hand, the stronger growth of the neurocentral epiphysis on the concave side seemingly increases it.

In the tables illustrating the development of scoliosis it was found, as was mentioned above, that the scolioses accomplished in rabbits almost regularly progressed as a function of post-operative time. On the other hand, some of the pig scolioses became somewhat straighter later on. This was particularly apparent in scolioses resulting from costal resection only. A probable cause of this could be the scars formed on the operative area, i.e. on the concave side, because such scars have been found to interfere with scoliosis (*Langenskiöld* and *Michelsson*). On the other hand the operation was obviously a greater trauma to rabbits than to pigs.

The greatest appositional changes were observed in those groups in which only costal resection had been performed. On the other hand, in the group in which fixation on the concave side was also carried out, the apposition percentages were clearly lower. This might be explained by the fact that in the group of fixed spines, the scoliosis-inducing stretching force, which grows continuously worse as the spine grows, is so severe, that it would not have been possible for reparative changes to effect the straightening analyzed in the following pages.

As was mentioned in the histological discussion, it was possible, after the scoliosis-provoking operation, to observe changes on the concave side of the vertebrae which might be interpreted as new bone. The same change is clearly visible in table 5, which gives the amount of apposition in percentages in pigs. Changes were found in all the test animals, which indicate that there is stronger growth towards the concavity in the vertebral bodies. From the histological

changes observed in the area of the neural canal, i.e. trabeculation on the convex side, it is possible to draw the conclusion that the entire neural canal has a tendency to drift towards the concavity.

The generally accepted opinion has been that the wedged vertebra is a consequence of passive deformation according to the *Hueter-Volkmann* law (Fig. 32), whereby increased pressure on the concave side would result in retardation of growth in the epiphyseal line of this area. These changes were also observed in the present study (Figs. 16 c, 21 c and 22 e), although their part in forming the wedged vertebra is relatively small. A concept deviating from this was presented by *Maass* in 1902 (Fig. 33). According to him, quantitative growth undergoes no changes through the effect of pressure but occurs in the direction that is free from pressure, towards the concavity.

This study does not completely corroborate the theory of *Maass*, because the retardation of growth observed in the end epiphyses does not quantitatively cover the amount of lateral apposition. Nor is the amount of apposition irrefutably explained by the periosteal stretching theory of *Stilwell*.

It is a generally known fact that pressure increases bone growth. A good example of this is seen in figure 37 which shows the tendency towards straightening in fractures that have healed at an angle. At the site of angulation, there is apposition on the concave and resorption on the convex side. There is therefore a drift towards the concavity in this bone.

The present study is also an example of the validity of *Wolff's* law. The spine, although composed of several vertebrae, is a functional unit which has a clear tendency to find its way to the midline.

The final result of the present study is shown by the diagram in figure 35.

In this study on rabbits and pigs with experimental scoliosis the conclusion was reached that the structural changes caused by scoliosis are not exclusively the results of passive deformation, but among the factors underlying the changes there is also a growth process that tries to counterbalance lateral deviation.

VI SUMMARY

The aim of the experimental study was to elucidate the structural changes occurring in scoliosis and to scrutinize normal growth of the vertebra.

The study was performed by using rabbits and pigs as test animals. There were 121 rabbits, and a scoliosis-provoking operation was performed on 78 of them. The number of pigs was 47, 30 of which were operated on (Table 1). 31 rabbits and 15 pigs served as control material.

Roentgenograms and the tetracycline labelling method were used. Histological preparations were also made of the sections (Table 1).

A scoliosis-provoking operation was performed on the rabbits by resecting 5 ribs dorsally on the right side. In the pigs, scoliosis was induced by four different methods: 1. by resecting 5 to 8 ribs dorsally on the right side; 2. by resecting 5 to 8 ribs dorsally on the right and by performing dacron-thread fixation on the left side; 3. by severing the ligaments attached to the dorsal end of the ribs; and 4. by resecting 5 ribs from the right side and by also performing hemilaminectomy on the same level (Table 4). The most severe scolioses were attained in the pigs by means of costal resection associated with fixation (Table 4).

The rabbit and pig vertebrae were found to grow to equal extents in both end epiphyses while apposition was symmetrical laterally (Figs. 1 to 5). Growth of the neural canal was found to be different, depending on whether the neurocentral epiphysis was closed or not (Figs. 6 to 7).

In histological examination of scoliotic vertebrae, additional bone growth was found on the concave side as well as in the medial part of convexity in the neural canal. The growth of the neurocentral epiphysis was found to be disturbed on the convex side almost uniformly as scoliosis developed. In the end epiphyses, irregularities of the cartilaginous cells were observed on the concave side (Tables 3 and 7, Figs. 8 to 17). On the other hand, the end epiphysis was often thickened on the concave side and the direction of maturation of the cartilaginous cells had turned towards the concavity (Figs. 17 c and 22 g).

By means of the tetracycline method, definite apposition towards the concavity was found in all examined scoliotic pig preparations (Figs. 19 to 25 and 30). The amount of apposition was measured percentually and was found to

be largest in animals with only costal resection (Table 5, Fig. 28). Although additional fixation resulted in the greatest deformities, the percentile amounts of apposition were smaller. The neurocentral epiphysis was found to grow more strongly on the concave than on the convex side (Figs. 25 to 27).

A study was performed in six pigs in order to unravel the actual rotation in relation to the vertebral structure at the time of operation with the tetracycline method. Distinct rotation was found in all and it increased, although not linearly, as the scoliotic curvature increased (Table 6, Figs. 29 and 30). The spinous process was found to have turned towards the concavity as a result of apposition and resorption (Fig. 31).

In this study on rabbits and pigs with experimental scoliosis the conclusion was reached that the structural changes caused by scoliosis are not exclusively the results of passive deformation, but among the factors underlying the changes there is also a growth process that tries to counterbalance lateral deviation.

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TABLE 7. — *Changes found in rabbits.*

Rabbit No.	Age at the time of operation in days					Post-operative follow-up period				Scoliosis in degrees			Histological changes
	Under 29	30—39	40—49	50—59	Over 60	0—19	20—39	40—69	Over 70	0—29	30—59	Over 60	
1		+						+		+			
3	+							+			+		
5				+			+			+			0
9			+									+	II
10	+									+			II
11	+										+		II
12			+					+				+	II
13	+								+				II
14			+			+					+		0
15		+				+					+		I
16		+					+			+			I
17		+				+					+		0
18	+							+				+	
19		+				+					+		0
20		+					+				+		II
21		+					+				+		I
22		+				+					+		I
24		+				+					+		I
25		+					+					+	II
26		+					+				+		I
28		+					+				+		II
31		+						+				+	II
32					+		+				+		I
33			+					+			+		
34			+					+			+		
35			+					+			+		
36			+			+					+		II
37			+				+			+	+		I
38			+			+	+			+	+		I
39			+			+	+			+	+		I
41			+				+				+		II
42	+					+					+		II
43	+					+					+		I
44	+					+					+		I
45	+					+					+		I
47				+		+					+		I
48					+		+				+		I
49				+			+				+		II
50				+		+					+		0
59				+					+			+	II
60	+						+					+	
61	+							+			+		
62		+									+		
63			+			+	+			+			II
64					+					+			I
65				+		+	+					+	II
68					+				+			+	II
70					+				+			+	II
75			+			+					+		I
76			+			+					+		II
77			+					+			+		I
78			+				+				+		II
79			+						+		+		II
80			+					+			+		II
81			+					+			+		II
82					+				+			+	II
83	+							+			+		II
85	+					+					+		II
88			+			+				+			0
89			+			+						+	0
90			+			+						+	II
92			+								+		
93	+		+				+			+			I
94									+		+		
95		+						+			+		I
96		+						+				+	II
97		+					+					+	II
98		+					+					+	II
99	+								+			+	
101	+								+			+	
104			+			+				+			0
107			+			+						+	II
108	+						+					+	II
109		+							+			+	
111	+								+		+		
112		+										+	II
116		+						+				+	II
117	+					+		+		+		+	II
Total	19	21	26	6	6	24	22	18	14	12	33	33	

0 = No changes I = Slight II = Severe

FIGURES

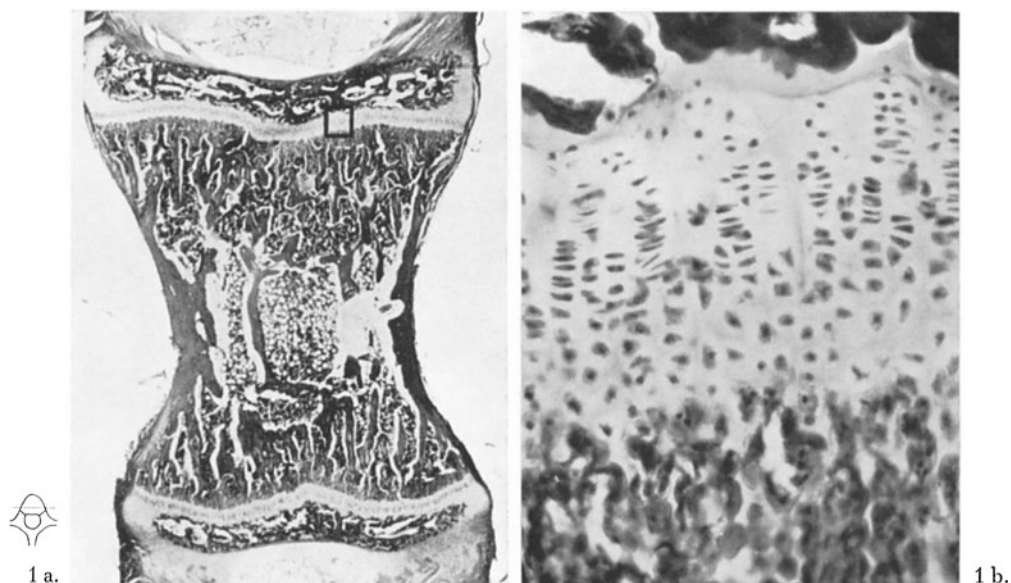


FIG. 1 a and b. — a. Frontal section of a normal vertebra (th 7), 60-day-old rabbit. Epiphyseal plates cranially and caudally, separated from diaphysis by epiphyseal line. — b. Magnification of epiphyseal area. Epiphysis is formed by cartilaginous cells maturing in one direction.

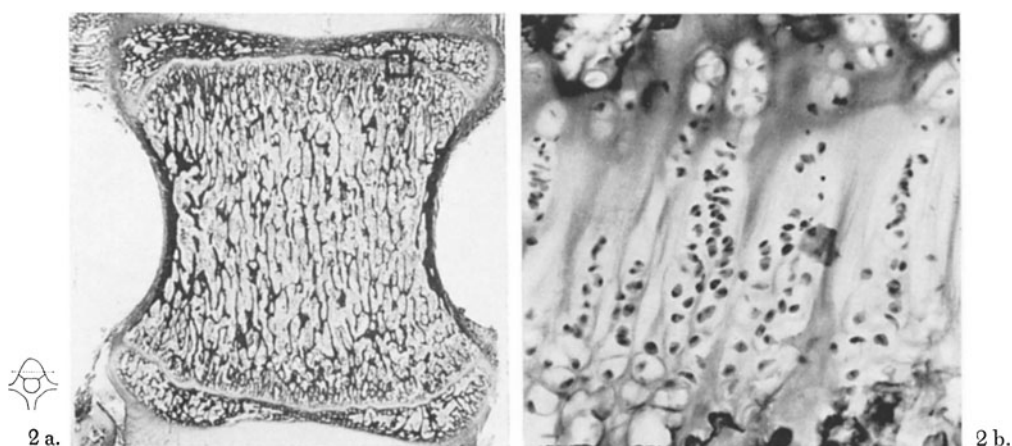


FIG. 2 a and b. — a. Frontal section of a normal vertebra (th 6), 92-day-old pig. Epiphyseal plates cranially and caudally, separated from diaphysis by epiphyseal line. — b. Magnification of epiphyseal line. Epiphysis is formed by cartilaginous cells maturing in one direction.

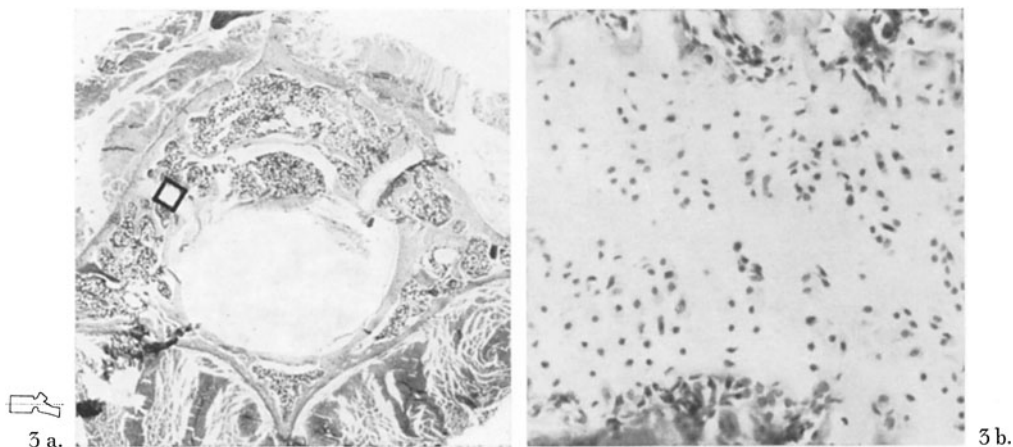


FIG. 3 a and b. — a. Cross-section of a normal vertebra (th 6), 52-day-old rabbit. Compact bone laterally and around neural canal. Between them loose spongiosa. In the border between corpus and arcus, symmetric neurocentral epiphyses on both sides. — b. Magnification of the neurocentral epiphysis. Epiphysis consists of cartilaginous cells maturing in two directions.

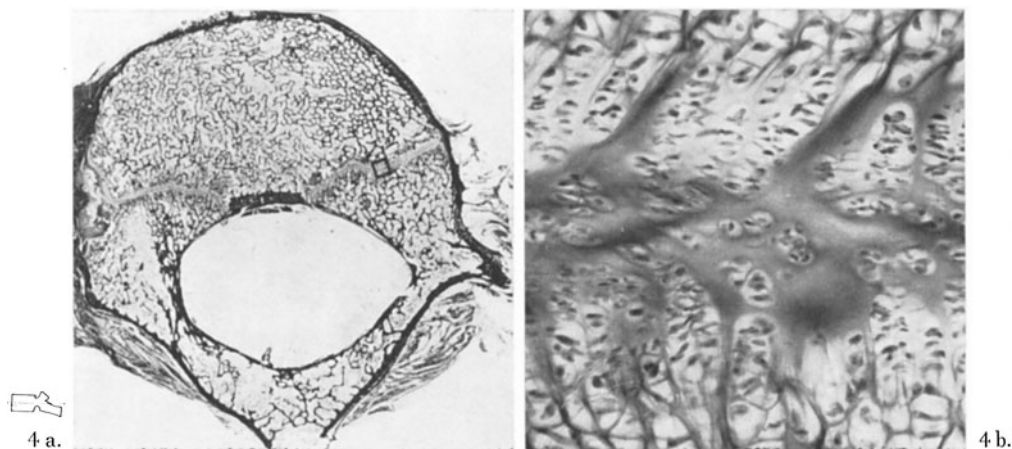


FIG. 4 a and b. — a. Cross-section of normal vertebra (th 6), 87-day-old pig. Compact bone laterally and in the area of neural canal, between them dense spongiosa. Neurocentral epiphyses symmetrically in the border between corpus and arcus. — b. Magnification of the epiphyseal area shown in fig. 4 a. Epiphysis consists of cartilaginous cells maturing in two directions.

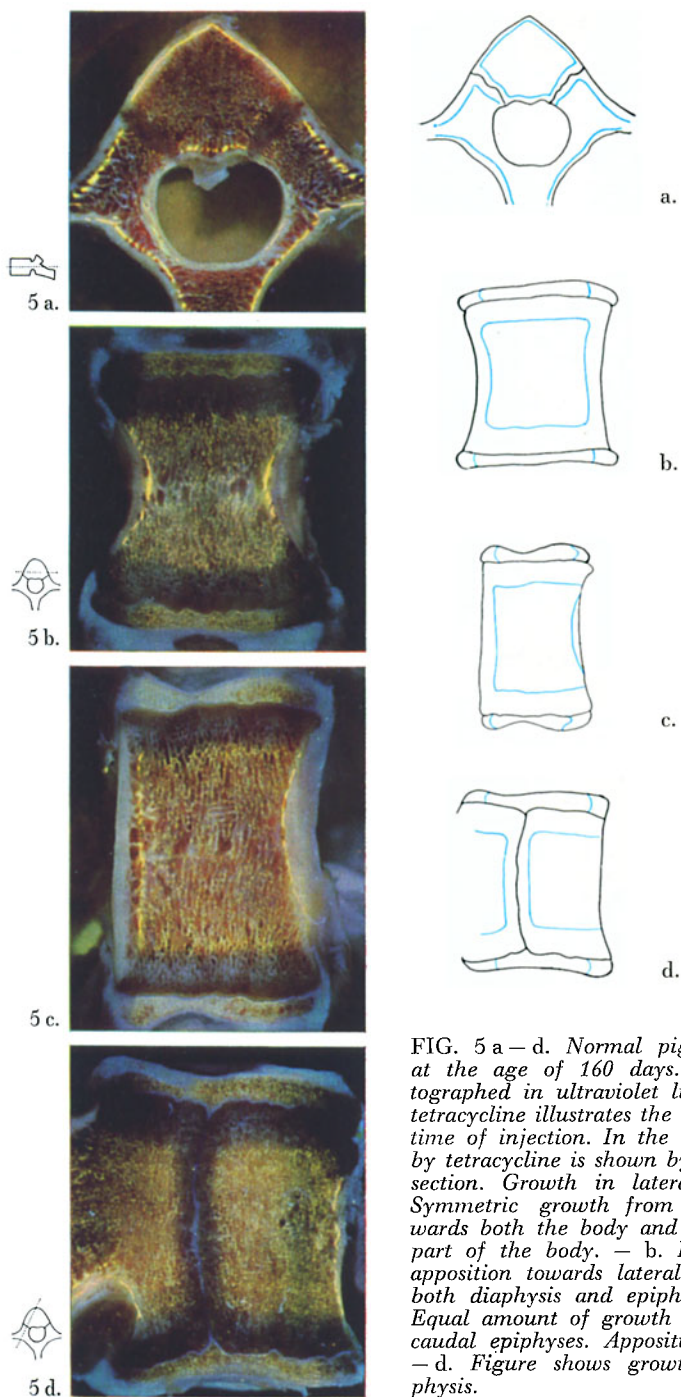


FIG. 5 a—d. Normal pig. The animal was killed at the age of 160 days. The sections were photographed in ultraviolet light. The area labelled by tetracycline illustrates the form of the vertebra at the time of injection. In the diagrams the area labelled by tetracycline is shown by the blue line. — a. Cross-section. Growth in lateral direction is symmetric. Symmetric growth from neurocentral epiphysis towards both the body and arch. Apposition in dorsal part of the body. — b. Frontal section. Symmetric apposition towards lateral direction in the areas of both diaphysis and epiphysis. — c. Sagittal section. Equal amount of growth from both the cranial and caudal epiphyses. Apposition ventrally and dorsally. — d. Figure shows growth from neurocentral epiphysis.

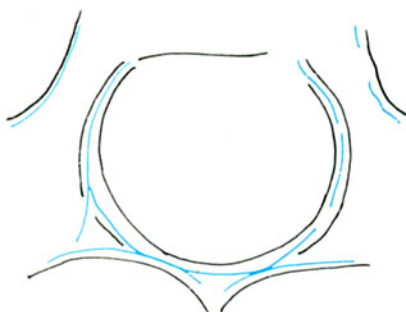
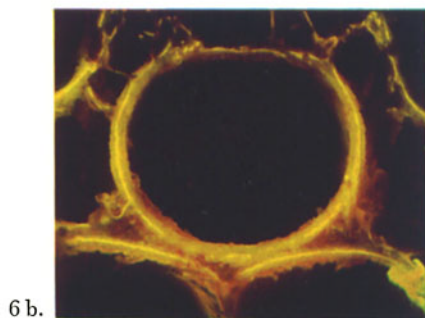
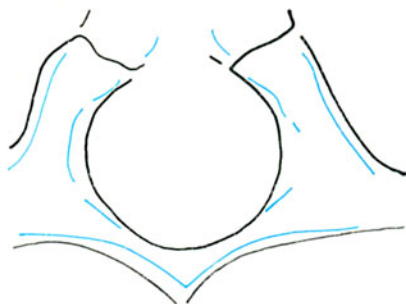
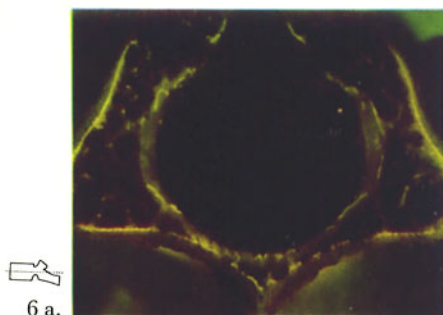


FIG. 6 a. Cross-section of normal rabbit vertebra (th 6). Tetracycline injection was administered 20 days before killing. Neurocentral epiphysis is open.

FIG. 6 b. Cross-section of normal vertebra (th 6), 83-day-old rabbit. Explanations in the text.

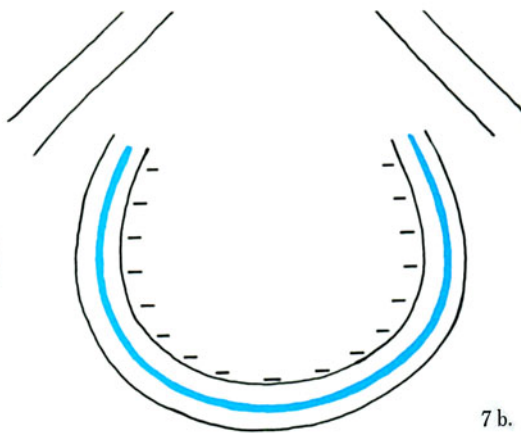
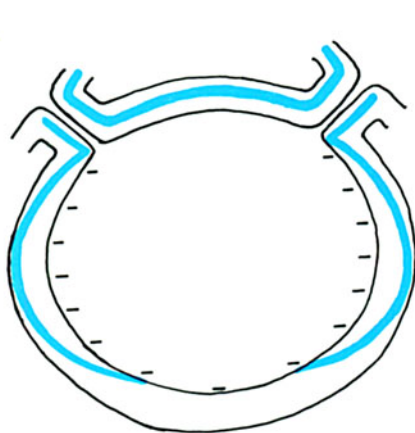


FIG. 7 a. Diagram of growth mechanism of the neural canal before closing of neurocentral epiphysis. Blue line shows area labelled by tetracycline, corresponding to previous form of neural canal. — Signs indicate resorption.

FIG. 7 b. Diagram of growth mechanism of neural canal following closure of neurocentral epiphysis. Explanations in the text.

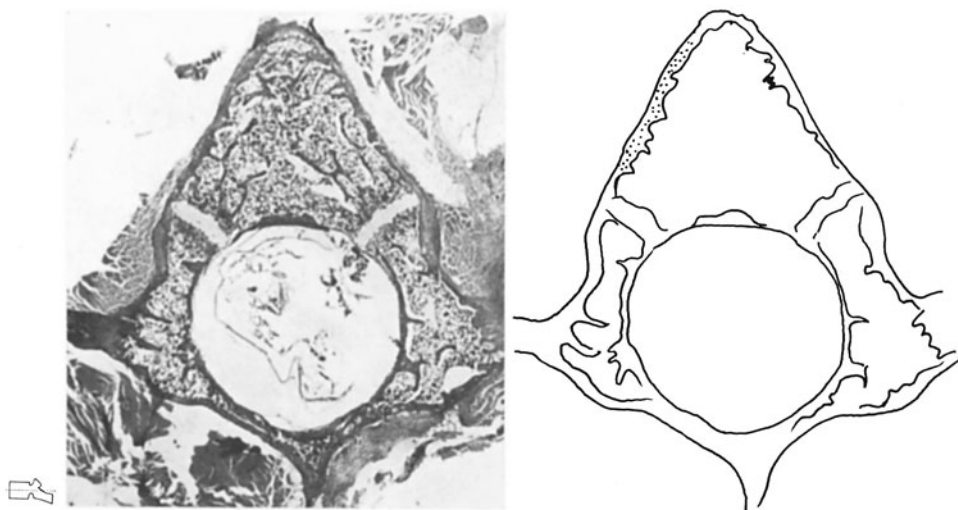


FIG. 8. Rabbit No. 43 was operated upon at the age of 28 days and killed 5 days later. Scoliotic curvature 41° . Cross-section of the apical scoliotic area. Bone structure somewhat thickened on the concave side.

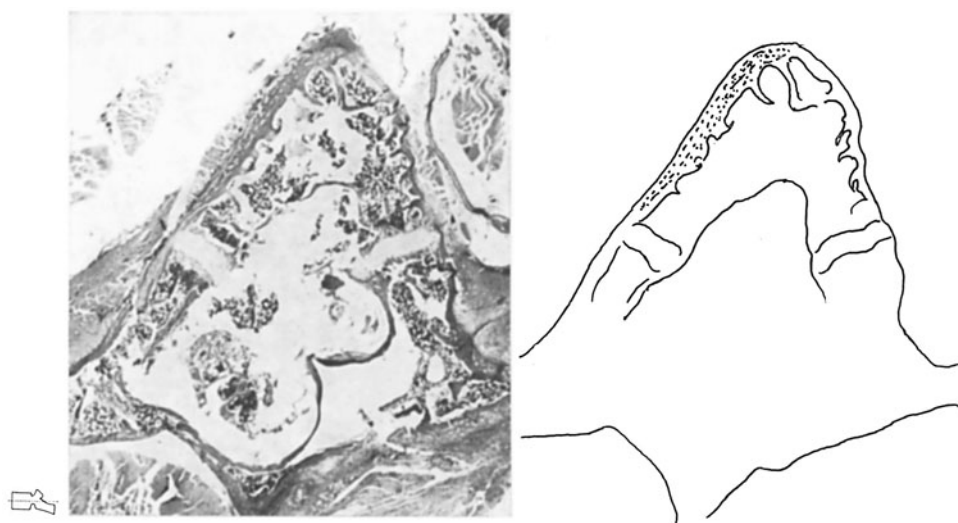


FIG. 9. Rabbit No. 42 was operated upon at the age of 22 days and killed 11 days post-operatively. Scoliotic curvature 61° . Cross-section of the apical scoliotic area. Increased trabeculation on the concave side. Neurocentral epiphysis is broader on the concave than on the convex side.

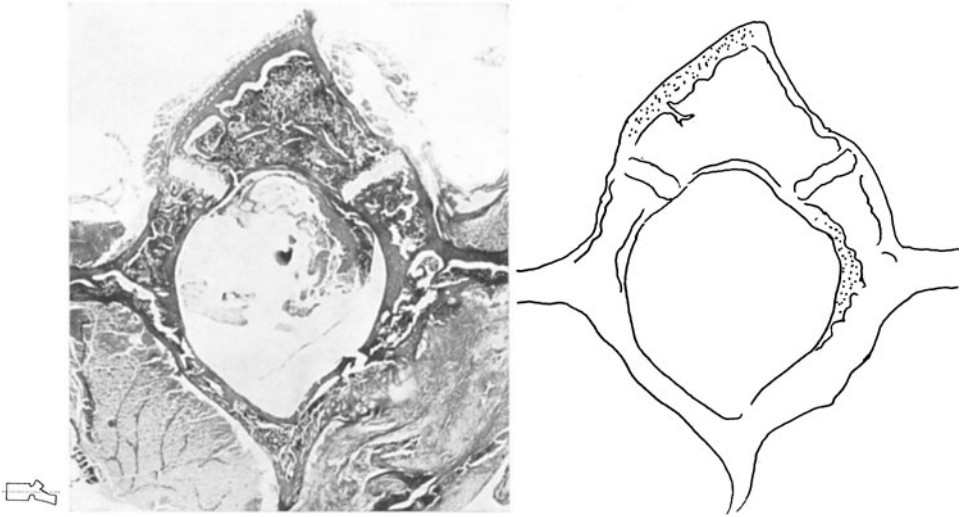


FIG. 10. Rabbit No. 39 was operated upon at the age of 43 days, killed 18 days post-operatively. Scoliotic curvature 35° . Increased trabeculation on the concave side. Neurocentral epiphysis broader on the concave side. Arch symmetric. Trabeculation increased in the medial part of arch on the convex side.

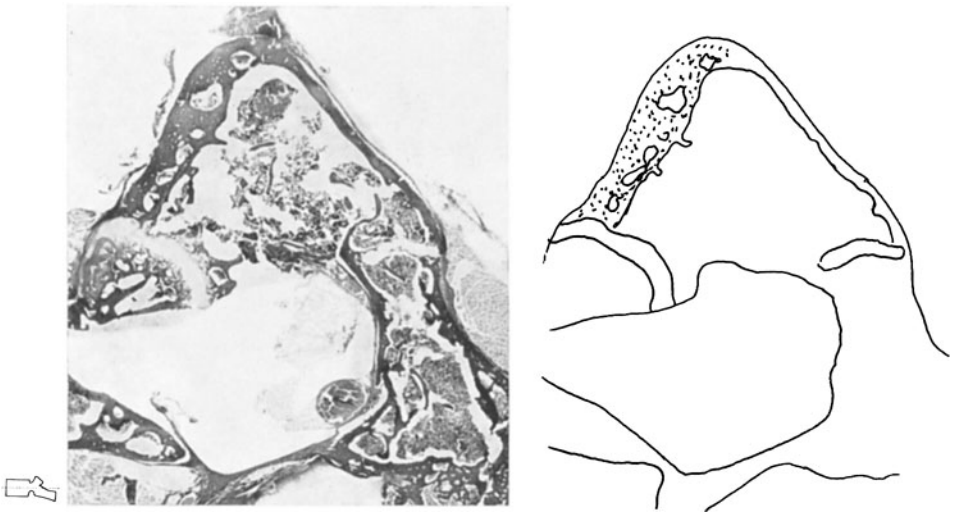


FIG. 11. Rabbit No. 77 was operated upon at the age of 45 days and killed 51 days post-operatively. Scoliotic curvature 57° . Strongly increased trabeculation on the concave side of the body. Neurocentral epiphysis greatly narrowed on the convex side.

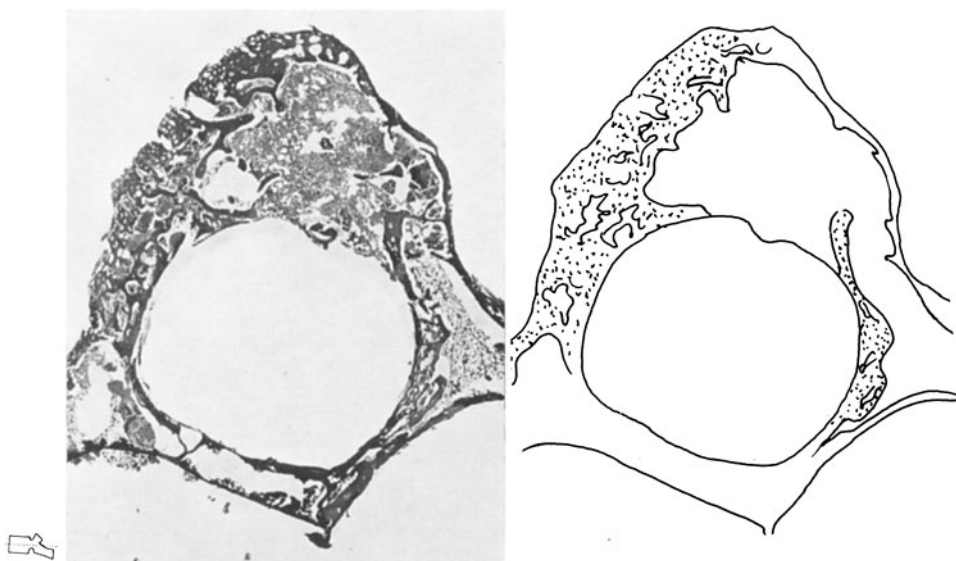


FIG. 12. Rabbit No. 98 was operated upon at the age of 38 days, killed 38 days later. Scoliotic curvature 78° . Trabeculation greatly increased on the concave side. Neurocentral epiphyses on both sides completely ossified. Neural canal asymmetric.

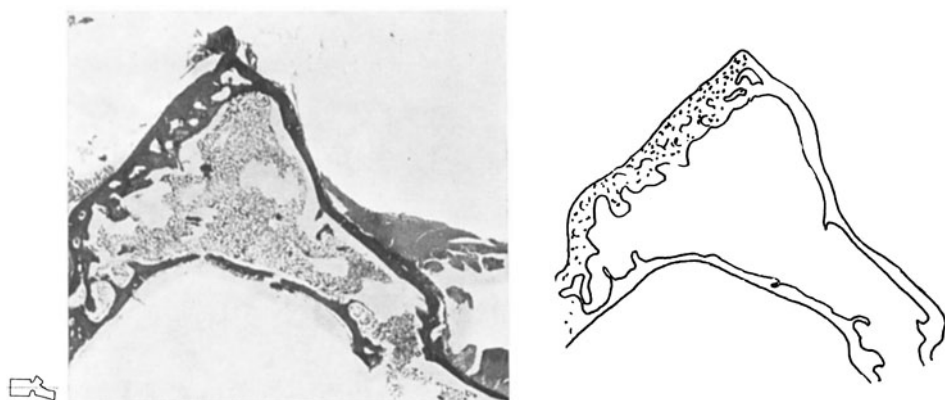
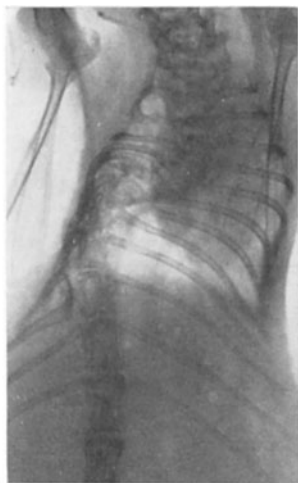
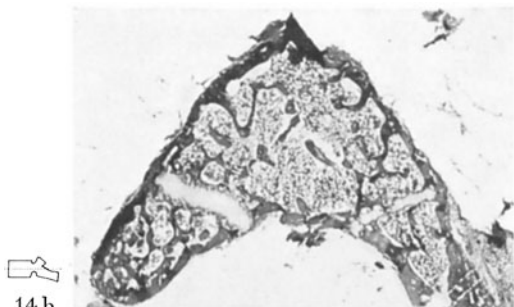


FIG. 13. Rabbit No. 68 was operated upon at the age of 76 days and killed 90 days post-operatively. Scoliotic curvature 95° . Trabeculation increased on the concave side. Neurocentral epiphyses closed.

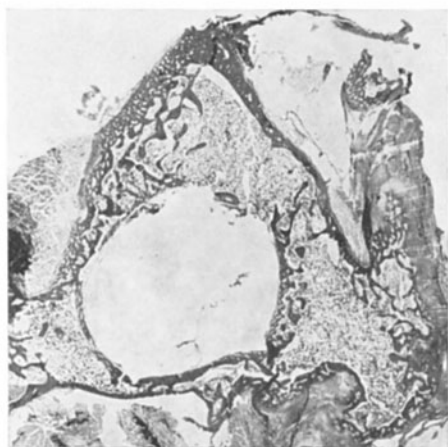


14 a.

FIG. 14 a—f. Rabbit No. 112 was operated upon at the age of 35 days and killed 51 days thereafter. Scoliotic curvature 98° . — a. X-ray immediately before killing. Vertebrae of the apical area severely deformed. — b. Th 6. Neurocentral epiphysis partly ossified on the convex side. Increased trabeculation on the concave side of corpus. — c. Th 7. Trabeculation clearly increased on the concave side and in the medial part of the arch on the convex side. Neural canal deformed. Neurocentral epiphyses closed on both sides. — d. Th 8. Changes similar to those in figure c. — e. Th 9. Increased trabeculation on the concave side and in the medial part of the arch on the convex side. Neurocentral epiphysis completely ossified on the convex, partly open on the concave side. — f. Th 10. Almost normal bone structure. Neurocentral epiphysis somewhat broader on the concave than on the convex side.

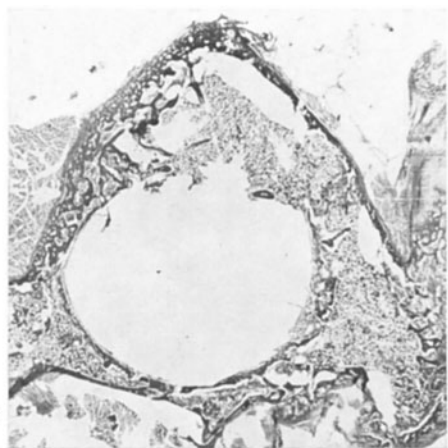


14 b.

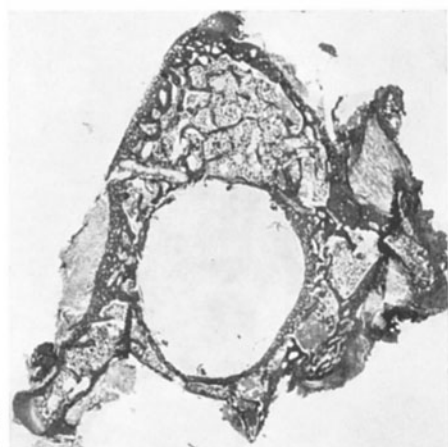


14 c.

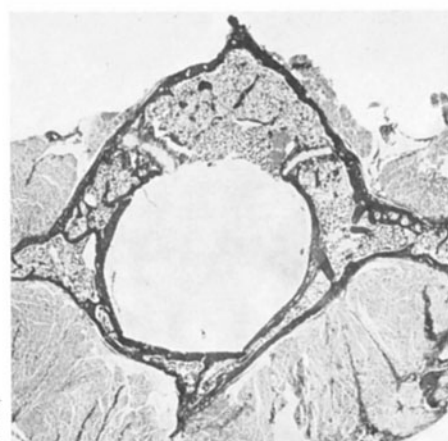




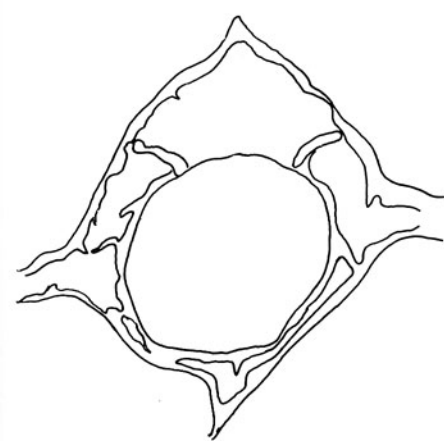
14 d.



14 e.



14 f.



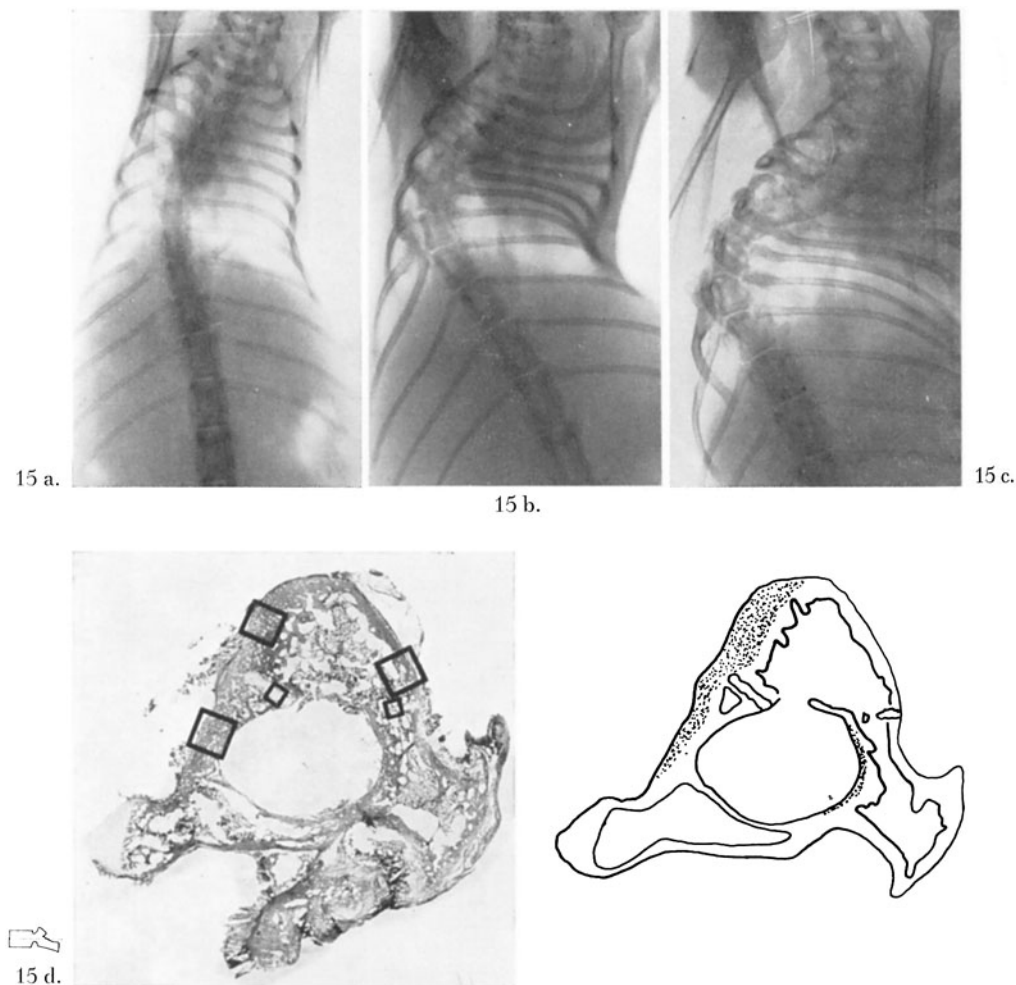
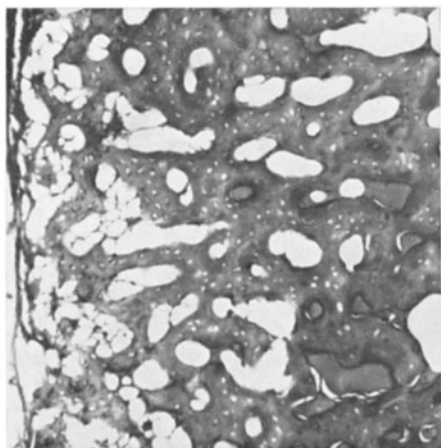
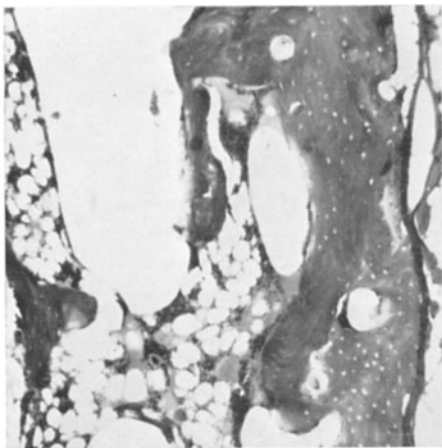


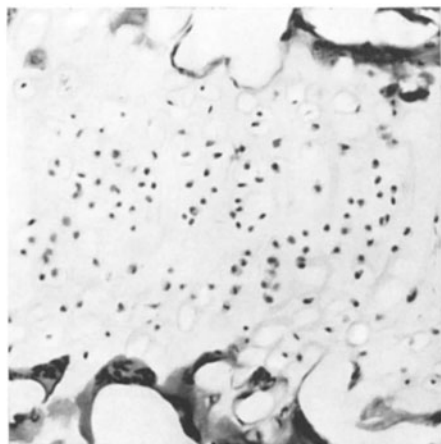
FIG. 15 a—i. Rabbit No. 81 was operated upon at the age of 45 days. It was killed 51 days post-operatively. Scoliotic curvature 95° . — a to c. X-ray changes. — a. Immediately after operation, curvature 35° . — b. 15 days post-operatively, curvature 84° , and — c. 45 days post-operatively, curvature 95° . — d. Histological section of apical vertebra in cross plane. Increased trabeculation on the concave side both in corpus and arcus. Neurocentral epiphysis is open on the concave side, partly ossified on the convex side. Increased trabeculation in the medial part of the arch on the convex side. — e. Magnification of the concave side of the body. Strong trabeculation. — f. Normal bone structure upon the convex side of the body. — g. Neurocentral epiphysis on the concave side. Normal epiphyseal structure. — h. Neurocentral epiphysis on the convex side is partly ossified, cellular structure extremely irregular. — i. Arch on the concave side. Increased trabeculation.



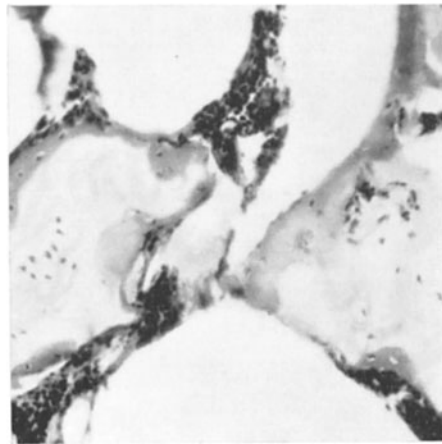
15 e.



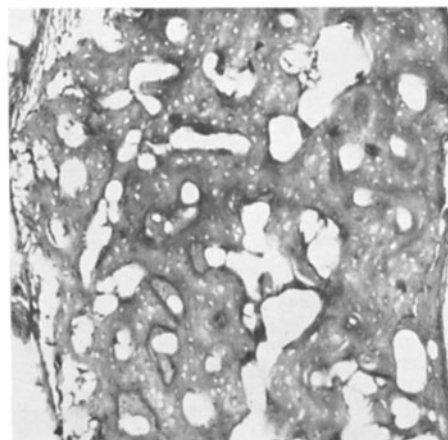
15 f.



15 g.



15 h.



15 i.

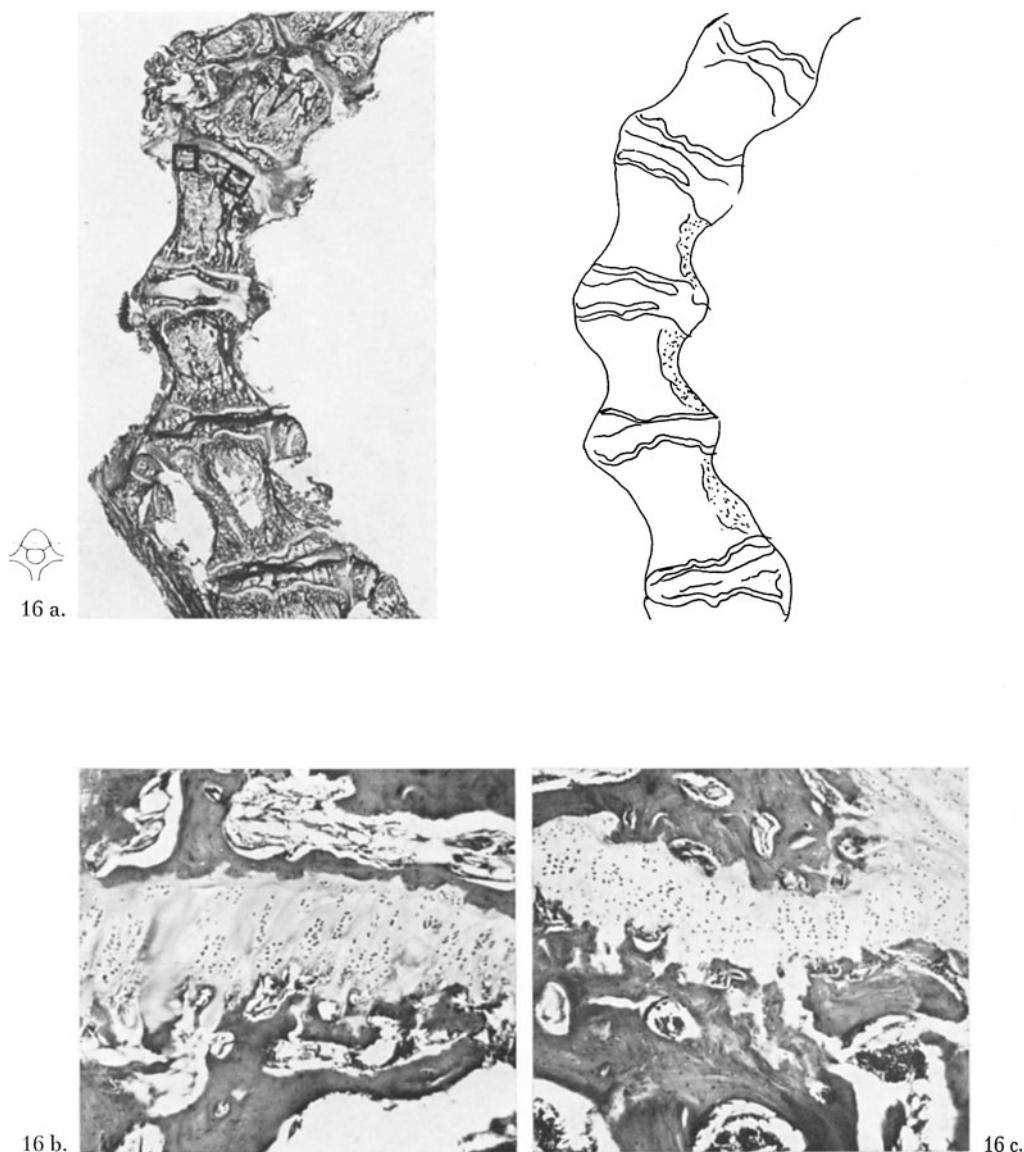


FIG. 16 a — c. Rabbit No. 96 was operated upon at the age of 31 days and killed 41 days post-operatively. Scoliotic curvature 62° . — a. Frontal section. Vertebrae severely wedge-formed and the nuclei pulposi have moved towards the convexity. Increased trabeculation on the concave side. — b. Magnification of the epiphyseal area on the convex side. Cartilaginous structure normal, palisades regular. — c. Magnification of the epiphyseal area on the concave side. Cartilaginous cells are unequally distributed. Cartilaginous layer is lowered and normal palisade formation disturbed.

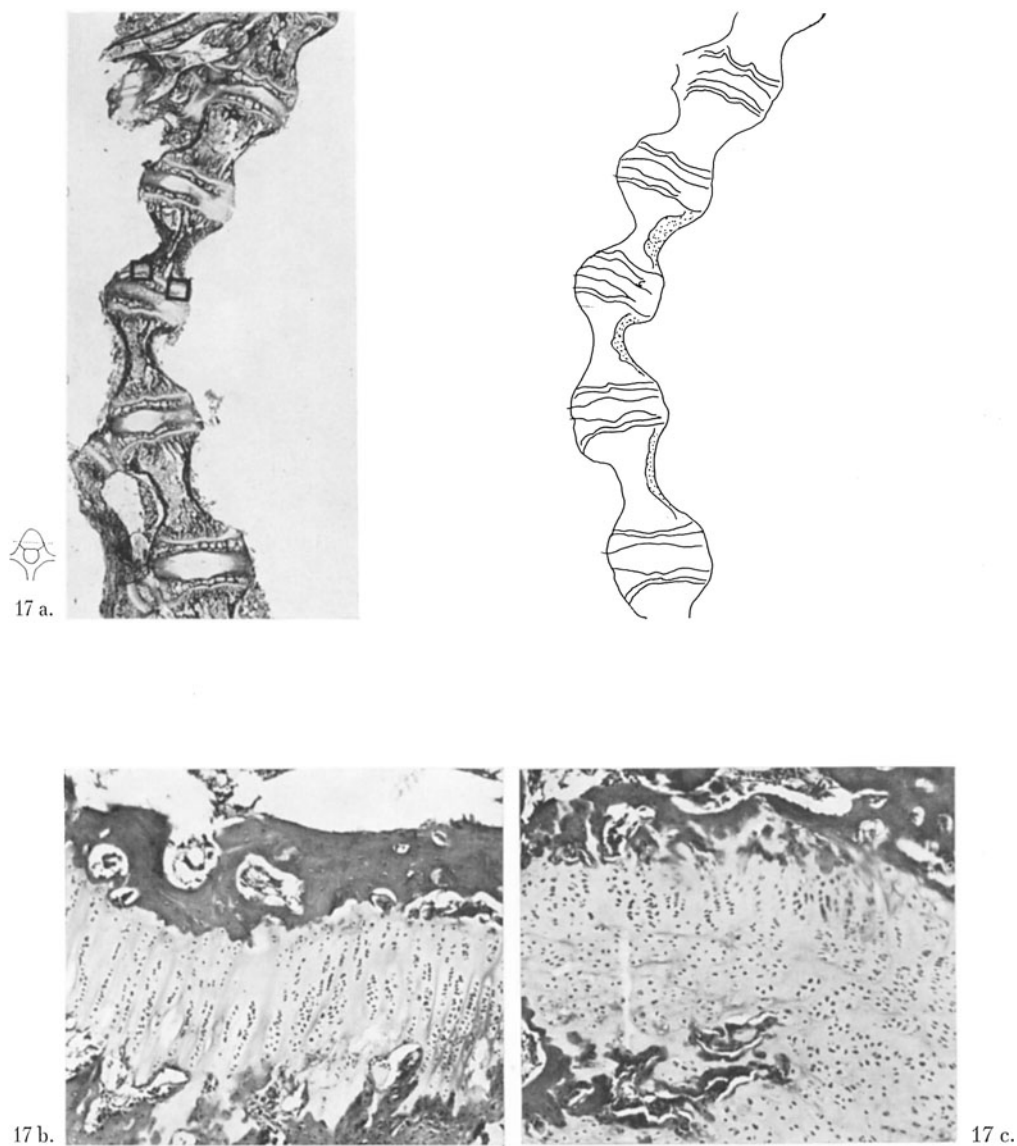


FIG. 17 a — c. Rabbit No. 75 was operated upon at the age of 48 days and killed 18 days post-operatively. — a. Scoliotic curvature 58° . — b. Magnification of the epiphyseal area on the convex side. Cartilaginous structure normal. — c. Magnification of the concave side. Cartilaginous layer is wider than normal and irregular.

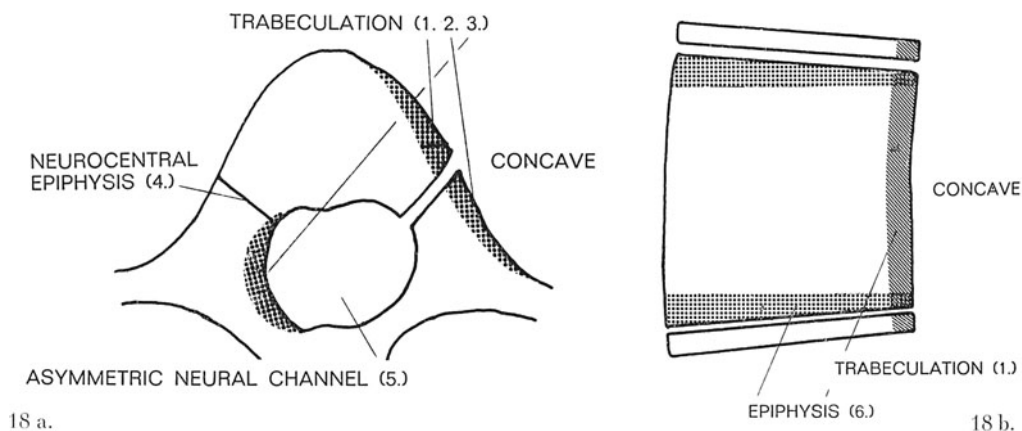


FIG. 18 a and b. *Diagrams of histological changes observed in scoliotic vertebrae. — a. Cross-section. — b. Frontal section. Explanations in the text.*

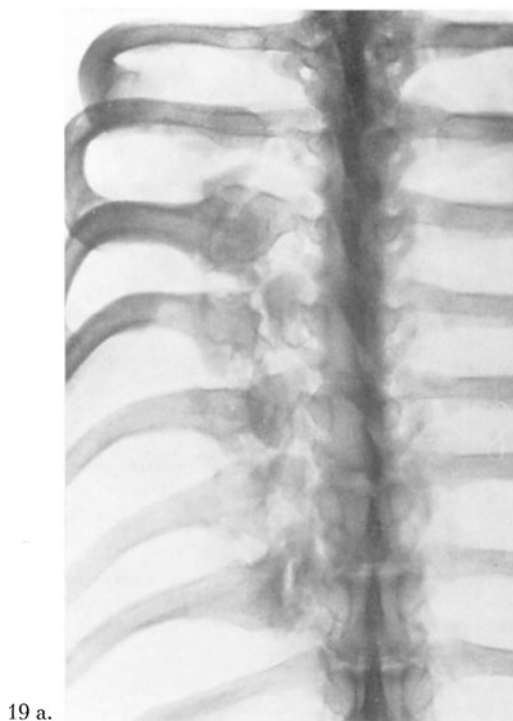


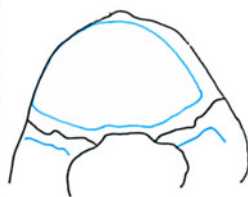
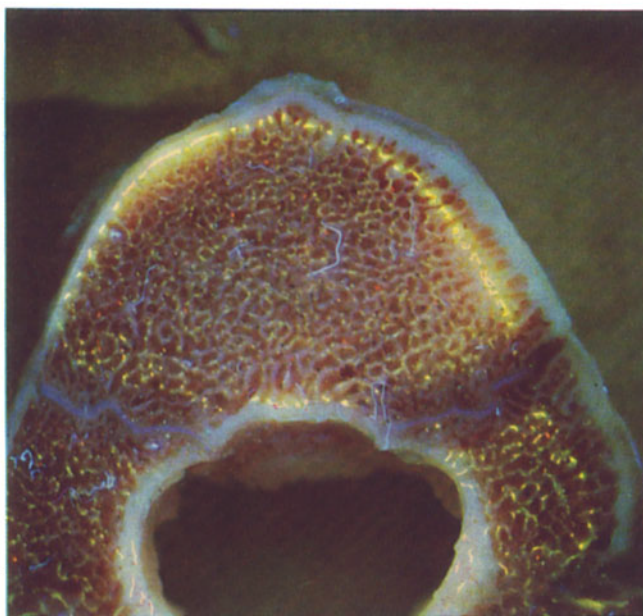
FIG. 19 a — c. *Pig No. 4. The right ribs 7–11 were resected at the age of 93 days. Ten days post-operatively the scoliotic curvature was 12°. The animal was killed 84 days post-operatively when the scoliotic curvature was 5°. — a. X-ray of the preparation with no noteworthy structural alterations. — b. Frontal section of apical area of scoliosis. Tetracycline injection was administered immediately before operation. Growth from cranial and caudal epiphyseal plates is symmetric. Definite apposition, 14 %, on the concave side. The tetracycline line has disappeared on the convex side showing resorption in this area. — c. Cross-section. Growth from neurocentral epiphysis occurs symmetrically. Definite apposition towards the concavity.*



19 b.



19 c.



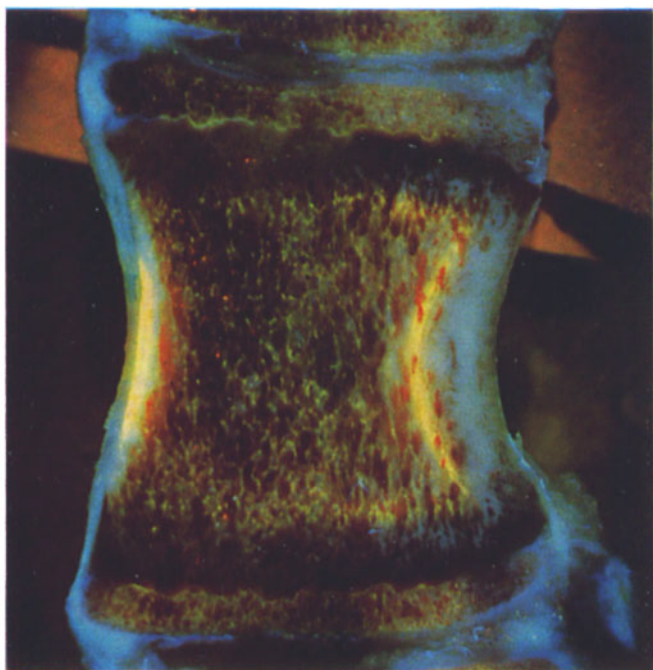


20 a.

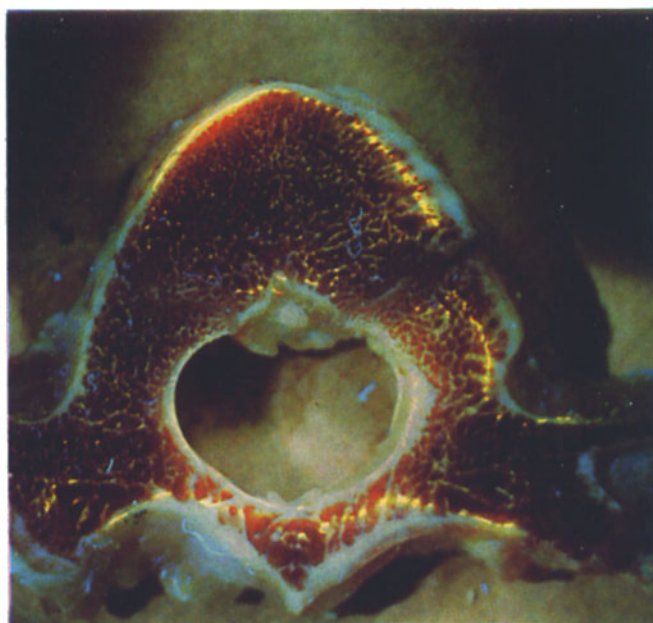
FIG. 20 a—c. *Pig No. 3. The right ribs 7–11 were resected at the age of 102 days. The animal was killed 74 days post-operatively. — a. In the preparation illustrated, the scoliotic curvature is 13° . Vertebrae of the scoliotic area somewhat deformed. — b. Frontal section of the apical area. Strong apposition on the concave side, 22 %. The tetracycline line has partly disappeared from the concave side showing resorption in this area. — c. Cross-section. Definite apposition towards the concavity. Growth from neurocentral epiphyses symmetric.*



20 b.



20 c.



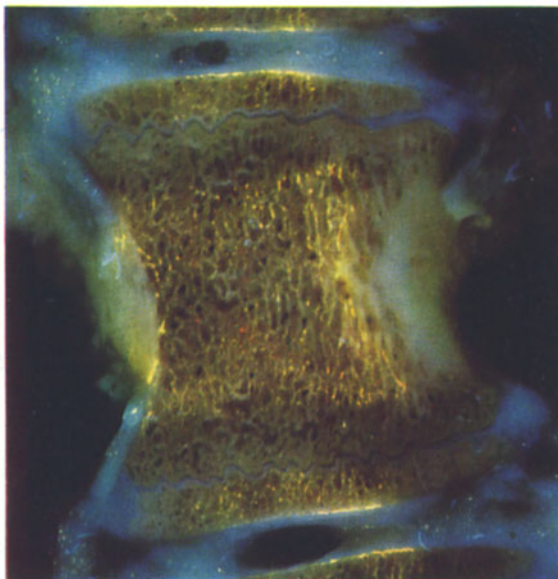
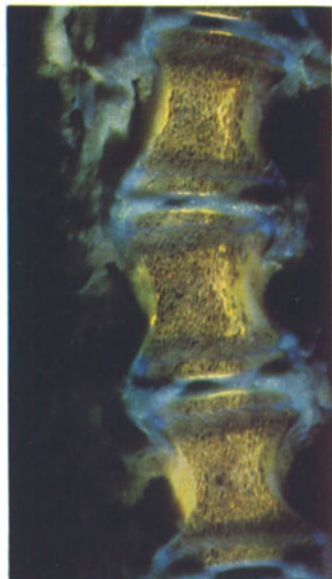


21 a.

FIG. 21 a—c. Pig No. 11. The right ribs 8–13 were resected at the age of 90 days. 43 days post-operatively the scoliotic curvature was 15° . The pig was killed 119 days post-operatively when the scoliotic curvature was 25° . — a. Picture of the preparation. The apical vertebrae show wedge-formed deformity. — b. Frontal section. Tetracycline injection was administered immediately before operation. There is definite apposition towards the concavity in all vertebrae. — c. Close-up of the apical scoliotic vertebra. Definite apposition of 24 %, towards the concavity. Appositional changes are clearly visible both in the vertebral diaphyses and epiphyses. The caudal epiphyseal line, and the tetracycline line which illustrates the location of the epiphyseal line at the moment of operation, form an angle with each other. This wedge shows retardation of growth in the end epiphysis.



21 b.



21 c.

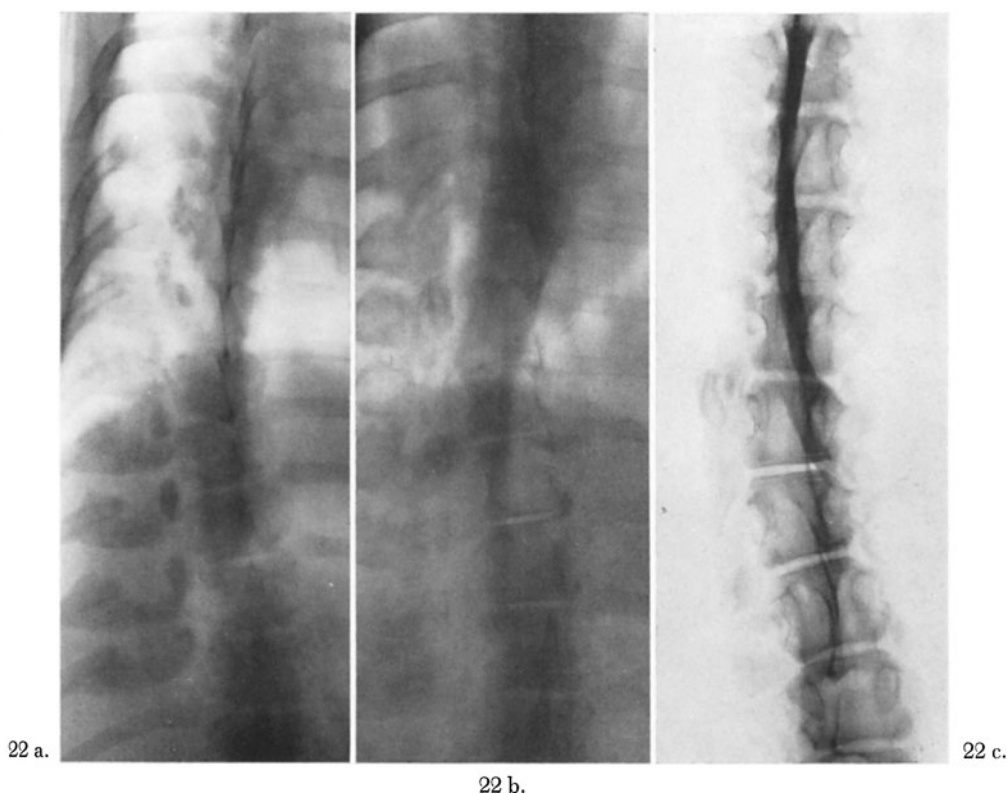
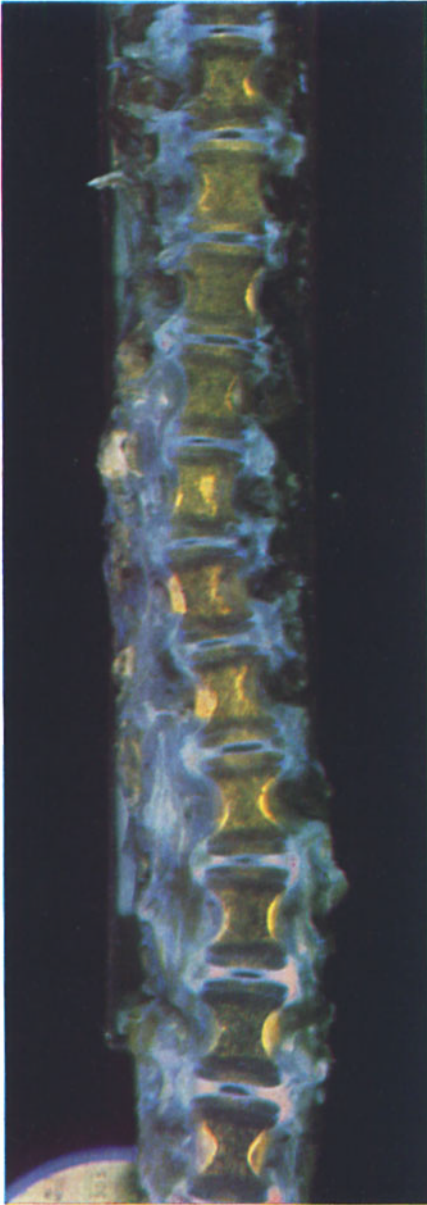


FIG. 22 a — h. Pig No. 18. The right ribs 5—12 were resected at the age of 59 days. Figures a to c show the roentgenological development of scoliosis. — a. Immediately after operation the scoliotic curvature was 13° . — b. 23 days post-operatively it was 13° . — c. In the preparation the scoliotic curvature is 23° . The pig was killed 81 days post-operatively. The vertebrae of the apical area are clearly wedge-formed.

continued

continued

22 d. Cross-section. In the cranial and caudal areas, growth is symmetric both from the end epiphyses and laterally. In the vertebrae of the scoliotic area, definite apposition towards the concavity may be observed.

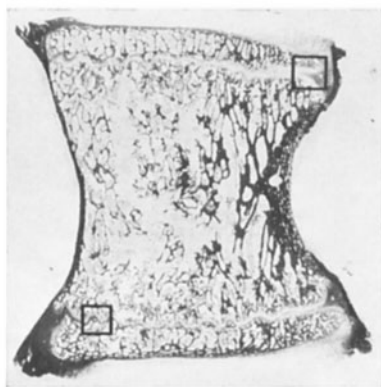
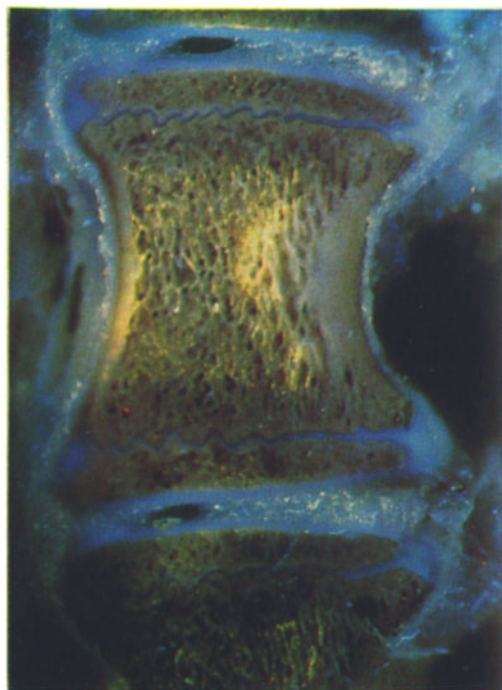


22 d.

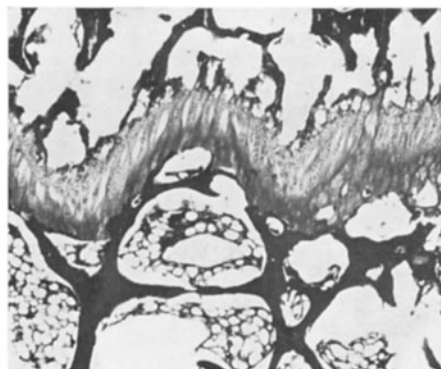
continued



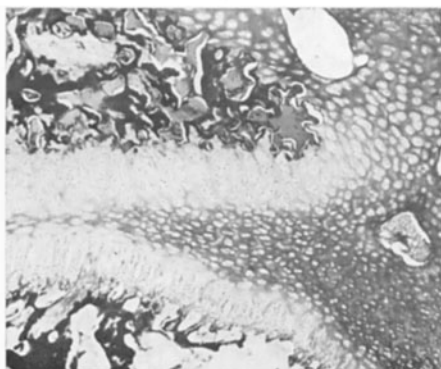
22 e.



22 f.



22 g.



22 h.

continued

22 e. Close-up of the apical vertebra. There is a definite apposition of 32 % towards the concavity. Both the cranial and caudal epiphyseal lines form an angle with the tetracycline line. This shows retardation of growth in both end epiphyses on the concave side. — f. Histological section of the specimen in e. Increased trabeculation is seen on the concave side of the diaphysis. — g. Epiphysis on the convex side is normal. — h. Magnification of the concave side epiphyseal area. The epiphysis is wider than normal. An increased number of cartilaginous cells also on the cranial side of the epiphysis. The direction of maturation of the cartilaginous cells has turned towards the concavity.

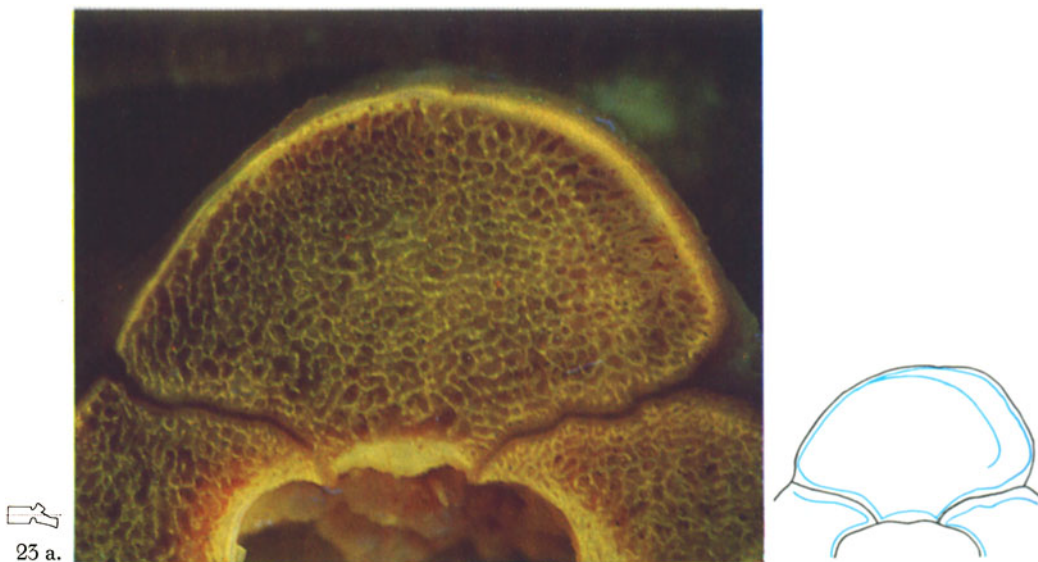
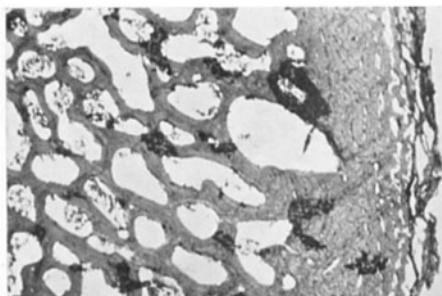
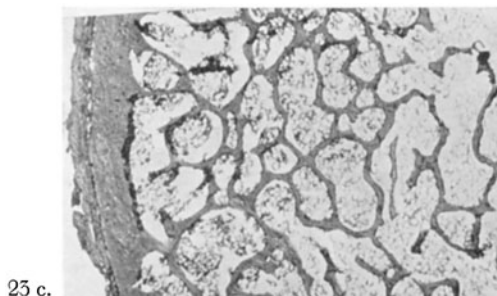
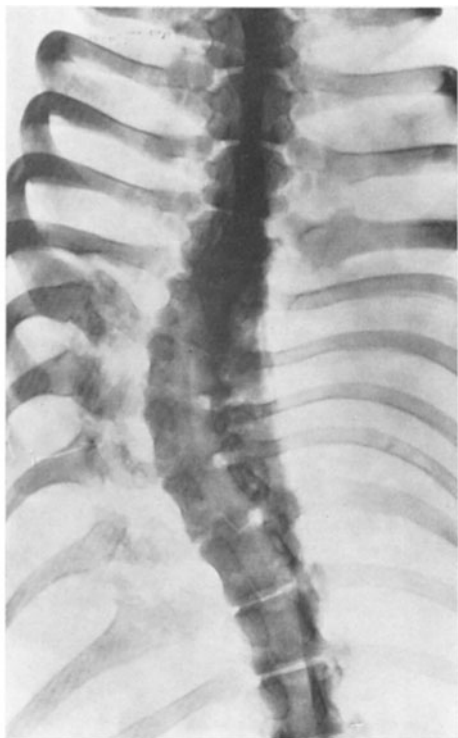


FIG. 23 a — d. Pig No. 5 was operated upon at the age of 56 days and killed 83 days post-operatively. The scoliotic curvature is 29° and percentile apposition 15 %. The pig received two injections of tetracycline, one prior to operation and the other immediately before killing. — a. Cross-section of the apical vertebra. The inner tetracycline line illustrates the form of the vertebra at the moment of operation and the outer one just before killing. Between the tetracycline lines on the concave side there remains an area which illustrates the additional bone growth since the operation.

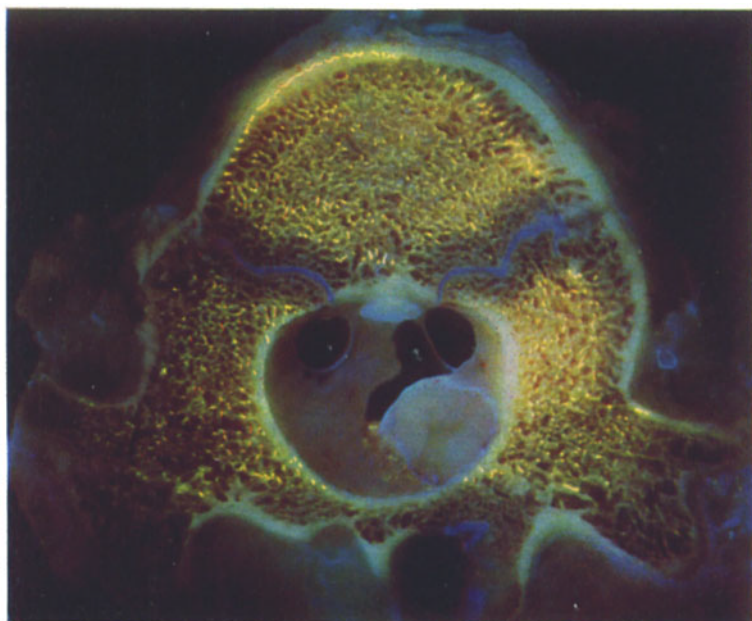
— b. Histological preparation of a. — c. Magnification of the convex side, part of the vertebral body, with normal bone structure. — d. Magnification of the concave side, part of the body, where the bone structure is trabeculated.





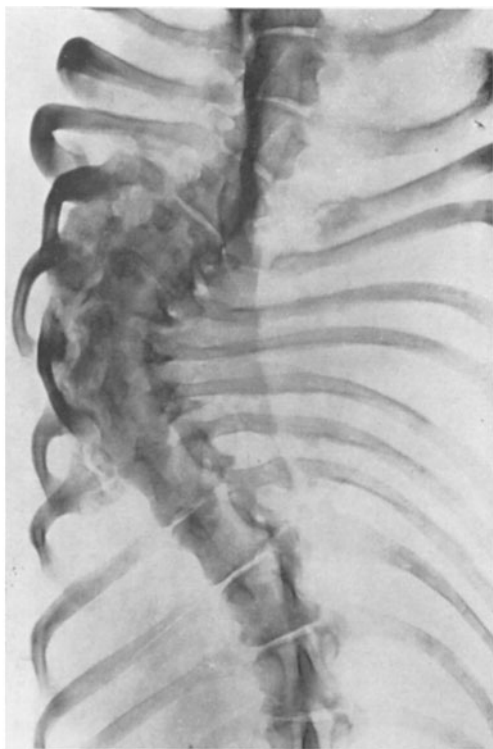
24 a.

FIG. 24 a and b. Pig No. 23. The right ribs 8–12 were resected at the age of 55 days, and the levels th 6–8 and th 13–7 were fixed with deflon thread on the left. Scoliotic curvature 53° . The animal was killed 82 days post-operatively. — a. X-ray shows strongly deformed vertebrae in the scoliotic area. — b. Tetracycline section of the apical scoliotic area in cross plane. Tetracycline injection was administered immediately prior to the operation. There is apposition towards the concavity, both in the body and arch, 14 %. Growth from the neuro-central epiphysis is somewhat greater on the concave side.



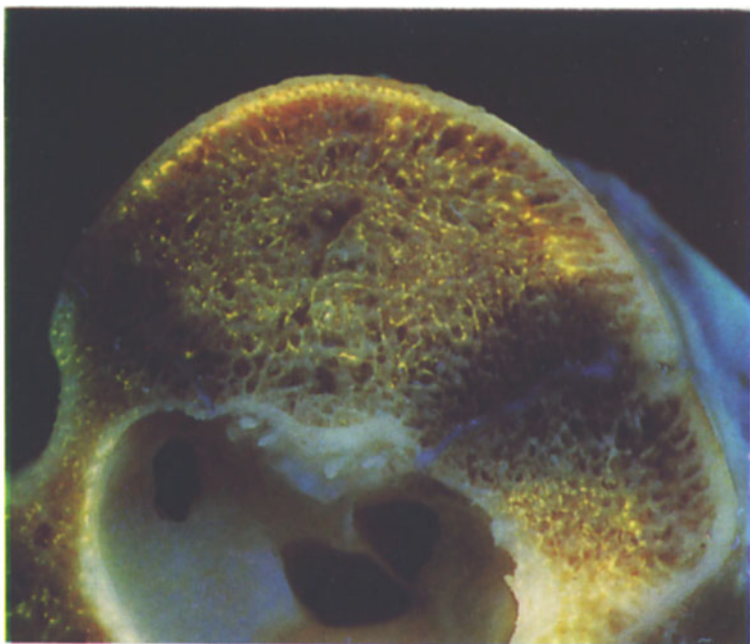
24 b.





25 a.

FIG. 25 a and b. Pig No. 27. The right ribs 8–12 were resected at the age of 56 days and defloration was performed to the left on areas th 6–9 and th 13–6. The pig was killed 115 days post-operatively. — a. Scoliotic curvature 84° . Vertebrae in the scoliotic area are severely deformed. — b. Cross-section from the apical area of figure a. There is definite apposition towards the concavity both in the body and arch, 23 %. In the neurocentral epiphysis, growth is clearly stronger on the concave than on the convex side.



25 b.



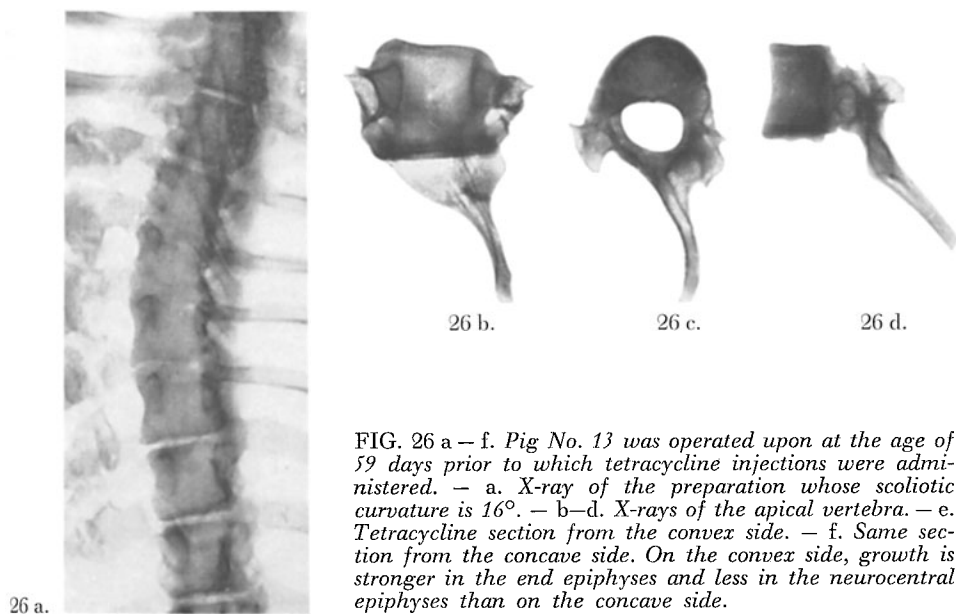
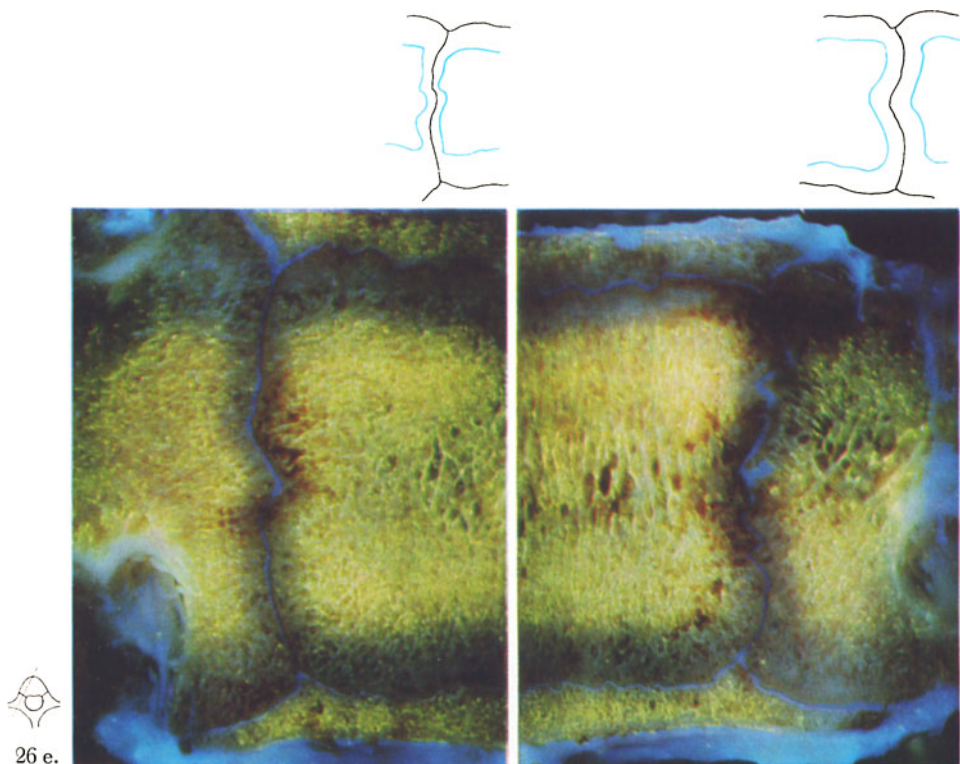


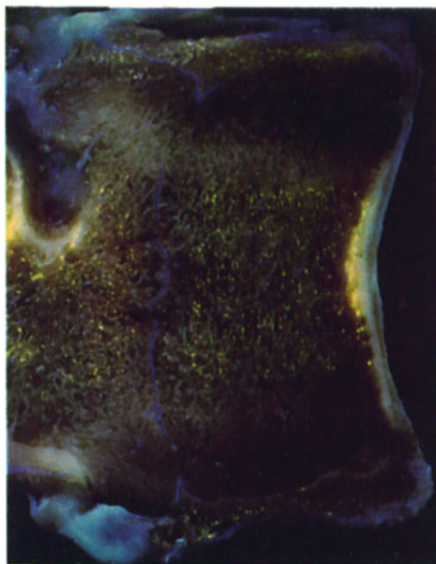
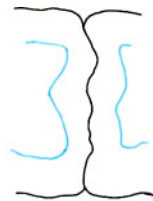
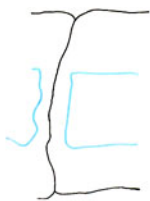
FIG. 26 a - f. Pig No. 13 was operated upon at the age of 59 days prior to which tetracycline injections were administered. — a. X-ray of the preparation whose scoliotic curvature is 16° . — b-d. X-rays of the apical vertebra. — e. Tetracycline section from the convex side. — f. Same section from the concave side. On the convex side, growth is stronger in the end epiphyses and less in the neurocentral epiphyses than on the concave side.





27 a.

FIG. 27 a — c. *Pig No. 24* Scoliosis-provoking operation was performed at the age of 55 days. — a. X-ray of the preparation. Scoliotic curvature is 48° . Tetracycline sections were taken as figure 26. — b. from the convex and — c. from the concave side. On the concave side growth has been greater in the neurocentral epiphyses and less in the end epiphyses.



27 b.

27 c.



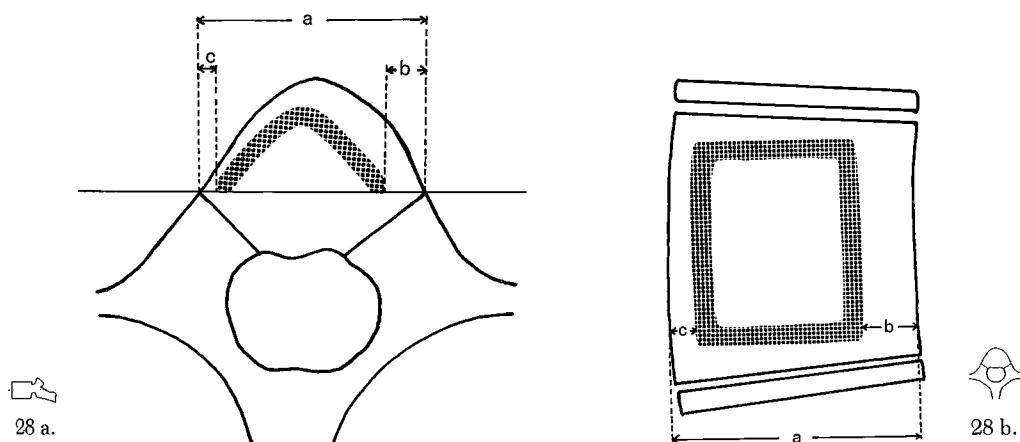


FIG. 28 a and b. Diagram of the principle according to which the percentile apposition was measured. *a* is thickness of the vertebral body at frontal level. *b* is amount of newly-formed bone from the tetracycline labelled area towards the concavity. *c* is amount of newly-formed bone on the convex side.

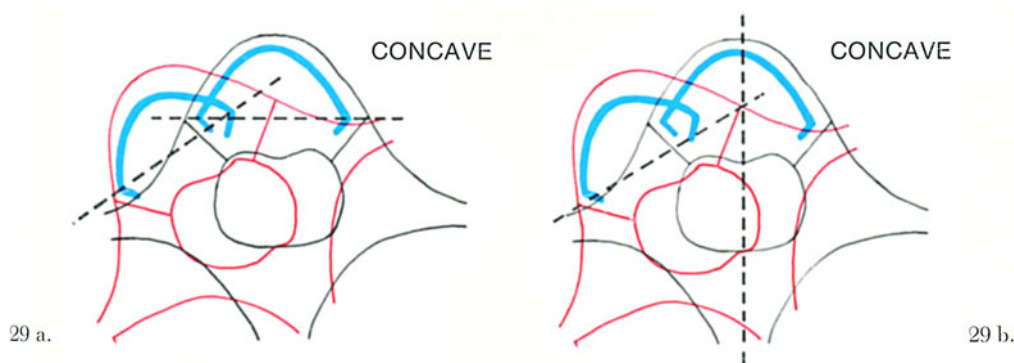


FIG. 29 a and b. Diagram of methods of study for determination of the real rotation. The neutral vertebra is denoted in black, the apical scoliotic vertebra in red. The blue area is that labelled by tetracycline and illustrates the shape of the vertebra at the moment of operation. — a. Method I. Broken line shows the axes according to which the rotation was determined. — b. Method II. Broken line shows the location of direction pins in the neutral and apical vertebrae. Fuller explanation of the methods is given in the text.

FIG. 30 a.



b.
←

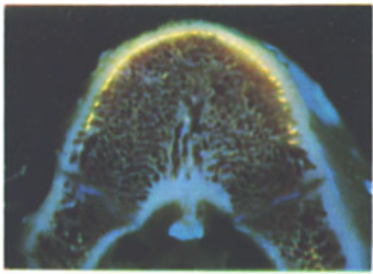
c.
←

d.
←

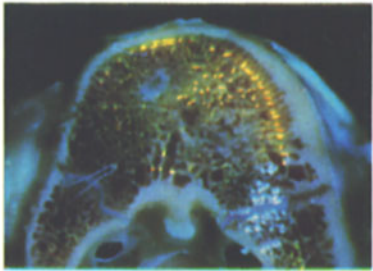
e.
←

f.
←

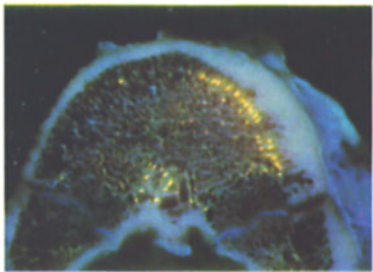
FIG. 30 b–f.



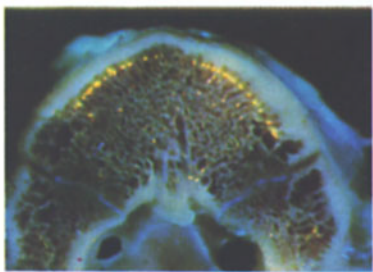
30 b.



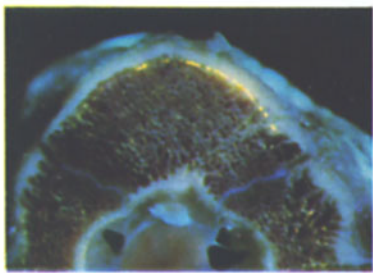
30 c.



30 d.



30 e.



30 f.

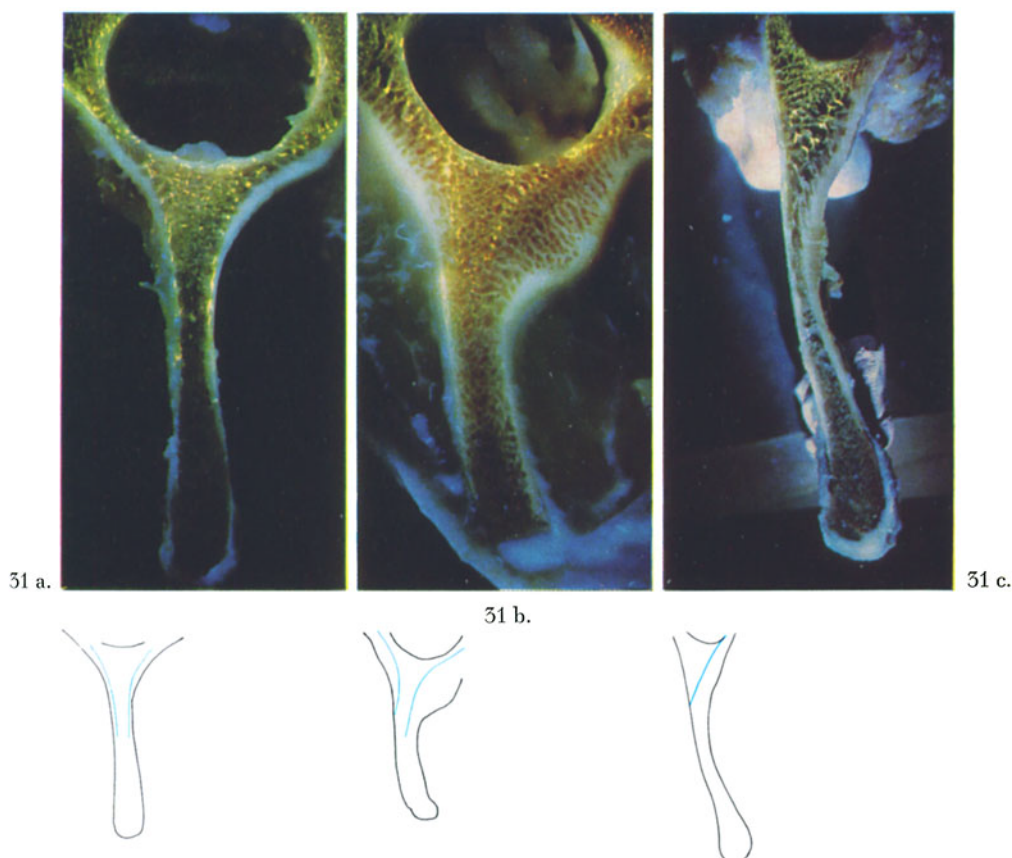


FIG. 31 a—c. Turning of spinous process towards the concavity in tetracycline sections. — a. Normal situation. Tetracycline occurs symmetrically in the center of the area. — b. Slight turning of spinous process towards the concavity. — c. Spinous process is deviating strongly towards the concavity. The area labelled by tetracycline is hardly visible.

FIG. 30 a—f. Pig No. 21. The right ribs 8–13 were resected at the age of 67 days. The animal was killed 98 days following resection. Tetracycline was injected immediately before operation. — a. Scoliotic curvature in the specimen 21° . Definite rotation is seen in the vertebrae of the sciotic area. Some wedge deformation in the vertebrae. Cross-sections at various levels of the preparation shown in the figure a. In figure b and f, showing upper and lower neutral vertebrae, the growth is symmetric. On the other hand, definite apposition towards the concavity is seen in the three apical vertebrae, greatest in the section d.

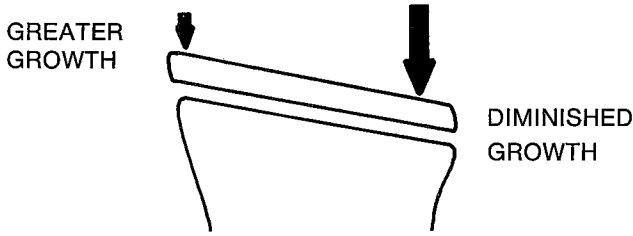


FIG. 32. Diagram of the principle of the Hueter-Volkman law. Increased pressure prohibits epiphyseal growth. On the side of lessened pressure the growth is greater.

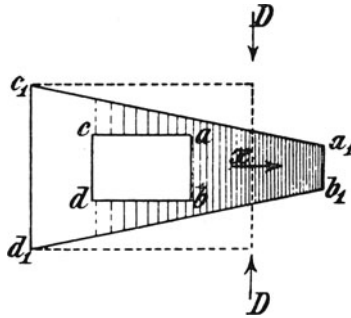
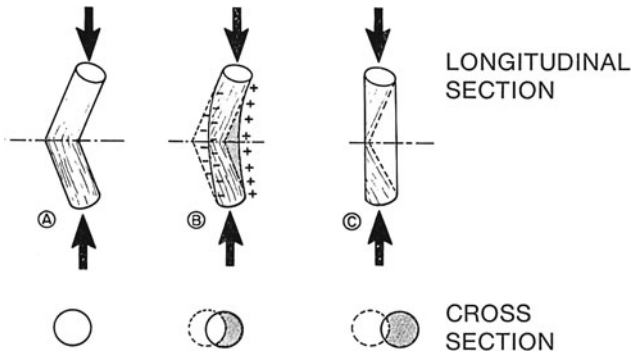


FIG. 33. A picture of the forming of scoliotic wedge-formed vertebra published by Maass in 1902. Increased pressure in the cranio-caudal direction does not prevent massy growth directed towards lesser pressure. x shows direction of growth. The area denoted by letters a to d illustrates the shape of the vertebra prior to development of scoliosis. Correspondingly, a^1 to d^1 give an indication of the shape of the vertebra following development of scoliotic structural changes.



With the courtesy of H. M. Frost.

FIG. 34. Diagram of the straightening mechanism of a fracture consolidated into an angle. + signs indicate apposition, - signs resorption. Increased apposition on the concave and correspondingly resorption on the convex side result in straightening of a fracture healed with angulation.

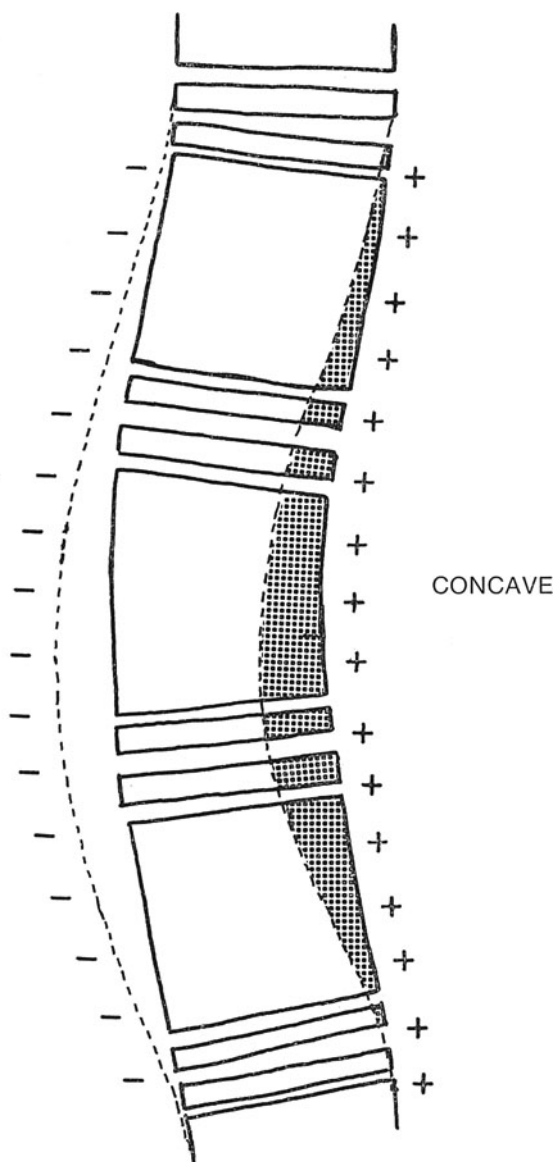


FIG. 35. Diagram of the straightening tendency of scoliotic vertebral column, shown in frontal section. The area denoted by dotted lines indicates the form the back would have had if the changes found in the study had not occurred. + signs indicate apposition, - signs resorption. The darker area shows newly-formed bone. If appositional changes on the concave side found in the study had not occurred the curvature of the scoliotic spine would be considerably greater.