ACTA ORTHOPAEDICA SCANDINAVICA
SUPPLEMENTUM NO. 192, Vol. 52

From the Research Laboratory of the Invalid Foundation,
Helsinki, Finland

Experimental Scoliosis:

Production of Structural Scoliosis by Immobilization of Young Rabbits in a Scoliotic Position

BY
SEPPO HAKKARAINEN

MUNKSGAARD · COPENHAGEN 1981

Vammala 1981, Vammalan Kirjapaino Oy

ISBN 87-16-09015-2
ISSN 0300-8827

CONTENTS

INTRODUCTION. PURPOSE OF THE INVESTIGATION

Scoliosis has been a frequent subject of orthopaedic research and a large number of articles have been written on it. Clear progress in the operative treatment of scoliosis has been made during the last few decades, particularly since the introduction of the Harrington method (1962). However, our knowledge of the pathogenesis and the etiology of idiopathic scoliosis is still deficient.

Experiments performed by Langenskiöld and Michelsson (1962) showed that transection of costotransverse ligaments or the posterior parts of intercostal muscles in a growing rabbit immediately results in a functional scoliosis which is sometimes followed by progressive structural scoliosis. The pathogenetic chain of the phenomenon has not been fully understood. However, experiments performed on the foot of a rabbit by Ritsilä (1969) gave the idea that if a functional scoliosis is present for a period of weeks, »myostatic contracture» and permanent growth disturbance of muscles may occur on the concave side of the scoliotic spine.

Thus, the working hypothesis of this investigation was that if the spine of a growing rabbit is kept in a scoliotic position in plaster for some weeks, growth disturbance of muscles on the concave side of the spine must occur and result in a progressive scoliosis.

The purpose of this study has been to investigate:

1. the possibility of provoking progressive structural scoliosis resembling human idiopathic scoliosis in young rabbits by a method implying maintenance of functional scoliosis without operative trauma.
2. the reaction of an experimentally provoked scoliotic curve when the soft tissue contracture is released by operation.
3. the anatomical changes in the muscles and other tissues in the vicinity of the curved part of the spine made scoliotic by the method used.

A preliminary report on this study was presented at the meeting of the Finnish Orthopaedic Association (Hakkarainen & Langenskiöld, 1971) and at the meeting of the Scandinavian Orthopaedic Association in Helsinki, 1972 (Hakkarainen 1973).

REVIEW OF THE LITERATURE

I Classification and Epidemiology of Human Scoliosis

Clinically, scoliosis is classified into functional and structural scolioses (Lovett 1891, Arkin 1949). The incidence of structural scoliosis is 1 to 2 per cent of the adult population (Kane & Moe 1970, Keim 1976, Nachemson 1976, Kane 1977) and it is more common in adolescent girls than in boys (Shands & Eisberg 1955, Wynne-Davies 1968) and also more common among white than black (Shands & Eisberg 1955).

Scoliosis was previously classified on the basis of etiology and pathogenesis, into myopathic, osteopathic, neuropathic and idiopathic forms (Cobb 1948). In the classification recommended by the Terminology Committee of the Scoliosis Research Society in 1966 scoliosis is separated into idiopathic, neuromuscular and congenital scoliosis (Goldstein & Waugh 1973, Waugh & Riseborough 1977). The group idiopathic scoliosis comprises 80 to 85 per cent of all cases of scoliosis (Osmond-Clarke 1950, Wynne-Davies 1968, Kane & Moe 1970, Keim 1976, Nachemson 1976). According to age of recognition in years idiopathic scoliosis is divided into infantile (under 4 years), juvenile (from 4 years to the beginning of puberty), and adolescent forms (beginning from puberty) (Wynne-Davies 1968, James 1970b). The adolescent type is the most common.

II Etiology of Idiopathic Scoliosis

Scoliosis with no known cause is referred to as idiopathic.

Many hypotheses have been published concerning the etiology and the pathogenesis of idiopathic scoliosis. The main theories have been:

— The primary skeletal hypothesis according to which the growth disturbance is in the epiphyseal plates of the vertebrae, in the neurocentral epiphysis or in the nucleus pulposus (Haas 1939, Bisgard & Musselman 1940, Arkin & Simon 1950, Nachlas & Borden 1950, Somerville 1952, Farkas 1954, Ponseti & Shepard 1954, Arkin & Katz 1956, Roaf 1958, Stillwell 1962, Ottander 1963, Karaharju 1967, James 1970b, Willner 1972).

— The neuromuscular hypothesis where the cause of scoliosis is supposed to be the muscular imbalance of different reasons (Arkin 1949,

Risser 1957, Gruca 1958, Roaf 1958, Liszka 1961, Langenskiöld & Michelsson 1961 and 1962, Lindahl & Reader 1962, Zuck 1962, Michelsson 1965, Bouillet & Vincent 1967, Badger 1969, Butterworth & James 1969, Yamada et al., 1969 and 1971, James 1970b, Langenskiöld 1971, Hirano 1972, Schultz et al. 1972, Keim 1976).

— The metabolic hypothesis according to which scoliotic growth is supposed to be due to different disturbances in protein metabolism (Ponseti & Baird 1952, Ponseti & Shepard 1954, Stearns et al. 1955, Ponseti 1957, 1959 and 1968, Schönenberger et al. 1961, Benson 1965, Kyselka 1965, Smith 1968, Zorab 1968, Badger 1969, Zorab et al. 1971, Hoppenfeldt & Spiro 1973, Nordwall 1973, Bradford et al. 1977).

— The heredity hypothesis where the inheritance is supposed to be dominant and sex-linked but with an incomplete penetrance (Wynne-Davies 1968, Mac Ewen & Cowell 1970, James 1970a, Cowell et al. 1972, Keim 1976).

Good reviews of the modern concepts of the etiology of idiopathic scoliosis have been presented by Harrington (1977), by Waugh and Riseborough (1977) and by Moe et al. (1978). Waugh and Riseborough write: »Many theories of pathogenesis exist, but the mechanism of production of the spinal curvature remains unclear».

III Experimental Methods to Provoke Scoliosis

A great number of methods to provoke experimental scoliosis have been presented in the literature. Most of them are operative and the general principle in all of them is either to disturb the longitudinal growth of the vertebrae unilaterally (Frey 1922, Engel & Richer 1939, Haas 1939, Arkin & Simon 1950, Nachlas & Borden 1950, Somerville 1952, Moser 1957, Ottander 1963, Badger 1969) or to cause muscular imbalance in the vicinity of the spine (Plageman 1926, Pusch 1926, Schwartzmann & Miles 1945, Miles 1947).

Scoliosis was provoked in rabbits and pigs by unilateral resection of the posterior parts of the ribs (Langenskiöld & Michelsson 1961, Michelsson 1965, Karaharju 1967, Snellman 1973). In monkeys scoliosis was similarly provoked after resection of two ribs (Plageman 1926).

The division of intercostal nerves provoked scoliosis, the convexity developing on the side of the severed nerves (Bisgard 1935, Miles 1947, Langenskiöld & Michelsson 1961, Liszka 1961).

Langenskiöld and Michelsson (1962) provoked scoliosis in rabbits by several different operations, all of which were directed to the proximity of the spine. Unilateral resection of several costotransverse ligaments caused scoliosis in some experiments but the effect of this procedure was often prevented by scar formation. They also showed that previously produced scoliotic spines in rabbits and pigs can be made to correct by

section of the costotransverse ligaments and parts of the intercostal muscles on the concave side.

In 1902 Wullstein published a non-invasive method to provoke scoliosis. He immobilized dogs of 7 to 13 months in a scoliotic or kyphotic position for several months using strips of leather and succeeded in provoking scoliosis in two dogs and kyphosis in two others. The scoliosis thus provoked was slight, the whole spine forming a mild curve wherein no primary or secondary curve could be distinguished. The dogs were killed immediately after the immobilization period so that the possibility of later progression or regression remained unknown. Wullstein in a post-mortem analysis described the muscles on the concave side of the experimentally produced scoliotic spine as being shortened and hypertrophic. Subsequently Bööm tried to repeat Wullstein's experiments but did not succeed in provoking scoliosis (Müller 1928).

Müller (1926, 1928) was able to provoke scoliosis in rats involving the entire spine, by maintaining them in a scoliotic position with the help of their tails, for several weeks.

In a related experiment Matsuoka (1904) provoked kyphosis in rabbits' tails, which are normally lordotic, by binding the tip of the tail ventrally at its base. Two weeks' immobilization was enough to provoke kyphosis.

In 1969 Bobechko demonstrated that experimental scoliosis can be provoked by electrical stimulation of the paraspinal muscles (quoted by Keim 1976).

IV Normal and Scoliotic Growth of the Vertebra

The spinal column of animals as well as the human spine has embryologically a mesenchymal origin (Keim 1976). The vertebral body of the rabbit and that of other quadrupeds grows in length by means of the plates of epiphyseal cartilage on the cranial and caudal surfaces (Bisgard 1935, Haas 1939, Bisgard-Musselman 1940). The rate of growth is about the same both in the cranial and in the caudal epiphyseal plate (Bisgard 1935, Moser 1957). Both the body and the lamina of the vertebra grow in width by apposition of bone from the periosteum. The vertebral body and the arch are joined together by the so-called neurocentral epiphysis in which growth occurs towards both the body and the arch (Pacher 1939, Knutsson 1961 and 1966). The physiological loading between the vertebral bodies caused by the muscles and the ligaments stimulates the growth in length of the epiphyseal plates of the vertebral body (Pusch 1926, Nachlas & Borden 1950, Arkin & Katz 1956). The effect of the distraction is less than the effect of the compression (Smith 1962, Stilwell 1962).

The pathological changes of the growth of the vertebrae in experimental scoliosis provoked by different operations have been extensively

studied by Langenskiöld and Michelsson (1972), Michelsson (1965) and Karaharju (1967). These authors showed that when progressive scoliosis occurred in their experiments all processes of growth in the vertebra were affected. The growth in length of the vertebral body was diminished on the concave side of the scoliotic curve. The growth in the neurocentral junction on the convex side slowed down and this junction closed before that on the concave side. The process of apposition and resorption at the surface of the vertebra changed and increased apposition on the concave side, and increased resorption on the convex side was shown to counteract progression of the scoliotic curve.

V »Myostatic Contracture»

In 1886 Moll demonstrated that immobilization of a skeletal muscle for a long time caused shortening of that muscle. If the immobilization period was short enough, the contracture could be corrected by either active or passive mobilization. A longer immobilization period, however, caused an irreversible contracture. In 1920 Fröhlich and Mayer demonstrated that this phenomenon was observed only if the innervation of the muscle was intact, and that the development of the contracture could be prevented by resecting the corresponding dorsal nerve roots. They also showed that an established contracture cannot be overcome by either deep anaesthesia or resection of the motor nerve. They also provoked similar contractures by cutting the tendon of a muscle. Ranson and Sams (1928) divided muscular contractures into hypertonic and myostatic types and found no histological changes in the myostatic contracture. In these contractures both the whole muscle and the single muscular fibres were shortened, and the weight of the muscle had decreased. By kymography, the contractility of the muscle was proved to have decreased. Davenport et al. (1929) studied the histology of the myostatic contracture in the gastrocnemius and soleus muscles of the rat. They found that the amount of connective tissue does not increase and only slight changes occur in the muscular fibres during the development of the contracture. Histologically striations become indistinct, their orderly arrangement is lost, and in a small number of muscular fibres some degeneration takes place. Davenport and Ranson (1930) defined a myostatic contracture as a situation where the muscle is permanently shortened. This may be caused by immobilizing a normally innervated muscle for a long time in a position shorter than its normal rest position.

By immobilizing the legs of a rabbit Thompson (1934) found a decrease in the weight of the muscles and histologically a decrease in the number of muscular fibres and an increase in fibrosis. When Summers and Hines (1951) immobilized the soleus and gastrocnemius muscles of a cat in a

lengthened, normal, or shortened position, they noted that muscular atrophy developed in each position but immobilization in a shortened position caused the severest atrophy. Experiments in guinea pigs carried out by Ralston et al. (1952) showed a 5 to 28 per cent decrease in the weight of the muscles when immobilized in a shortened position. His results of the immobilization in a lengthened position were contradictory showing either decrease or increase in the weight of the muscles. Ferguson et al. (1957) found that in adult rabbits the gastrocnemius and the tibialis anterior muscles reacted dissimilarly in spite of the immobilization position. The tibialis anterior muscle seemed to develop hypertrophy when immobilized in a shortened position whereas atrophy seemed to be the prevailing change in the gastrocnemius. They also found an increase in sarcolemma in atrophied muscles while other histological changes were few. By using a mathematical model Knowlton and Hines (1936) proposed that the susceptibility to the myostatic contracture increases with the increase in the growth rate of the animal.

Eccles (1944) proved that muscular atrophy caused by tenotomy could be partially prevented if the muscles were stimulated electrically. This effect, however, was less significant if the muscle was immobilized in a shortened position.

The electromyographic results obtained by Eisenhauer and Key (1945) showed up to a 90-per-cent decrease in the contractile power of a cat's muscle if the muscle was immobilized in a shortened position for 6 to 8 weeks. This loss of power was partially regained during the follow-up of a month. However, their results were inconsistent.

Ritsilä (1969) provoked foot deformities in new-born rabbits by different methods of immobilization and found changes resembling myostatic contracture in the medial muscles of the leg.

According to Davenport and Ranson (1930) myostatic contracture is »a condition of permanent shortening in a resting muscle which is maintained in the entire absence of nerve impulses, the muscle having acquired, usually as a result of prolonged immobility, a new and shorter resting length». It was found by Alder et al. (1958, 1959) that the contracture following immobilization in a shortened state of muscles in a growing animal is even more marked than in adults because of inhibited muscle growth. Crawford (1972, 1973) concluded that everything that restricts the movements of muscles, even allowing partial movements, inhibits the longitudinal growth of a muscle.

Myostatic contracture can easily be provoked experimentally and can be macroscopically defined. However, definite microscopic or chemical changes in a muscle permanently shortened after immobilization in a shortened state have not been found. Ferguson et al. wrote in 1957: »Disagreement as to the presence or absence of histological changes runs throughout the literature on disuse atrophy and myostatic contracture».

MATERIAL AND METHODS

I Experimental Animals

The present study is based on experiments conducted on 473 growing rabbits. Fifty-three rabbits were used in planning the immobilization techniques, 20 rabbits served as a normal control group, and 147 rabbits died during the immobilization period. The material thus consists of 253 rabbits, grouped according to the age of the animal at the beginning of immobilization and the period of immobilization (Fig. 1). The age at the beginning of immobilization was 2 weeks in 94 rabbits, 3 weeks in 101 rabbits, and 5 weeks in 58 rabbits. Later in the study these groups are referred to as 2/2, 2/3 . . . 3/4 etc., where the first figure denotes the age of the animal in weeks at the beginning of immobilization and the second figure the immobilization period in weeks.

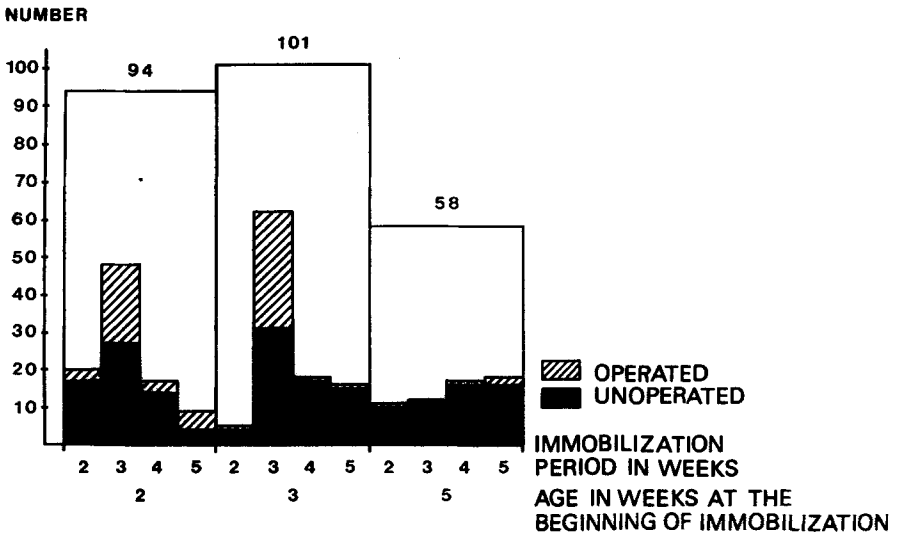


Fig. 1. Diagram showing the material of 253 rabbits divided into groups according to the age at the beginning of immobilization and the length of the period of immobilization.

II Technique

A. Immobilization technique

The animals were immobilized in a scoliotic position by using a three-point plaster-of-Paris corset padded with a thin layer of foam rubber as shown in Fig. 2. The corset was applied around the thoracic cage and molded manually to form a thoracic scoliosis with the concavity on the right side. A plaster shoulder strap was applied in order to prevent the cast from slipping.

The immobilization period ranged from 2 to 5 weeks as shown in Fig. 1. The plaster cast was changed weekly to allow the unhindered growth of the animal without changing the scoliosis.

B. Operative technique

Section of soft tissue structures was performed on 70 scoliotic experimental animals chosen at random. The scoliosis was radiologically veri-

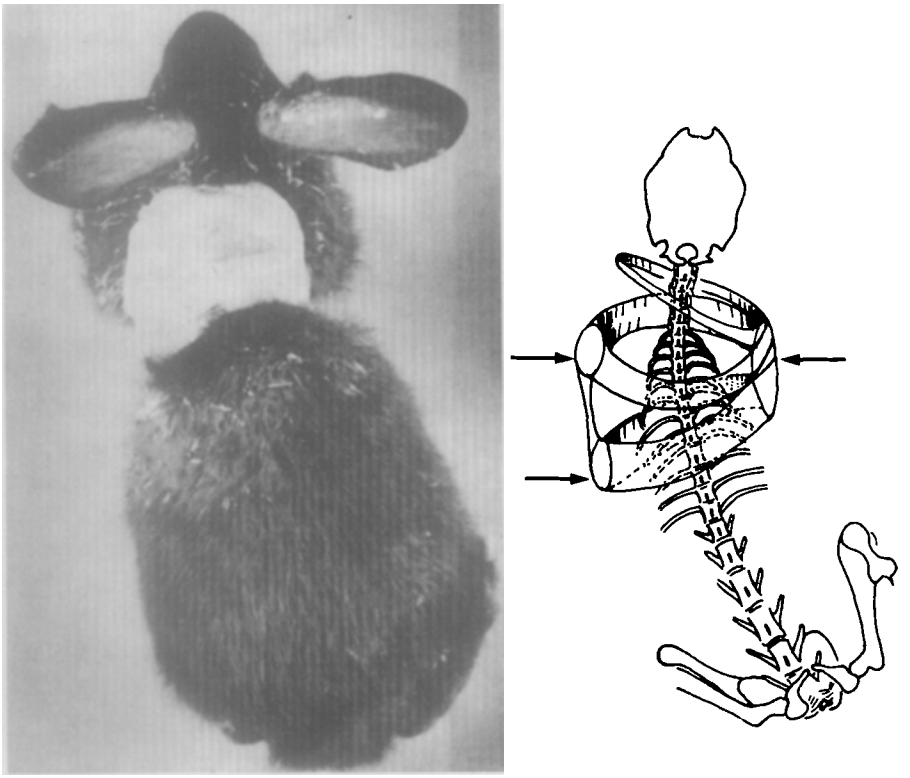


Fig. 2. Method of immobilizing the thoracic spine of a rabbit in a scoliotic position using a three-point plaster-of-Paris cast.

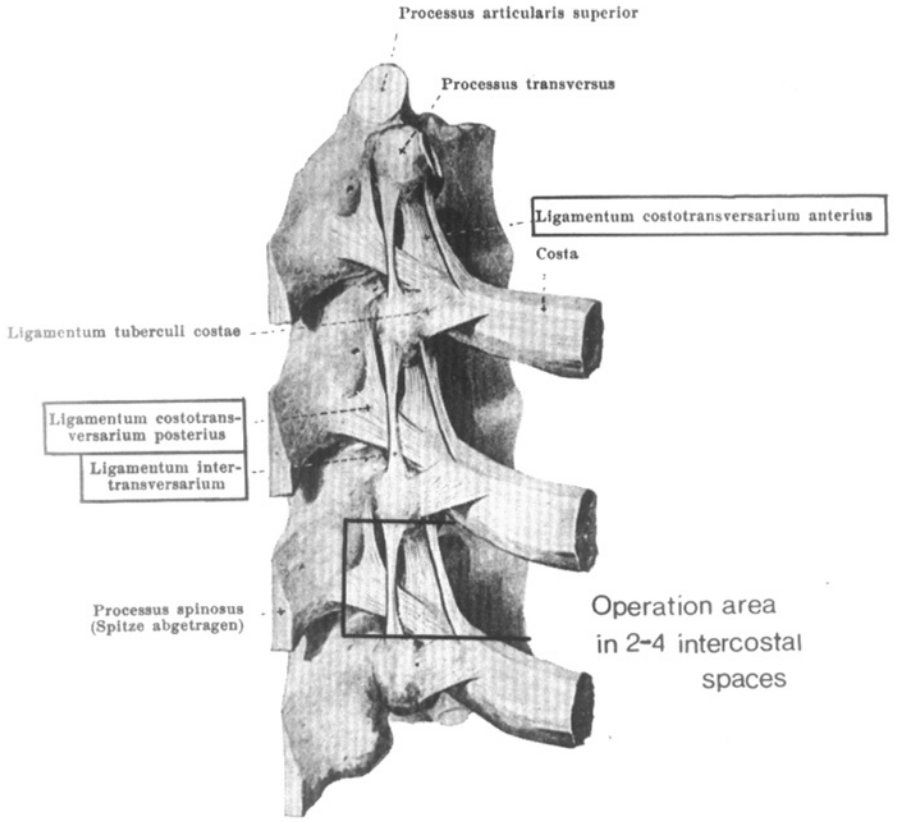


Fig. 3. Ligaments connecting the ribs and the spine in man (from Spalteholz). In animal experiments the corresponding intertransverse and anterior and posterior costotransverse ligaments and the dorsal parts of the intercostal muscles were removed from 2—4 intercostal spaces on the concave side.

fied a week before operation. The operation was performed using the same method as Langenskiöld and Michelsson (1962). The operation was always performed on the primary curve. The operative area was localized by x-ray. The operation was performed under local anaesthesia (0.25 per cent Xylocain-Exadrin®, Astra).

The spine was exposed through a dorsal midline skin incision, by releasing the muscles from the spinous processes and the laminae on the concave side. Following the exposure a 1.5 cm broad dorsal part of the intercostal muscles and the corresponding costotransverse ligaments were removed at 2—4 levels (Fig. 3). To prevent scar tissue formation and regeneration of the muscle the intercostal spaces were filled with free fat tissue transplants taken from the interscapular space of the rabbit (Lexer 1919, Langenskiöld & Michelsson 1960, Österman 1972, Kiviluoto 1976, Langenskiöld & Kiviluoto 1976). Sulphonamide powder was used

locally and no systemic antibiotics were used. The wound was closed in layers with continuous catgut sutures.

Two rabbits died on the day of the operation, 3 on the first postoperative day, and 2 more rabbits died during the first postoperative week.

C. Radiological technique and measurements

The development and course of scoliosis were followed roentgenologically. X-ray pictures were taken in the anteroposterior projection with the animal in a supine position and in the lateral projection with the rabbit lying on its left side. During the exposure the rabbit was placed under light traction. Radiographs in the antero-posterior and lateral projections were taken at the end of the immobilization period, immediately before operation, and after killing the animals. In addition, AP x-rays were taken at weekly intervals during the first month following immobilization or operation, and subsequently at monthly intervals. No x-ray pictures were taken during the immobilization period because the plaster precluded adequate radiographs. The focus distance was 90 cm and the film was Ilford Ilflex for the non-screen technique.

The magnitude of the scoliosis was measured with Cobb's (1948) method. In the cases where radiographs were taken in the antero-posterior and lateral projections the measurements were performed also by using the Edholm (1967) measuring disc as suggested by Lindahl & Movin (1968). This method did not, however, give any additional information when compared to the Cobb method. Because two parallel methods would have complicated the statistical analysis the method was given up in spite of the fact that radiographs had been taken of the whole material. The course of the scoliosis of each experimental animal was described by a diagram (Figs. 6, 7, 8) and the scolioses were classified according to these diagrams into five classes (Table 1 page 17).

D. Statistical analysis

The age of the experimental animal, the length of the immobilization period and the measurements of scoliosis were recorded on punch cards. The data were handled according to normal statistical methods in automatic data processing at the Computing Centre of the University of Helsinki.

E. Section of specimens

The spine and thoracic cage were dissected so that the muscles remained undisturbed in place. Samples for histological study were taken from 35

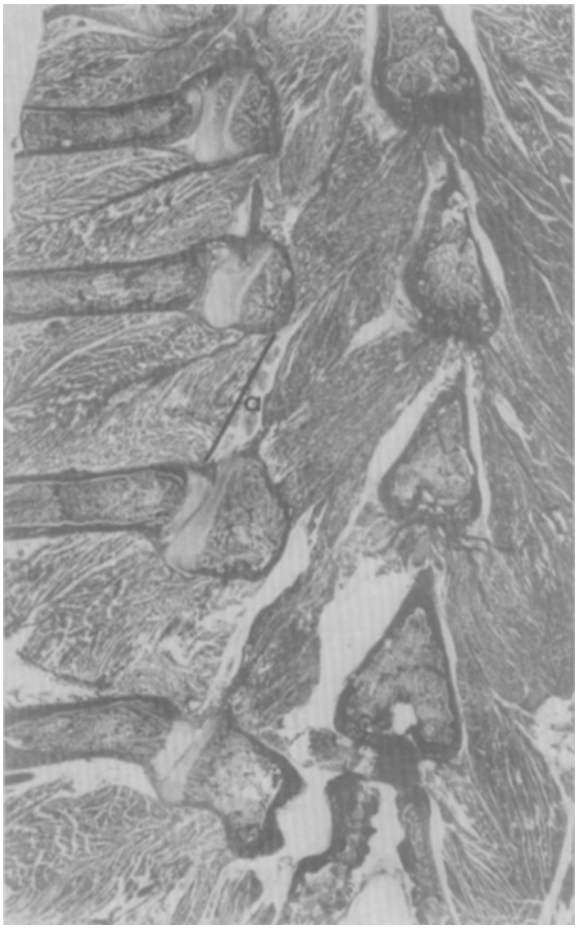


Fig. 4. Method of measuring the length of intercostal muscles on the concave side of the scoliotic curve using an ocular micrometer. a = the length of the dorsal part of the intercostal muscle (Rabbit No. 362).

unoperated and 19 operated animals and from 7 normal controls. The sample consisted of the area including the spinal curve and the dorsal ends of the ribs, together with the muscles. The samples were fixed in neutral formalin, decalcified in 10 per cent ethylene diamine tetra-acetic acid (EDTA), embedded in paraffin wax, and sectioned in several planes in order to localize the intercostal muscles and ligaments on the concave side. The sections were stained with haematoxylin van Gieson and examined under a light microscope (up to 400 x). Attempts were made to investigate the possible presence of shortening of intercostal muscles on the concave side of the curved part of the spine. The length of the dorsal intercostal muscles of the scoliotic spines was measured using an ocular micrometer (Fig. 4).

RESULTS

I Development, Course and Classification of Scoliosis

The material consisted of 253 rabbits in which the thoracic spine was immobilized in a scoliotic position.

Fig. 5 gives a graphic representation of the material following the

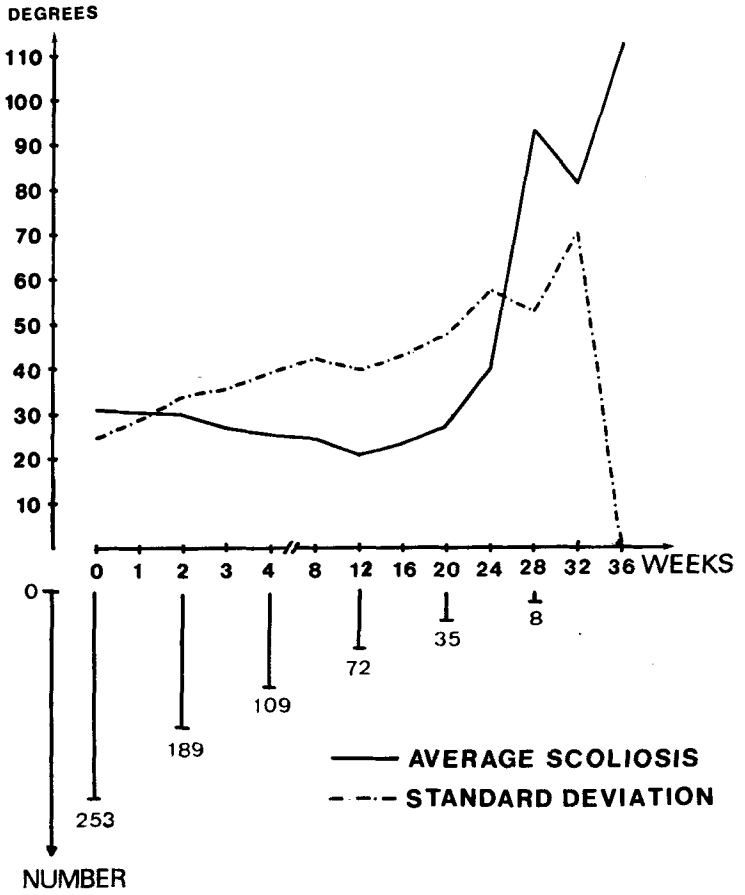


Fig. 5. Graphic representation of the total material after the immobilization period, showing the average course of scoliosis, its standard deviation, and the decrease in the number of animals. On the x-axis time in weeks after immobilization period.

Development of scoliosis	Class of scoliosis (CS)	Number of experiments	Per cent
No scoliosis	0	38	15
Resolving scoliosis	1	58	23
Constant scoliosis	2	52	20
Progressive scoliosis	3	80	32
Indistinct scoliosis	4	25	10
TOTAL		253	100

52 — 85

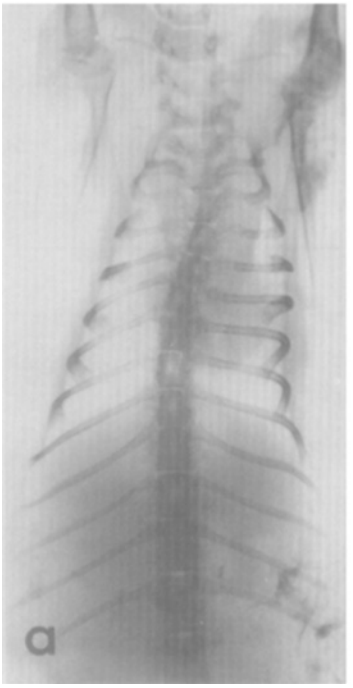
Table 1. Development of scoliosis and division of the material into different classes of scoliosis.

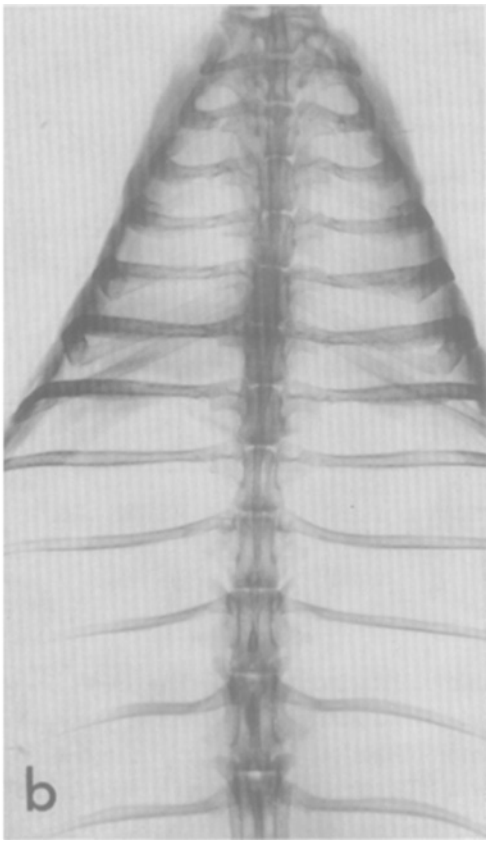
immobilization period. The cases in which no scoliosis was provoked were also included as well as the operated animals from the end of the immobilization period up to the time of operation. The average scoliosis was 30 degrees at the end of the immobilization period.

The scoliotic deformities were divided into 5 classes (CS) according to their course as shown in Table 1. Indistinct scoliosis was considered to be present when the course of scoliosis could not be evaluated, for one reason or another, e.g. early death of the animal. The average initial scoliosis in groups CS_4 was 50.5 degrees, whereas it was 48.5 degrees in groups CS_3, 36.0 degrees in CS_2 and 13.5 degrees in CS_1. Scoliosis appeared in 215 cases, i.e. 85 per cent in all. Constant or progressive scoliosis was found in 132 rabbits, i.e. in 52 per cent. In 38 animals (15 per cent) no scoliosis was seen (Table 1).

Figures 6, 7, and 8 present examples of resolving, constant and progressive scoliosis.

The data concerning the different groups of scoliosis are shown in Figs. 9—11 where the average course of scoliosis, its standard deviation, and the numerical distribution of the material are presented. It should be noted that no single diagram alone gives a complete picture of the whole group but the overall impression of the diagrams must be considered.





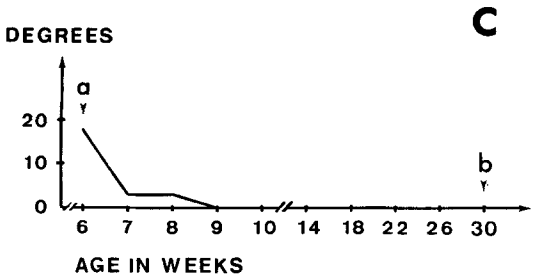


Fig. 6. Example of resolving scoliosis. Age at the beginning of immobilization 3 weeks, immobilization period 3 weeks. Radiograph (a): scoliosis of 18° at the end of immobilization period, (b): final result: no scoliosis, (c): curve showing the course of scoliotic deformity, (Rabbit No. 384).

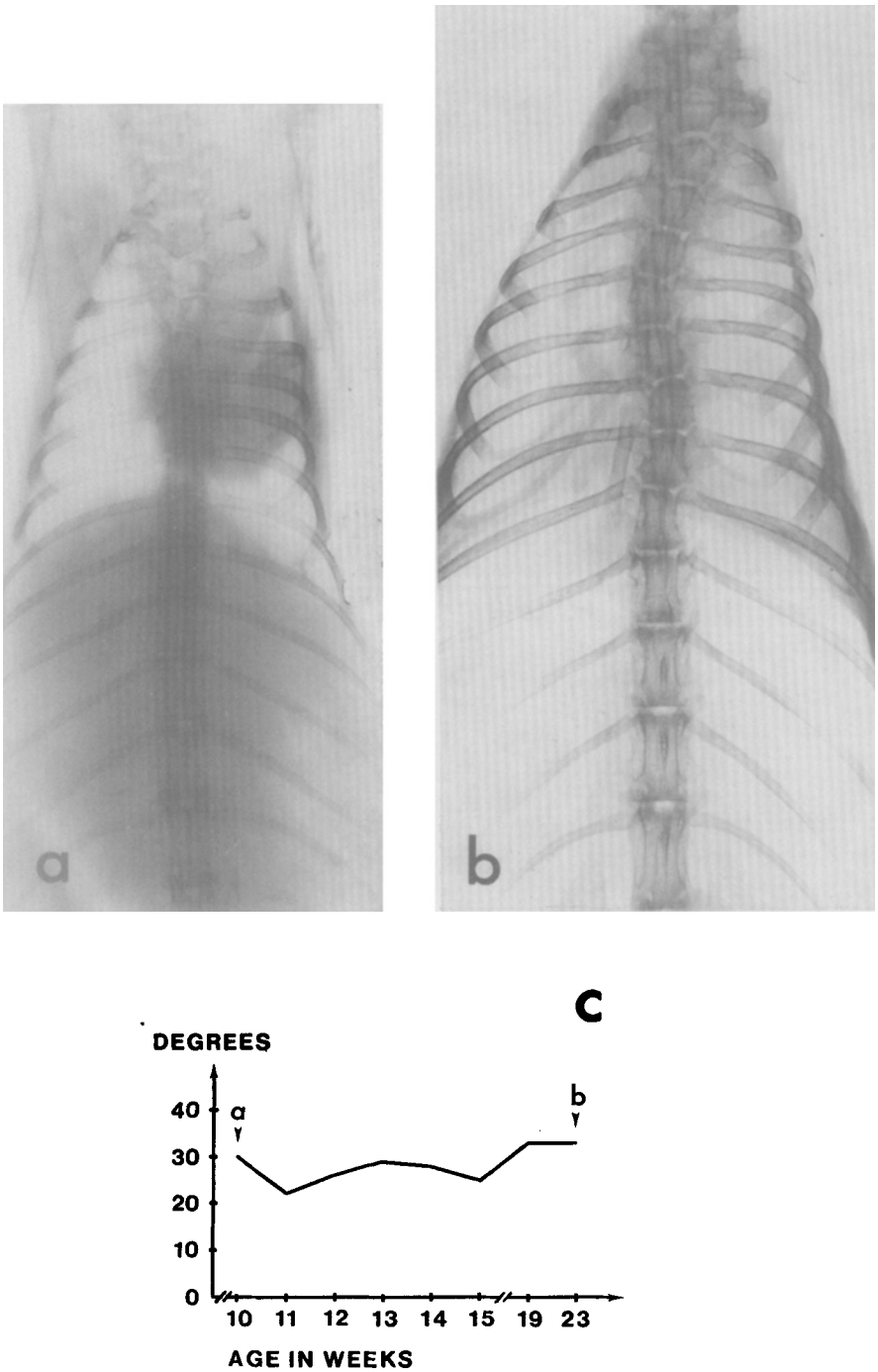
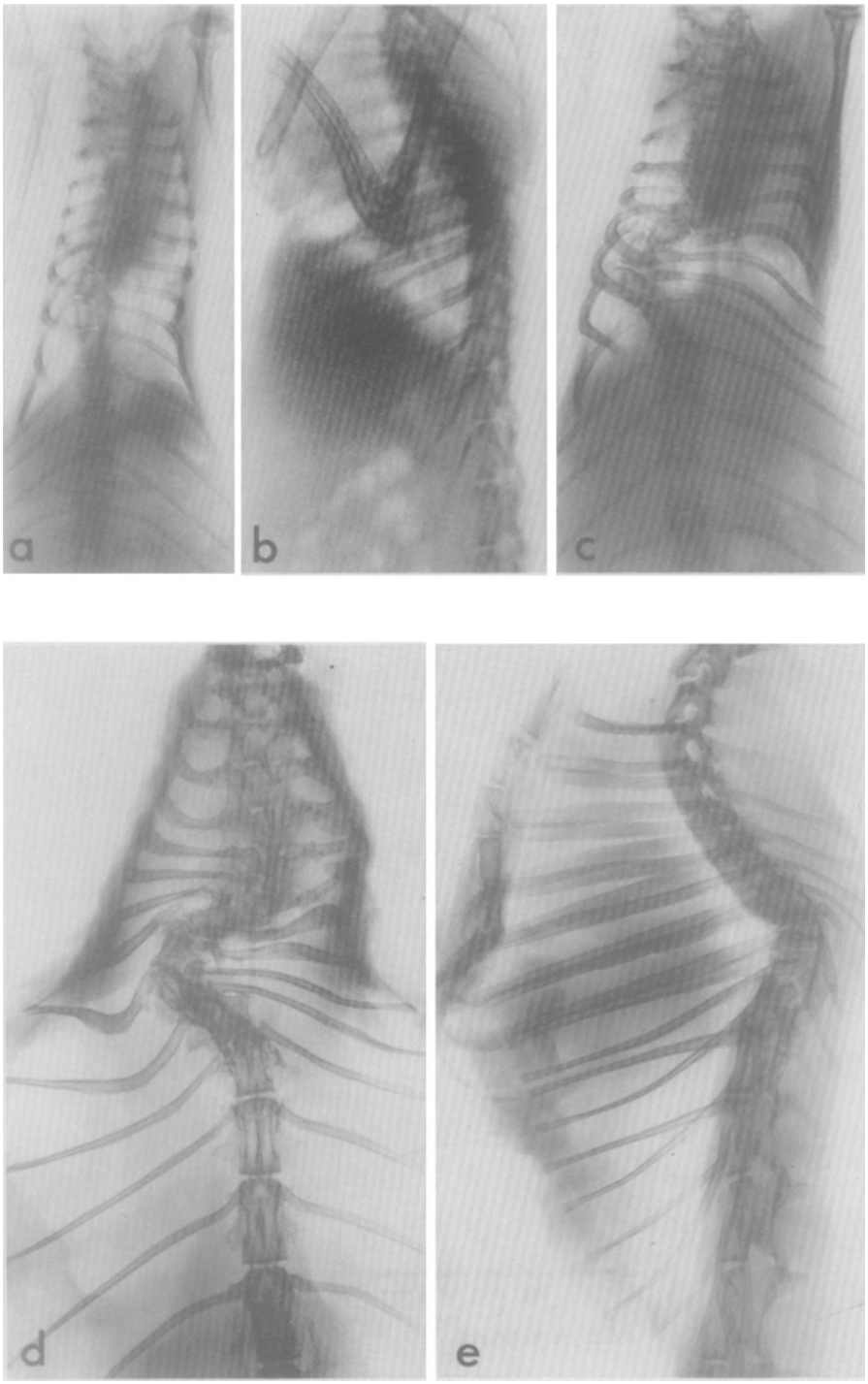


Fig. 7. Example of constant scoliosis. Age at the beginning of immobilization 5 weeks, immobilization period 5 weeks. Radiograph (a): scoliosis of 30° at the end of the immobilization period, (b): final result: scoliosis of 33°, (c): curve showing the course of scoliotic deformity, (Rabbit No. 256).


a
b
c
d
e

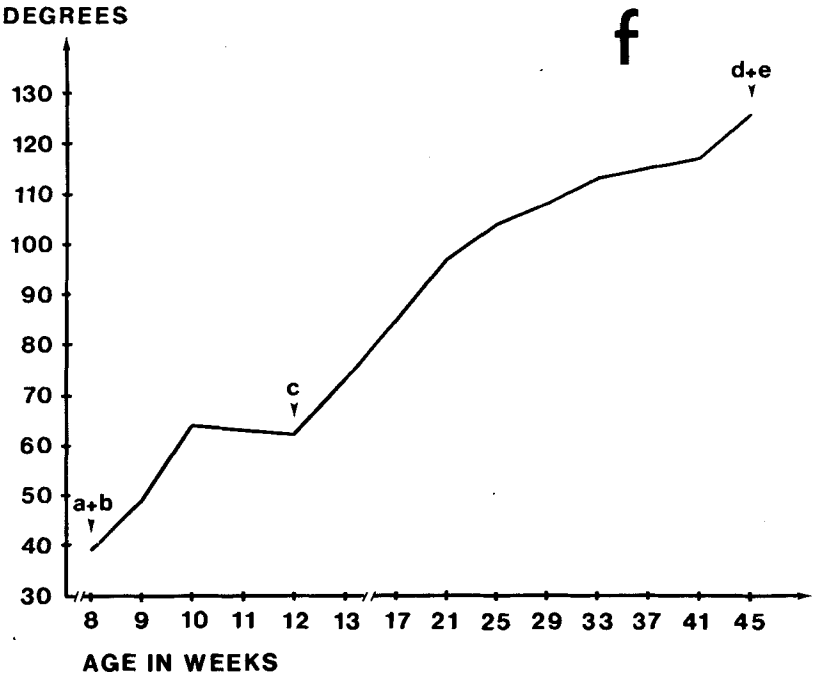


Fig. 8. Example of progressive scoliosis. Age at the beginning of immobilization 3 weeks, immobilization period 5 weeks. Radiographs (a) and (b): scoliosis of 39° at the end of the immobilization period, (c): 62° four weeks later, (d) and (e): final result 113°. Note a considerable kyphosis and pectus excavatum deformity in (e). (f): curve showing the course of scoliotic deformity, (Rabbit No. 129).

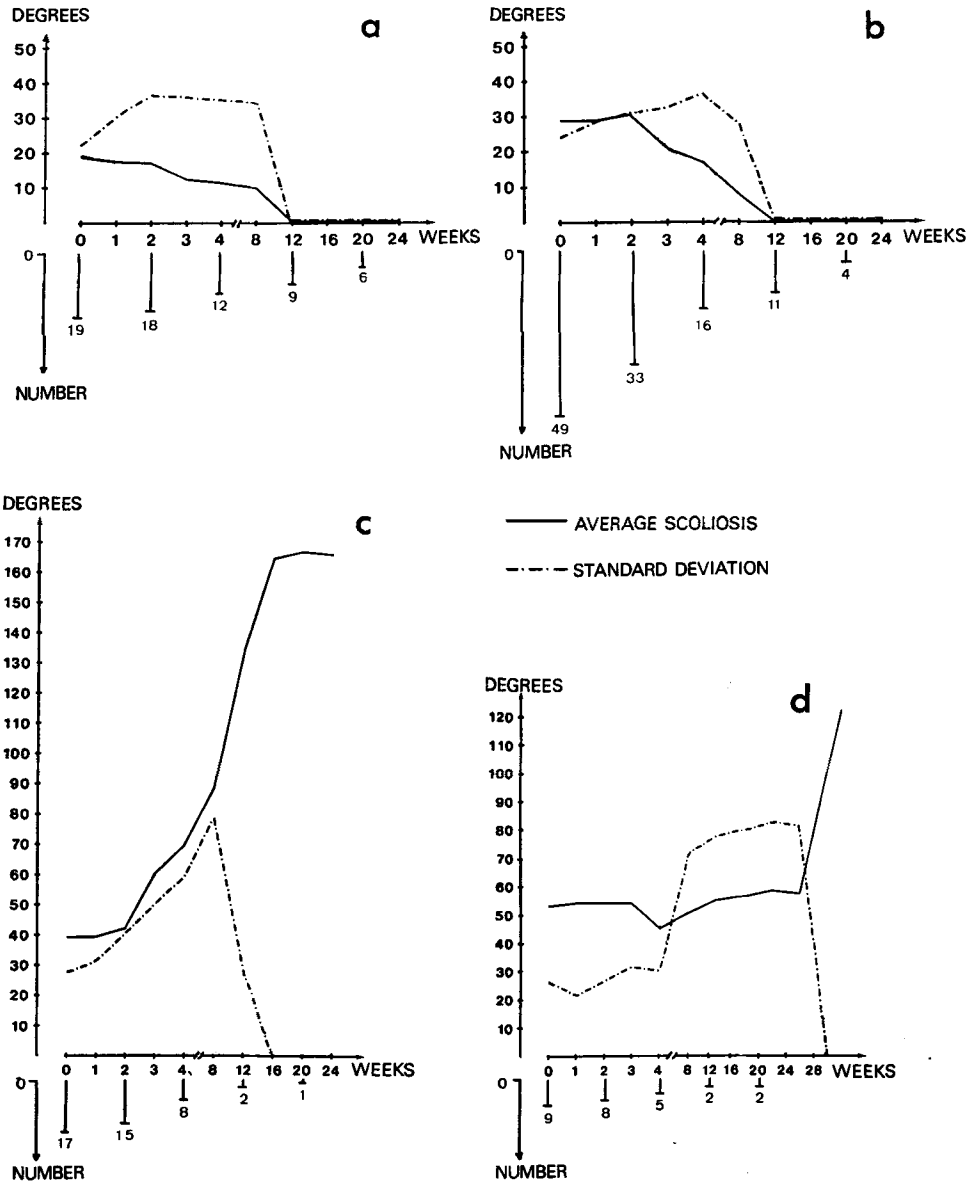


Fig. 9 a, b, c, d. Graphic representation of the course of average scoliosis after immobilization period in groups 2/2, 2/3, 2/4, 2/5 (see the text on p. 23). The X-axis shows time in weeks after immobilization period.

Group 2/2 (Fig. 9 a)
The group consisted of 19 rabbits immobilized at the age of 2 weeks for 2 weeks. The average initial scoliosis was 20 degrees, which is 10 degrees less than the average of the whole material (Fig. 5). The average scoliosis decreased slowly. The standard deviation was initially 22 degrees, thus a considerable number of the rabbits had a mild scoliosis. Scoliosis was no longer found in 40 per cent of the animals observed for 12 weeks or more.

Group 2/3 (Fig. 9 b)
The group consisted of 49 rabbits immobilized at the age of 2 weeks for 3 weeks. 21 rabbits from this group were chosen for operation. The average initial scoliosis was about 30 degrees, which is the same as that of the whole material. Up to two weeks scoliosis progressed gradually but after that decreased. Twelve weeks after immobilization 19 per cent of the group were alive with no scoliosis any longer. During the first 4 weeks the standard deviation increased but then decreased.

Group 2/4 (Fig. 9 c)
The group consisted of 17 rabbits, immobilized at the age of 2 weeks for 4 weeks. The average initial scoliosis was about 40 degrees, which is about 10 degrees higher than that of the whole material. Between 2 to 16 weeks the average scoliosis increased sharply and the standard deviation followed the course of the average scoliosis up to 8 weeks after which it decreased abruptly and decreased to the 0-axis at the time of 16 weeks.

Group 2/5 (Fig. 9 d)
The group consisted of 9 rabbits, immobilized at the age of 2 weeks for 5 weeks. 7 rabbits died during the course of 8 weeks. The average initial scoliosis was 53 degrees, remaining stable up to 8 weeks, after which a slight progression took place. After 24 weeks only one severe case remained. This group consisted of 3.5 per cent of the whole material. The number of animals in this group was too small for statistical comparison. However, the homogeneity of the group makes it comparable with other groups.

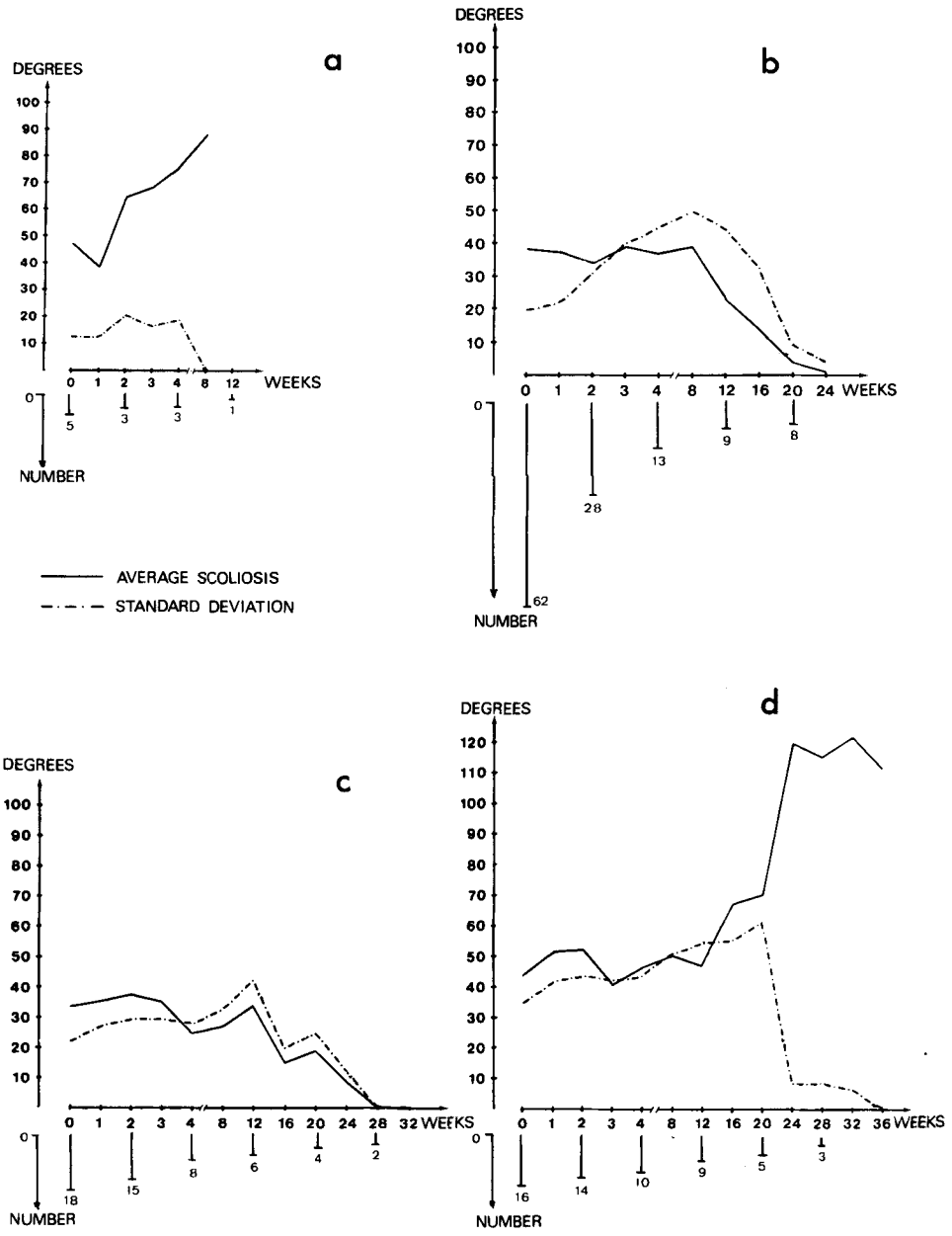


Fig. 10 a, b, c, d. Graphic representation of the course of scoliosis after immobilization period in groups 3/2, 3/3, 3/4, 3/5 (see the text on page 25). The x-axis shows time in weeks after immobilization period.

Group 3/2 (Fig. 10 a)
The group consisted of 5 rabbits, 3 rabbits after 2 weeks and only one rabbit after 8 weeks. The rabbits were immobilized at the age of 3 weeks for 2 weeks. The average initial scoliosis was 47 degrees. During the first week some straightening could be found on average scoliosis and after that a marked progression took place. The standard deviation curve is low throughout, which means that the whole group had progressive scoliosis. The number of animals in this group was too small for statistical comparison. However, the homogeneity of the group makes it comparable with other groups.

Group 3/3 (Fig. 10 b)
The group consisted of 62 rabbits immobilized at the age of 3 weeks for 3 weeks. 31 animals from this group were chosen for operation. The average initial scoliosis was 9 degrees higher than that of the total material and remained the same up to 8 weeks, after which the course of scoliosis was corrective. The standard deviation follows the average scoliosis diagram to a large extent. The increase seen in the standard deviation diagram from 3 to 8 weeks indicates that the group consisted of a considerable number of cases with progressive scoliosis.

Group 3/4 (Fig. 10 c)
The group consisted of 18 rabbits immobilized at the age of 3 weeks for 4 weeks. The average initial scoliosis was a few degrees higher than that of the total material and the average scoliosis as a whole is slightly decreased with occasional periods of progression. The standard deviation follows the average scoliosis diagram closely.

Group 3/5 (Fig. 10 d)
The group consisted of 16 rabbits immobilized at the age of 3 weeks for 5 weeks. The average initial scoliosis was about 13 degrees higher than that of the total material and the average scoliosis was clearly increasing. The standard deviation follows the average scoliosis up to 20 weeks and decreases after that to 10 degrees. Thus, at the final stage all of the cases had severe scoliosis of 110 to 120 degrees.

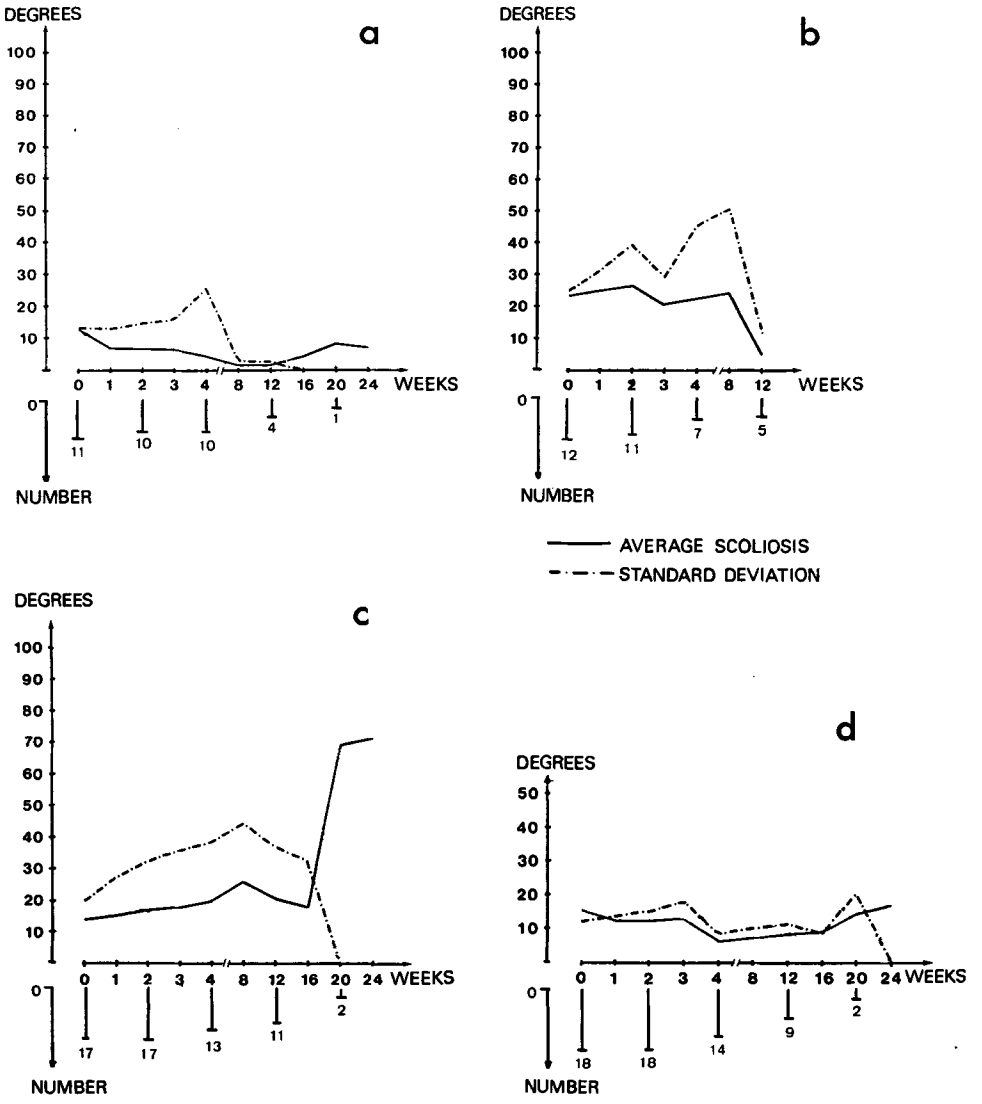


Fig. 11 a, b, c, d. Graphic representation of the course of scoliosis after immobilization period in groups 5/2, 5/3, 5/4, 5/5 (see the text on page 27). The x-axis shows time in weeks after immobilization period.

Group 5/2 (Fig. 11 a)
The group consisted of 11 rabbits immobilized at the age of 5 weeks for 2 weeks. The average initial scoliosis was one third of the corresponding value of the whole material and the average scoliosis is mildly decreasing up to 12 weeks. The standard deviation remains under 20 degrees nearly all the time and the group is homogenous.

Group 5/3 (Fig. 11 b)
The group consisted of 12 rabbits immobilized at the age of 5 weeks for 3 weeks. The average initial scoliosis was 7 degrees lower than that of the whole material remaining constant up to 8 weeks. The standard deviation follows the average scoliosis closely.

Group 5/4 (Fig. 11 c)
The group consisted of 17 rabbits immobilized at the age of 5 weeks for 4 weeks. The average scoliosis was 14 degrees and increased slightly up to 8 weeks after which it decreased slightly. At the time of 16 weeks only a few animals survived of the whole material. They had severe scoliosis.

Group 5/5 (Fig. 11 d)
The group consisted of 18 rabbits immobilized at the age of 5 weeks for 5 weeks. The average initial scoliosis was 17 degrees and remained constant throughout. The standard deviation is very small.

II Factors Influencing the Development and Course of Scoliosis

A. Effect of immobilization time and effect of age at immobilization

The effect of the immobilization time was analyzed by dividing the animals into 3 groups according to the age at the time of immobilization

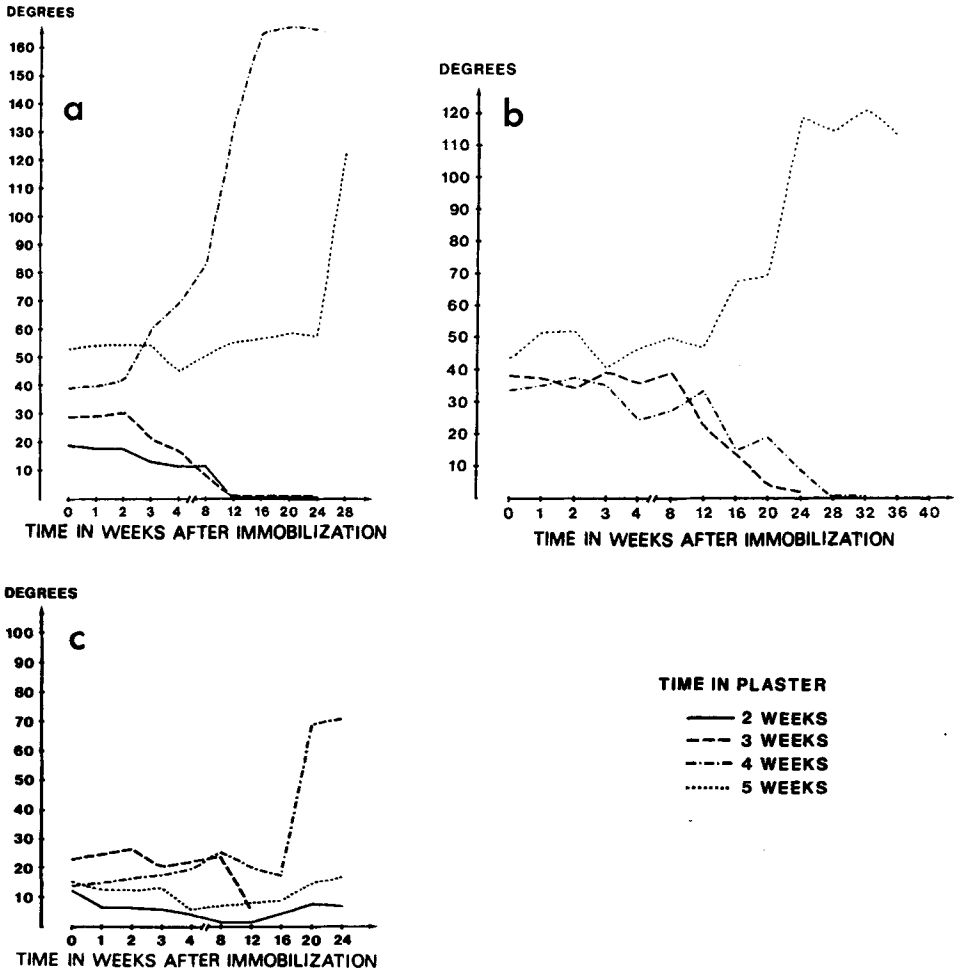


Fig. 12. Effect of immobilization time and age at immobilization on the development and course of scoliosis.
(a) In rabbits immobilized at the age of 2 weeks the initial scoliosis was severe and the progression of scoliosis increased with a longer immobilization period.
(b) In rabbits immobilized at the age of 3 weeks the effect of the immobilization period was evident but not so remarkable as in younger rabbits (a).
(c) In rabbits immobilized at the age of 5 weeks the effect of the immobilization period on the initial scoliosis and on the progression of scoliosis was considerably less than in younger age groups.

and comparing the development and course of scoliosis in each group after variably long immobilization times (Fig. 12).

Fig. 12a shows the development of scoliosis in Groups 2/2, 2/3, 2/4 and 2/5 where the age of the animal at immobilization was 2 weeks and initial scoliosis 19, 29, 39, and 53 degrees respectively. The scoliosis in the groups with immobilization times of 2 and 3 weeks (Groups 2/2 and 2/3) was clearly resolving while with an immobilization time of 4 weeks (Group 2/4) progressive scoliosis was seen and that with an immobilization time of 5 weeks (Group 2/5), constant scoliosis occurred. The unexpected course of scoliosis in the last group may be explained by the small number of cases (9 rabbits).

Fig. 12b shows the average scoliosis of Groups 3/3, 3/4, and 3/5. The initial scoliosis was between 33 and 47 degrees in every group. The groups with an immobilization time of 3 or 4 weeks (Groups 3/3, 3/4) showed a clearly correcting course, those with an immobilization time of 5 weeks (Group 3/5) a progressive course.

Fig. 12c shows the average scoliosis of Groups 5/2, 5/3, 5/4, and 5/5. The smallest initial scoliosis, 12 degrees, was found in Group 5/2, the severest, 23 degrees, in Group 5/3. The course of scoliosis within each group was considerably homogenous. In Group 5/4 the average scoliosis was progressive, while in all other groups it was resolving.

Generally, the initial scoliosis increased and the course of scoliosis became more progressive with a longer immobilization time, especially in younger animals. Thus in older animals the initial scoliosis was smaller after immobilization and the progression of scoliosis was less than in younger animals as shown in Fig. 12.

B. Effect of initial scoliosis on the course of scoliosis

In the present study initial scoliosis means the degree of scoliosis measured immediately at the end of immobilization. The effect of magnitude of the initial scoliosis on the course of scoliosis is presented in Fig. 13 where Diagrams A, B, C, and D present the average course of scoliosis and Diagrams a, b, c, and d present the corresponding standard deviation. Diagram A represents the cases where the initial scoliosis was 1 to 10 degrees, B 11 to 30 degrees, C 31 to 50 degrees, and D more than 50 degrees.

Fig. 13 shows that in Groups C and D where the initial scoliosis is more than 30 degrees, a significant progression of scoliosis occurred, whereas in Groups A and B with an initial scoliosis of less than 30 degrees, a constant or slight correction was seen.

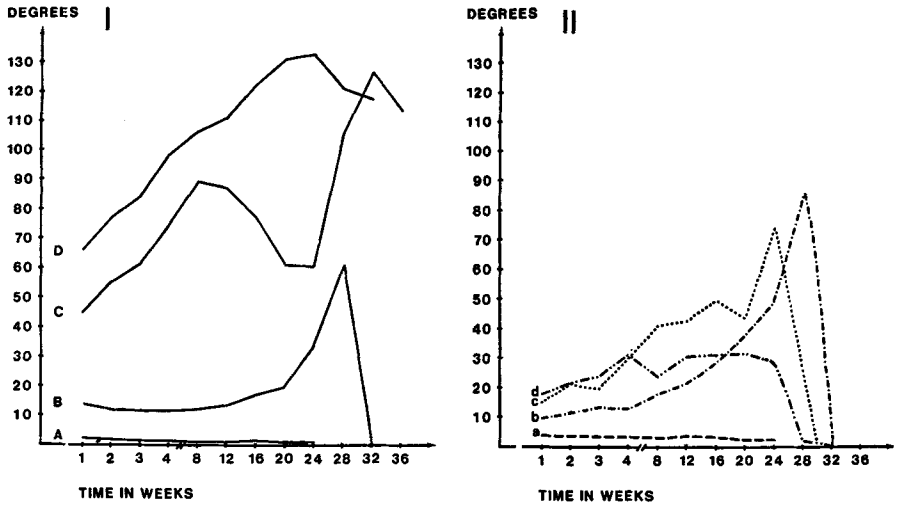


Fig. 13. Relationship of severity of initial scoliosis to the course of deformity.
I : A initial scoliosis 1°—10° (72 animals)
B » 11°—30° (62 »)
C » 31°—50° (58 »)
D » more than 50° (61 »)
II: Standard deviation of the corresponding initial scoliosis curves (a, b, c, d). The tendency to progression of scoliosis increases with a severer initial scoliosis. The critical point seems to lie between 30° and 40° of scoliosis.

III Effect of Soft Tissue Release Operation on the Course of Scoliosis and Classification of the Results

Seventy scoliotic rabbits were operated on. The operated material was divided into 5 classes (CO) according to the postoperative course of scoliosis as follows:
The operation:

— had no effect on the course of scoliosis CO_0
— slowed down the progression of scoliosis CO_1
— prevented the progression of scoliosis CO_2
— had a corrective effect on scoliosis CO_3
— had an indistinct effect on scoliosis CO_4

Table 2 shows the postoperative course of scoliosis in different classes of scoliosis. No operations were performed in Class CS_0 and only 3 animals belonged to CS_1 whereas of the unoperated animals 51 per cent belonged to these classes of scoliosis. In 19 cases the operation was performed on a constant and in 47 cases on a progressive scoliosis. These classes consisted of 94 per cent of the operated material, whereas of the non-operated material only 36 per cent (66 animals) belonged to these 2 classes.

Postoperative course of scoliosis (CO)		Number of experiments	Class of scoliosis (CS)					Total	Per cent
			0	1	2	3	4		
			Number of experiments						
	0				4	12		16	23
	1					8		8	11
	2					21		21	30
	3			3	9	2		14	20
	4				6	4	1	11	16
Total				3	19	47	1	70	
Per cent				5	27	67	1		100

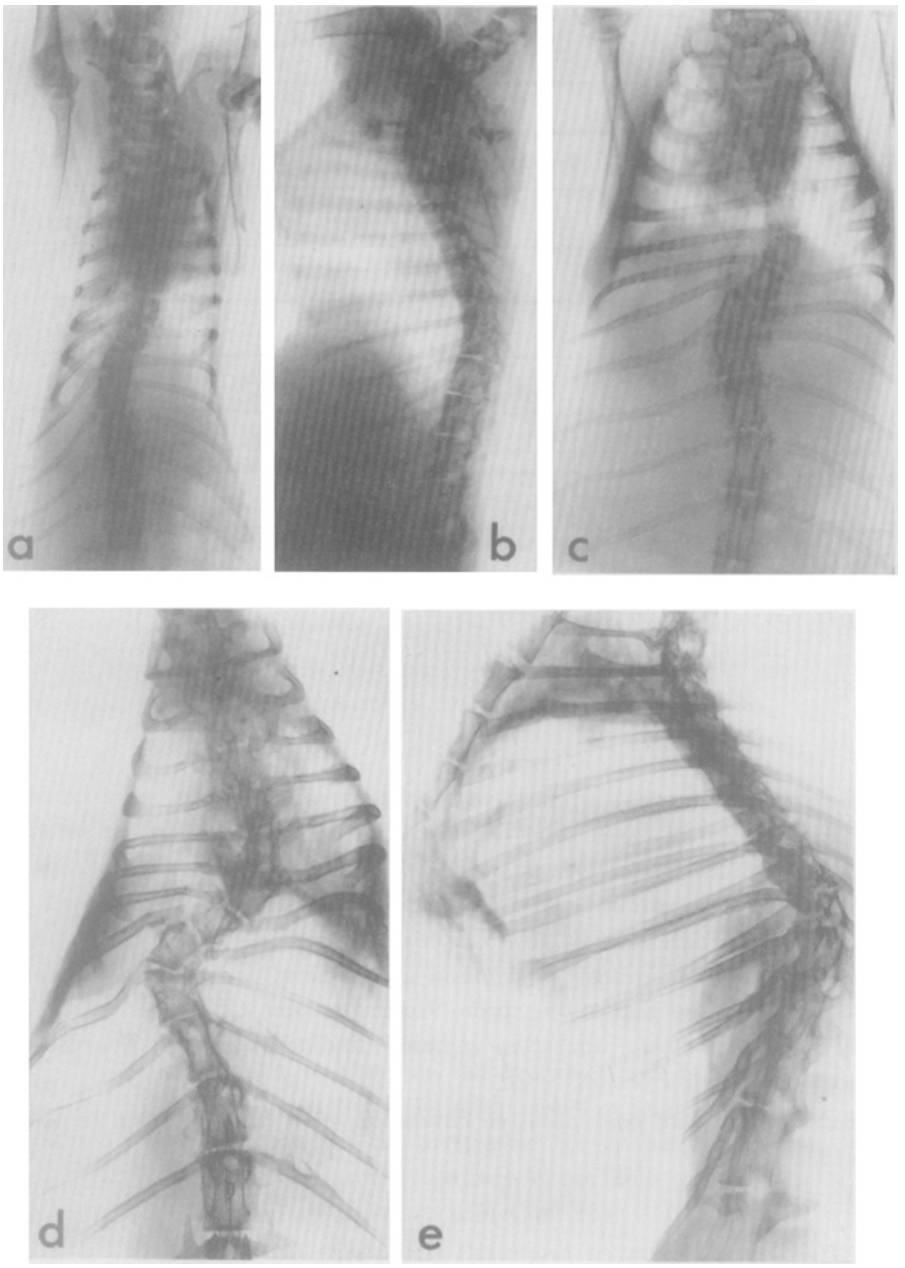
Table 2. Distribution of operated experimental animals according to preoperative class of scoliosis and postoperative course of scoliosis. (Class of scoliosis see Table 1 on page 17 and postoperative course of scoliosis see the text on page 30).

This demonstrates that animals with more severe scoliosis were chosen for surgery. In 16 cases the operation had no corrective effect on the course of scoliosis. Twelve of these were progressive before operation. In 8 cases the operation slowed down the progression of scoliosis and in 21 cases the progression of scoliosis ceased after operation. In 14 cases a straightening of scoliosis was found after operation. Of these cases 3 were straightening before operation, 9 constant and 2 progressive. In 11 cases the effect of the operation remained indistinct usually because of a short observation period.

Examples of the postoperative course of scoliosis are shown in Figs. 14—16.

A. Effect of operation on progressive scoliosis

Of the operated animals 47 (67 per cent) had progressive scoliosis (Table 2). Because of the importance of this group, the effect of the operation in it is considered in Fig. 17. Diagram B represents the average course of scoliosis in Class CS_3 (47 animals) after operation. Diagram A represents the average course of progressive scoliosis of the unoperated cases (80 animals). The real starting point of Diagram A and B is not the same be-


a
b
c
d
e

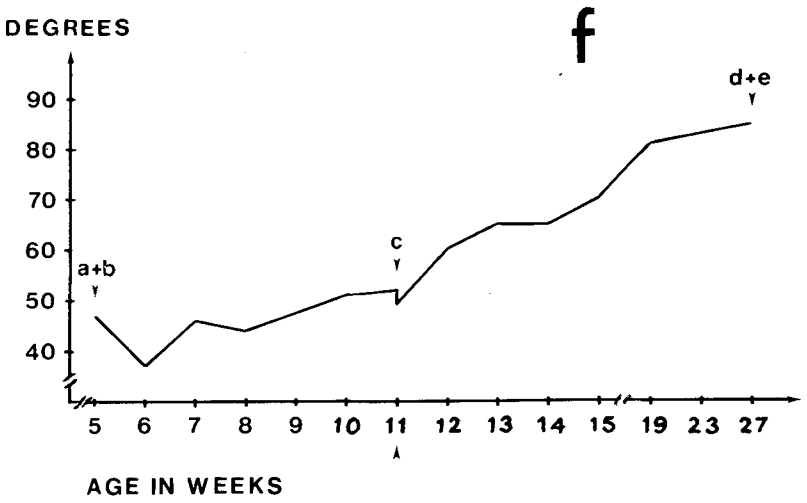
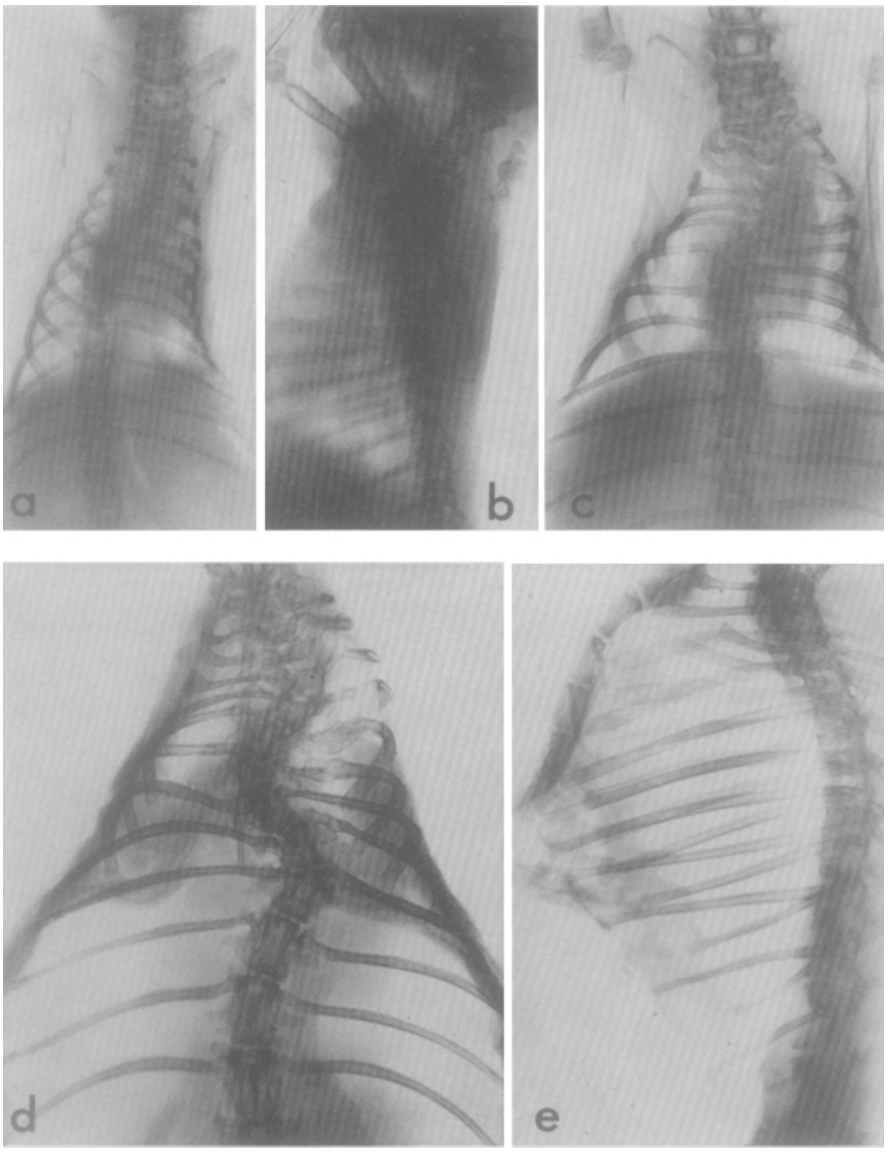


Fig. 14. Example of progressive scoliosis where the operation had no effect on the course of progression (CO_0). Age at the beginning of immobilization 2 weeks, immobilization period 3 weeks. Initial scoliosis (a + b) 47°, operation (indicated by an arrow on the x-axis) 6 weeks later on the right intercostal spaces 5—8 when the scoliosis was 52° (c). Final scoliosis 87° (d + e). (f) Curve showing the course of the scoliotic deformity. (Rabbit No. 176).


a
b
c
d
e

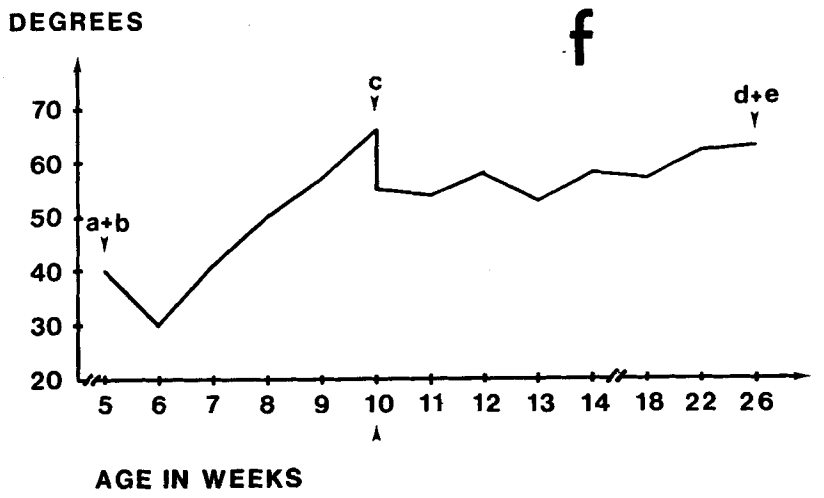
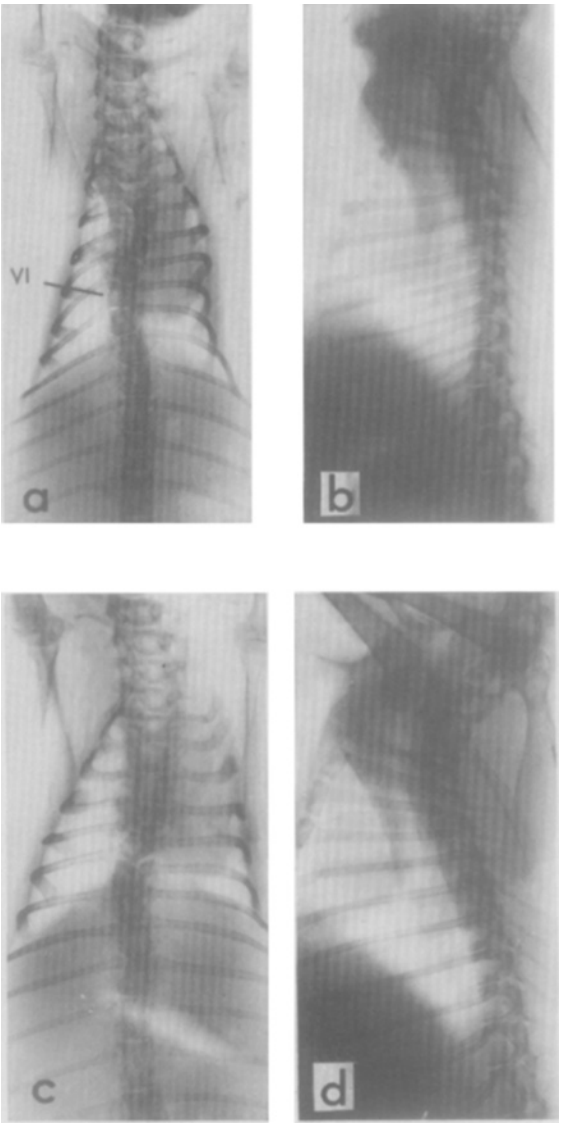


Fig. 15. Example of progressive scoliosis where the operation slowed down the progression of scoliosis (CO_2). Age at the beginning of immobilization 2 weeks, immobilization period 3 weeks. Initial scoliosis 40° (a + b), operation (indicated by an arrow on the x-axis) 5 weeks later on the left intercostal spaces 4—7 when the scoliosis was 66° (c). Final scoliosis 63° (d + e). (f) Curve showing the course of scoliotic deformity. Note the immediate correction of scoliosis following surgery. (Rabbit No. 312).


VI
a
b
c
d

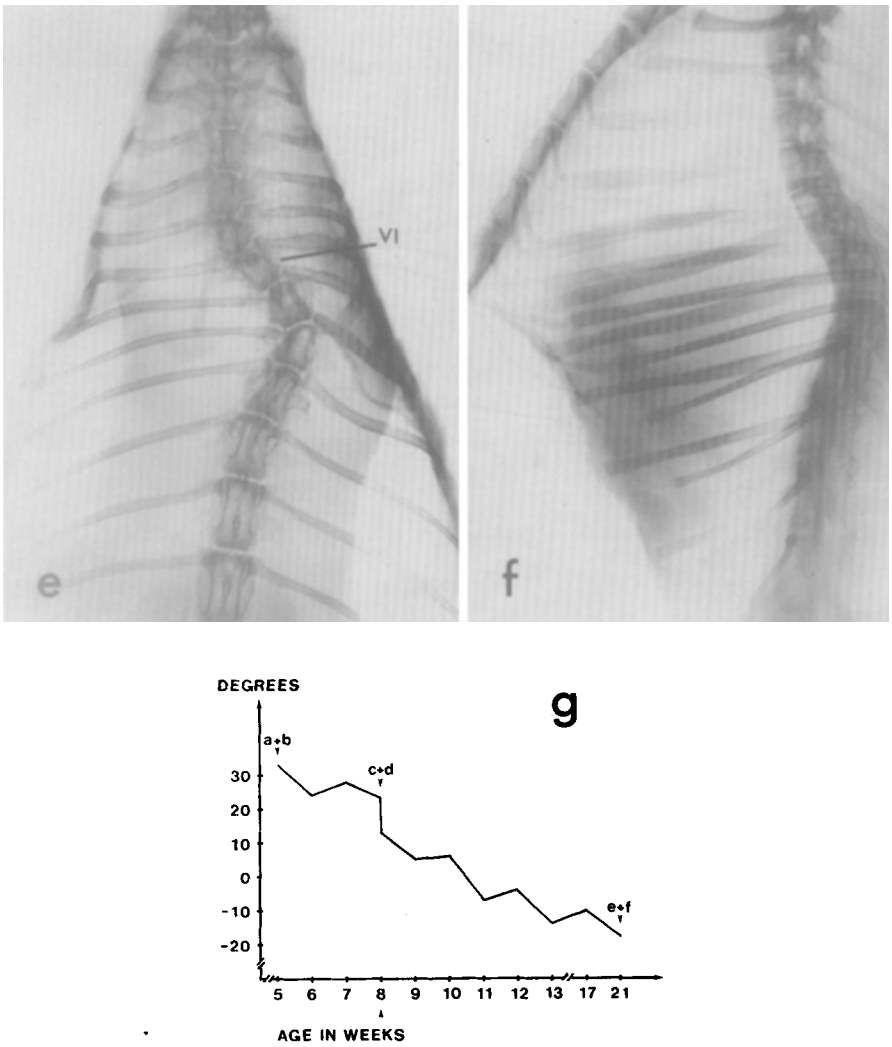


Fig. 16. Example of overcorrection of scoliosis after operation (CO_3). Age at the beginning of immobilization 2 weeks, immobilization period 3 weeks. Initial scoliosis convex to the right 33° (a + b), operation (indicated by an arrow on the x-axis) 3 weeks later on the left intercostal spaces 5—7 when the scoliosis was 23° (c + d). Final scoliosis convex to the left 18° (e + f) when measured from the V—VII thoracic vertebrae as in (a) and (c) but 53° when measured from the thoracic vertebrae VI—IX. (g) Curve showing the course of scoliotic deformity. (Rabbit No. 444).

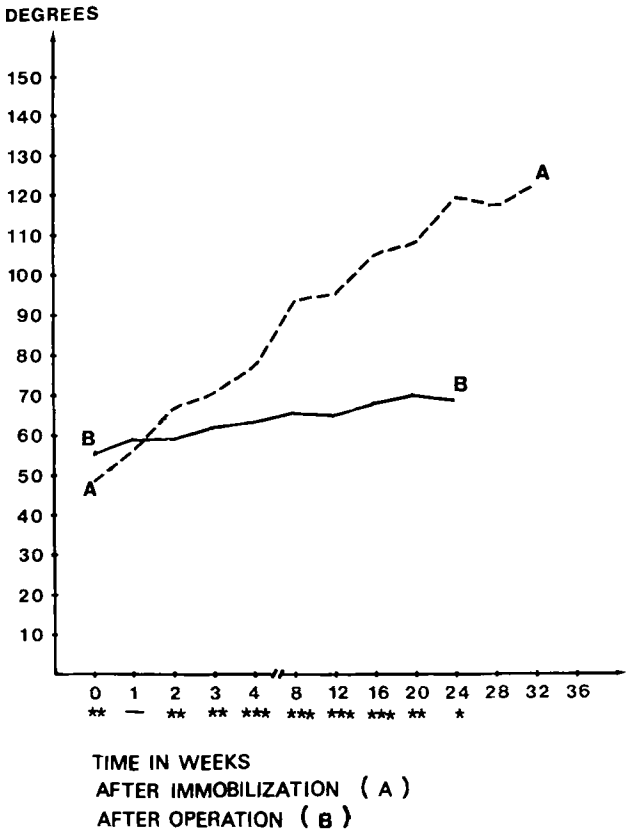


Fig. 17. Effect of operation on progressive scoliosis. Diagram B represents the average postoperative scoliosis in Class CS_3 (47 animals) and Diagram A average scoliosis of unoperated animals in CS_3 (80 animals).
Statistical significance:
$* = p < 0.05$; $** = p < 0.01$; $*** = p < 0.001$
— = *n.s.*

cause, to make comparison easier, the end point of immobilization (A) and the time of operation (B) were considered simultaneous events.

The average scoliosis in the group of the unoperated animals is highly progressive whereas that of the operated group is nearly constant. Thus the operation has nearly stopped the progression of scoliosis.

B. Effect of age at operation

The effect of the age at operation on the operative results was studied by dividing the material according to the age at operation into 3 groups. The results can be seen in Fig. 18.

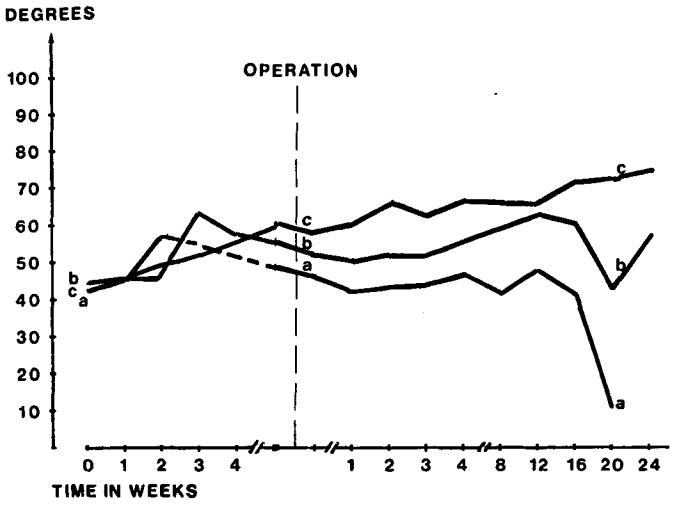


Fig 18. Effect of age at the operation on the course of scoliosis. The diagrams are formed as follows:

(a)	*age less than 7 weeks,*	*18 animals*
(b)	*age 7—10 weeks,*	*35 animals*
(c)	*age more than 10 weeks,*	*17 animals*

Diagram (a) includes the animals younger than 7 weeks at operation (18 animals), (b) the animals of 7 to 10 weeks (35 animals) and (c) the animals older than 10 weeks at the time of operation (17 animals). The initial scoliosis in all the curves is about 43 degrees. Before the operation the diagrams show a slight progression and the difference between the diagrams at the time of the operation is only about 10 degrees. Before the operation the results segregate according to the age at operation so that the youngest show the mildest curves. The immediate effect of the operation in each group is a correction of 3 degrees. After this Group (c) continues to progress slightly, and (a) decreases mildly. When comparing scoliosis before the operation and at the time of 16 weeks after the operation, Group (c) shows a progression of 15 degrees, (b) has remained nearly the same, and (a) shows a correction of about 20 degrees. Thus, the correction caused by the operation is more effective in younger animals.

C. Effect of magnitude of scoliosis on operative results

The relation between the degree of scoliosis and the operative result was studied by dividing the material according to the scoliosis angle before the operation into 4 groups and observing the course of scoliosis before and

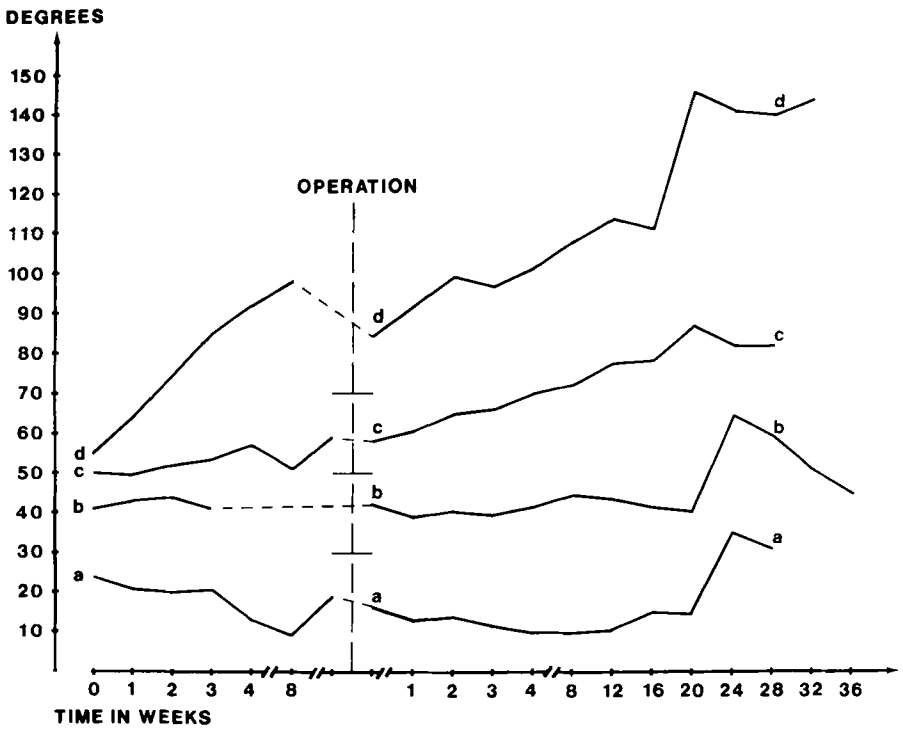


Fig. 19. Effect of magnitude of scoliosis on operative results. The diagrams are formed as follows:

(a)	*preoperative*	*scoliosis*	*1—30*	*degrees,*	*15 animals*
(b)	»	»	*31—50*	» ,	*18* »
(c)	»	»	*51—70*	» ,	*20* »
(d)	»	»	*more than 70*	» ,	*17* »

after operation. The results can be seen in Fig. 19. The groups are separated as seen in Fig. 19.

The average preoperative scoliosis in Group (a) was 24 degrees and the course of scoliosis was slightly correcting before operation and continues in the same fashion after operation. The average preoperative scoliosis in Group (b) was 42 degrees. The preoperative constant course of scoliosis remained unchanged after operation. The average preoperative scoliosis in Group (c) was 50 degrees and the slight preoperative progression continued postoperatively. The strong progression of scoliosis in Group (d) resulted in a preoperative scoliosis of almost 90 degrees. The progression of scoliosis in this group continued after operation but was slightly less than before operation.

The figure indicates that scoliosis exceeding 50 degrees could not be corrected by this operative method, but the progression of scoliosis slowed down postoperatively even in this group.

IV Findings in Section of Specimens

In the study of section of specimens attention was paid to the muscles and ligaments on the concave side of scoliosis. No specific morphological changes could be found in them compared to the controls. The length of the dorsal parts of the intercostal muscles on the concave side were measured and they consisted of 75 intercostal spaces in 32 animals. Seven animals served as normal controls and of them the muscles of 56 intercostal spaces were measured. The results can be seen in Fig. 20.

With the exception of a few cases, the intercostal muscles were shorter on the concave side than in the normal control.

The operated area in 5 rabbits consisting of 16 intercostal spaces was studied microscopically (Fig. 21). In all of them the transplanted fat tissue seemed to be normal. Some collagen fibres had grown into it but the border between the fat tissue and the surrounding tissue had remained distinct all the time. No excessive scar formation could be found.

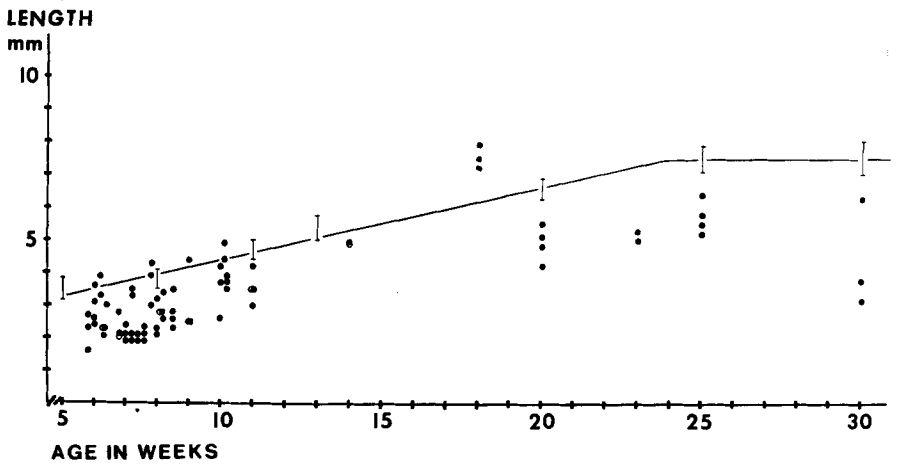


Fig. 20. Length of dorsal parts of intercostal muscle on the concave side of the scoliotic curve. The continuous line shows normal growth of intercostal muscles in control group, the points show measurements from scoliotic rabbits.

V Other Findings

A. Pectus excavatum

Some scoliotic rabbits had quite a typical pectus excavatum which could be found in the x-ray pictures and in the specimens as seen in Fig. 8e.

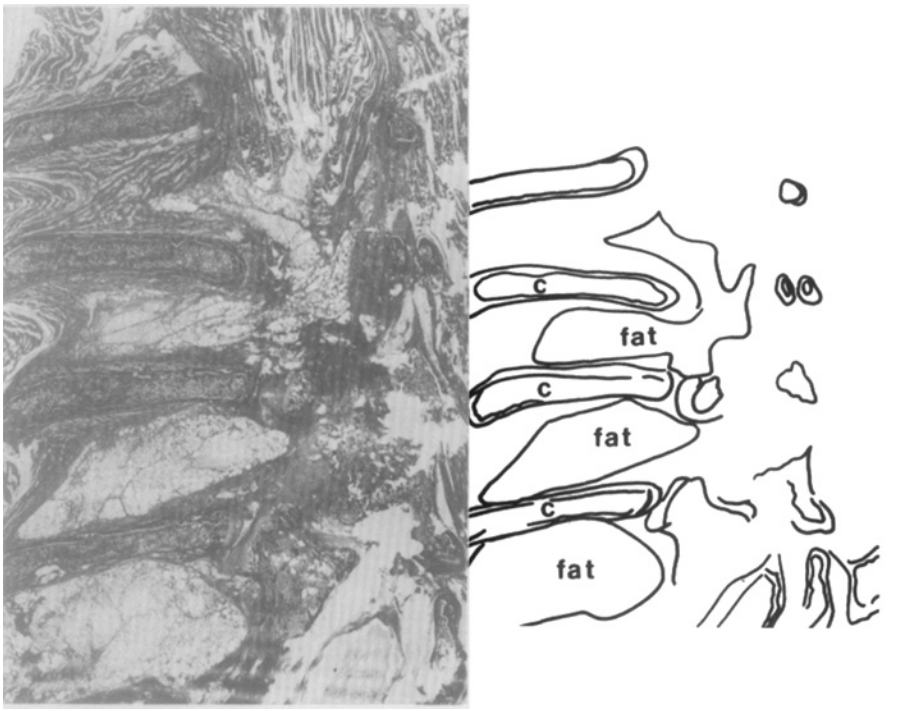


Fig. 21. Histological picture 27 days after removal of contracted soft tissue structures and transplantation of fat tissue. The fat tissue transplant seems to be normal. (Rabbit N:o 356).

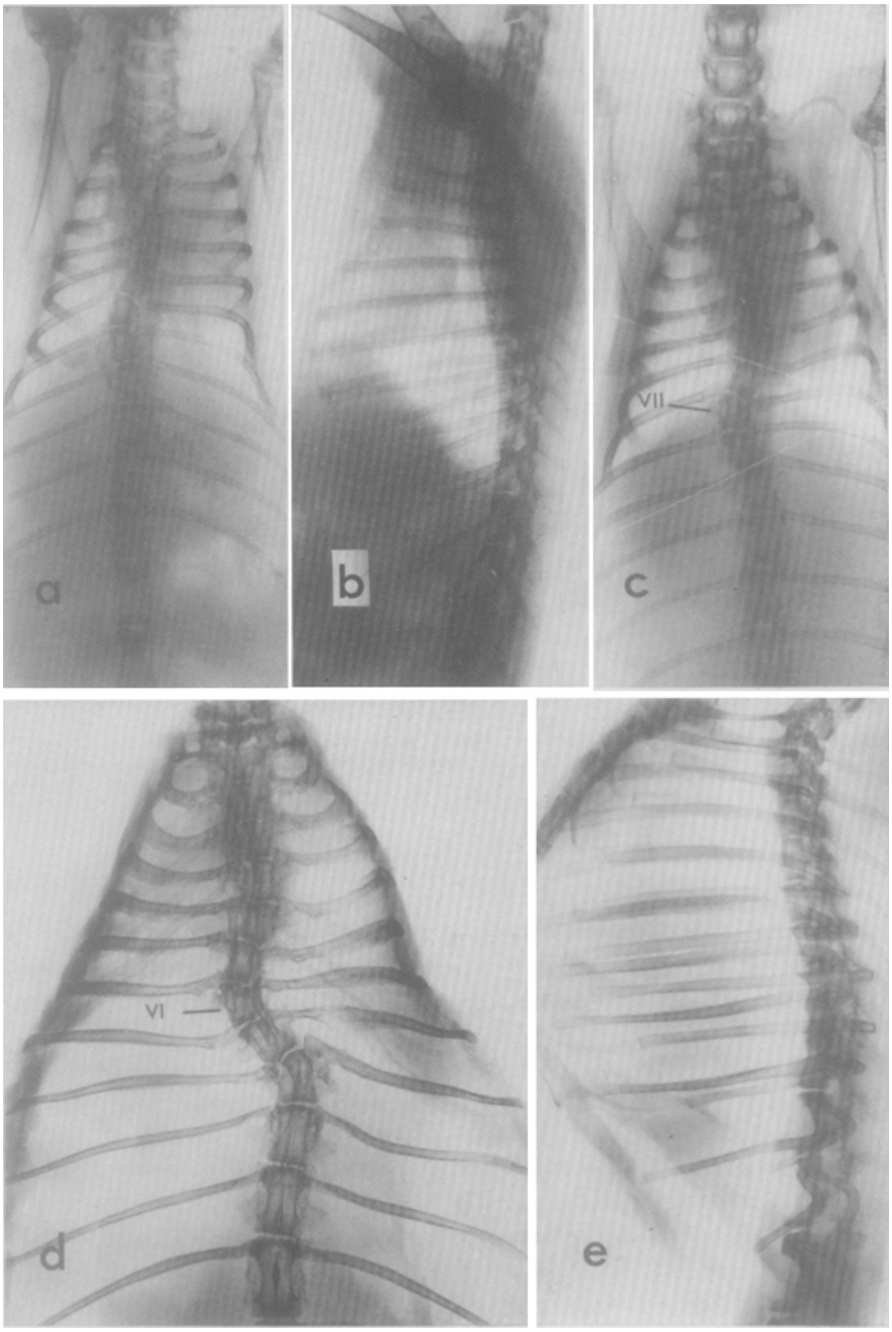
This deformity could be verified roentgenologically only in the old rabbits, whereas in the specimens the deformity was also found in some young rabbits, where it was localized to the xiphoid process.

B. Sliding of the apex of the curve

Some operated animals displayed a phenomenon called »sliding» in the present study, as shown in Fig. 22. The primary preoperative scoliotic curve was established and the operation was made on the concave side. After the operation the apex of the primary curve, however, gradually slid in the caudal or in the cranial direction. This occurred whether the primary curve straightened, remained the same or progressed, as shown in Fig. 22. This phenomenon was always accompanied by the progression of the secondary curve, and in the cases where progression had gone further no difference between the primary and the secondary curve could be distinguished except by comparing them with the earlier x-ray pictures.

C. Costal exostoses

Some animals developed exostoses of the ribs in the operated area. It is obvious that when the intercostal muscles and costotransverse ligaments were operated on, the periosteum of the ribs was injured. As a result, exostoses developed and are regarded as operative complications.


a
b
c
VII
d
VI
e

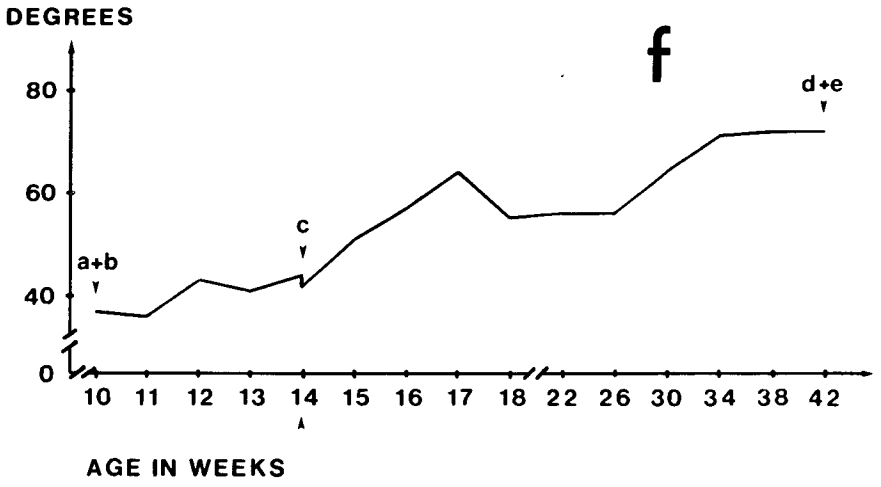


Fig. 22. Sliding of the apex of the curve. Initial scoliosis convex to the right 37° (a + b). Four weeks later (c) the apex of the curve is in thoracic vertebra VII and the operation was performed on the left intercostal spaces 6—8. The final result at the age of 42 weeks shows a right convex scoliosis of 72° but the apex of the curve is at the level of thoracic vertebra VI and the caudal secondary curve has progressed from 10 degrees to 43 degrees. (f) Curve showing the course of scoliotic deformity. (Rabbit No. 233).

DISCUSSION

In the present study scoliosis was provoked in rabbits by keeping their spine in a scoliotic position by means of a three-point plaster cast for 2 to 5 weeks. The principle is not new. Wullstein (1902)) used the same method in dogs, but he did not follow the development of scoliosis thus produced after the immobilization period. The method used by Müller (1926, 1928) in rats was basically very similar to the present method though it was not actually aimed at imitating human scoliosis but was aimed at making the whole spine of the animal bent. The present method, instead, is completely different from all other methods previously used to provoke experimental scoliosis. It is non-invasive, thereby causing less damage to tissues and scar tissue formation is avoided. It it cilincally known that an asymmetrical scar tissue formation in the thoracic area, caused e.g. by a burn, can provoke scoliosis concave to the side of the scar (Langenskiöld & Michelsson 1962, Lindholm et al. 1977).

Physiologically, loading is considered to have a stimulating effect on bone growth e.g. the vertebrae. If the pressure exceeds the physiological limits growth is retarded (Arkin & Katz 1956, Smith 1962, Karaharju 1967, Davis 1968, Österman 1972). It may by supposed that in the present study an asymmetrical compression has been caused to the vertebral growth plates by bending the spine in a scoliotic position. However, the spine was bent in a slightly scoliotic position only, as shown in Fig. 2, thus the asymmetrical effect can be regarded as insignificant.

The data in the present study were obtained from measurements of scoliosis angles from the roentgen pictures. When a scoliotic spine is x-rayed, the size of the scoliosis angle in the picture depends on the position of the object with respect to the direction of the x-rays and the position of the x-ray film (Lindahl & Reader 1962, Lindahl & Movin 1968). Attempts were made to eliminate this error by taking roentgen pictures of the spine, sometimes in two perpendicular planes, and by using the Edholm (1967) measuring disc. Although this disc is reliable in measuring curves, in the statistical analysis this second mode of measurement proved to be confusing, so this technique of measurement was not performed throughout the study. The measurements obtained by the Edholm measuring disc did, however, correlate well with the scoliosis angles obtained by the Cobb method.

Several authors (Knowlton & Hines 1936, Ferguson et al. 1957, Alder et al. 1959, Crawford 1972 and 1973) have shown that immobilization in a shortened state of muscles in a growing animal leads to growth disturbance and permanent shortening of the muscles. Ritsilä (1969) demonstrated that this type of myostatic contracture in a growing animal may provoke skeletal deformity.

When the animals in this study were immobilized in a scoliotic position the muscle groups on the concave side of the spine, including at least parts of the intercostal muscles, were kept for 2—5 weeks in a shortened state. Undoubtedly growth disturbance and permanent shortening of muscles is a process which must, as predicted, have come into play in these experiments. This is also the probable cause of the type of structural scoliosis which could be provoked in these experiments without operative trauma.

In the present study the susceptibility to develop scoliosis seems to be greater in younger animals and with a longer immobilization period. However, rabbits younger than 2 weeks are so small that the plaster cast immobilization is difficult or impossible technically.

In the present study it was demonstrated that progressive scoliosis is likely to occur if the degree of scoliosis present after a period of immobilization in a scoliotic position exceeds 30 degrees in a rabbit aged 2—5 weeks.

In these experiments resolving scoliosis was found in 23 per cent of the unoperated material (Table 1, page 17). These are corresponding phenomena described in the literature. In 1967 J. I. P. James wrote about infantile idiopathic scoliosis: »The majority of these structural curves in infants spontaneously resolve". The group showing resolving scoliosis after the immobilization period could perhaps be compared to the type of human infantile scoliosis which resolves from a state with structural changes.

An interesting phenomenon, first demonstrated by Langenskiöld and Michelsson (Michelsson 1965) in experiments with alizarin, is the counteraction of the progression of a scoliotic curve by the apposition and resorption of bone on the lateral aspect of the vertebrae. This process, which tends to resolve an existing scoliotic curve, was further studied by Michelsson (1965) by means of metal implants and by Karaharju (1967) by means of tetracycline.

It seems reasonable to assume that the regularly occurring phenomenon mentioned above has been a factor influencing the results in the present study. Especially the resolving of scoliosis produced by immobilization may here have its explanation.

The scoliosis treated operatively in the present study was severer on average than the scoliosis of the whole material (Page 30). This apparently increases the reliability of the results in the operative group.

The operative treatment of experimentally provoked scoliosis was aimed at cutting the structures on the concavity which prevented the correction of the scoliosis. An operation on these structures was used by Langenskiöld and Michelsson (1961, 1962) to provoke experimental scoliosis. These authors also provoked the straightening of experimental curves by means of soft tissue release on the concave side (1962). The present operation consisted of the cutting of the costotransverse ligaments and the removal of the dorsal part of the intercostal muscles with interposition of free fat to prevent adhesions and the resultant deforming effect of scar tissue. Free fat has been used successfully for this purpose by several authors (Lexer 1919, Langenskiöld & Michelsson 1960, Österman 1972, Kiviluoto 1976, Langenskiöld & Kiviluoto 1976). Histologically, fat tissue remained unchanged in its new position, and scar formation was virtually unseen (Fig. 21).

The preventive effect of the fat tissue transplants on scar tissue formation in the operative area seemed to be of great importance in preventing the progression of scoliosis and in allowing the correction of scoliosis.

In the immediate postoperative period the scoliosis spontaneously corrected by a few degrees as shown in Fig. 15 (Page 35). This phenomenon was seen in several cases including those where scoliosis later progressed (Fig. 14), and can be explained by the relaxing effect of the local anaesthesia.

The results of the present study show that the progression of a provoked scoliosis can be prevented more efficiently if this operation is performed on younger animals. If the operation was performed on animals under 7 weeks a slight correction of scoliosis was obtained. A partial correction was achieved with animals operated on at the age of 7 to 10 weeks, but after 10 weeks progression continued in spite of the operation. The groups were comparable with regard to initial scoliosis (43°) and they were of sufficient size (17—35 animals) to imply that the conclusions from the analysis of the results are reliable. The effect of the corrective operation is evidently based on the observation in a similar, unoperated group.

Scoliosis exceeding 50 degrees could not be corrected by this operative method (Fig. 19). However, the progression of scoliosis was significantly decreased following surgery in the group where scoliosis at the time of operation was more than 70 degrees. Fig. 19 shows that the rate of progression of scoliosis decreased in the postoperative period but the operative procedure was not able to completely stop it or to result in correction.

The operative results were dependent on the age of the animal at the time of operation, the degree of scoliosis, and the extent of the spinal changes. Thus, when the operation was performed on a young rabbit with

slight scoliosis and even with small deformation of vertebrae and discs, the operation prevented the progression of scoliosis or had a corrective effect on it.

The pectus excavatum deformity found in some experiments in the present study is probably caused by the compression of the plaster corset. This deformity does not seem to be important to the course of scoliosis.

The sliding of the apex of the curve that was observed in the present study is known to occur in human cases as well. The primary curve that is clearly visible in the beginning may become indistinguishable in the course of treatment. When found in connection with ligament discision, this phenomenon can be explained as follows: the stabilizing force of the muscles and ligaments in a certain segment affects a wider area than one intercostal space, as proved by Frey (1922). The operation area is determined by using x-ray identification, which does not reveal the underlying effects of the ligaments to be excised. Thus the effect of the operation may be partially directed to the secondary curve, which begins to progress. This occasional progression of a secondary curve after operation on the concave side of a primary curve was also described by Langenskiöld and Michelsson in 1962.

SUMMARY AND CONCLUSIONS

The main purpose of the present study was to investigate the possibility of producing an experimental model of human idiopathic scoliosis without operative trauma. In the experiments 253 growing rabbits aged 2—5 weeks were kept in a plaster cast in a scoliotic position for 2—5 weeks. In 85 per cent of the animals scoliosis was provoked by this method (Table 1) and it was permanent or progressive in 52 per cent (132 rabbits). Scoliosis was provoked more easily and it developed severer in younger animals. The control animals showed no scoliosis.

The initial degree of scoliosis immediately after immobilization correlated with the course of the deformity. When the initial curve exceeded 30 degrees, a progressive scoliosis developed whereas when the initial curve was less than 30 degrees, a stable or correcting scoliosis was observed.

Seventy scoliotic rabbits were operated on in order to release the soft tissue contracture on the concave side of the primary curve. The operation consisted of removal of 1.5 cm of the dorsal parts of the intercostal muscles, costotransverse and intertransverse ligaments in 2 to 4 intercostal spaces on the concave side with interposition of a free fat tissue transplant to prevent scar formation.

The initial preoperative scoliosis was severer in the operated animals than in the unoperated control group. Following surgery the progression of scoliosis ceased in 21 rabbits, was slowed down in 8 rabbits and corrected in 14 rabbits (Table 3). In 16 rabbits the operation had no effect on the course of scoliosis.

The age of the animal at the time of operation correlated with the operative results. The correcting effect of the operation was better in younger animals. The degree of scoliosis at the time of surgery also correlated with the operative result in that that the corrective effect of the operation was obvious if the scoliosis was mild and was absent if the scoliosis angle exceeded 50 degrees.

Shortening of the intercostal muscles on the concave side of the curve was observed using stained sections of specimens.

The following conclusions can be drawn from the present study: A progressive scoliosis which resembles human idiopathic scoliosis can be provoked in a growing rabbit by immobilizing the animal in a scoliotic

position for a period of 2—5 weeks. The role of growth disturbance of a muscle and accompanying myostatic contracture in the pathogenesis of the scoliotic deformity thus produced is suggested by the observation that some structural changes of the intercostal muscles were seen.

The operative elimination of the contracture on the concave side of the provoked primary curve often resulted in either correction of the deformity or cessation or retardation of progression of the curves. These observations further indicate that growth disturbance and shortening of muscles play a role as a pathogenetic factor in the production of deformity of the spine in this study.

The examination of sections of specimens revealed a shortening of the dorsal intercostal muscles on the concave side of the primary curve.

ACKNOWLEDGEMENTS

The theme of the present study was suggested to me by Anders Langenskiöld, M.D., former professor of Orthopaedics and Traumatology at the University of Helsinki. He has followed the study with keen interest and has offered his wide knowledge and extensive experience to help me with my problems. His encouraging support was decisive for carrying through this study. I like to express my sincerest gratitude to him for everything.

I want to thank my present head Prof. S. Viikari, M.D., head of the Surgical Clinics of Turku University and my former teacher Prof. L-E. Laurent, M.D., former chief of the Orthopaedic Hospital of the Invalid Foundation for their interest throughout the work.

I am greatly indebted to Prof. M. Sussman, M.D., Virginia University, USA., who has kindly revised my manuscript and suggested many valuable alterations.

Prof. P. Vilkki, M.D. and Doc. E. Karaharju, M.D. have officially revised the present thesis and devoted much of their time and expertise to my benefit for which I want to express my gratitude.

To my good friend Kalevi Österman, M.D. who has been my closest adviser throughout the study and to his wife Aune Österman, M.A. who translated the study into English I owe my warm thanks. Without their support, I feel, I would not have been able to accomplish my work.

My thanks are also due to M. Pellinen, M.A. who carried out the statistical analysis in his expert way.

I also want to thank Miss R. Sohlman for her assistance with the animal experiments and histology and Miss L. Mikkola for her expert help in photography. Furthermore, I want to thank my niece Mrs R. Ohlsson for drawing the graphs and Mrs K. Lundstedt for typing out the manuscript.

Finally I want to thank my wife Kirsti and my daughter Sari for their patience and support in the course of my work.

This study was financially supported by a grant from Invalidisäätiön Kannatusyhdistys Mrs Kosti Foundation.

Turku, May 1981

Seppo Hakkarainen

REFERENCES

Alder, A. B., Crawford, G. N. C., Edwards, R. G. (1958) The growth of the muscle tibialis anterior in the normal rabbit in relation to the tension-length ratio. Proc. R. Soc. Ser. B. biol. Sc. (Lond). 148, 207—216.

Alder, A. B., Crawford, G. N. C., Edwards, R. G. (1959) The effect of limitation of movement on longitudinal muscle growth. Proc. R. Soc. Ser. B. biol. Sc. (Lond.) 150, 554—562.

Arkin, A. M. (1949) The mechanism of the structural changes in scoliosis. J. Bone Jt Surg. 31-A, 519—527.

Arkin, A. M., Katz, J. E. (1956) The effects of pressure on epiphyseal growth. The mechanism of plasticity of growing bone. J. Bone Jt Surg. 38-A, 1056—1076.

Arkin, A. M., Simon, N. (1950) Radiation scoliosis. An experimental study. J. Bone Jt Surg. 32-A, 396—401.

Badger, V. M. (1969) Correlation studies on muscle in scoliosis: Histochemistry, electromyography, electron microscopy, and quantitative enzymes. J. Bone Jt Surg. 51-A, 204.

Benson, P. (1965) Hydroxyproline excretion in scoliosis. Proceedings of a symposium on scoliosis held in London. Ed. by P. A. Zorab, pp. 47—49, Livingstone, London.

Bisgard, J. D. (1935) Experimental thoracogenic scoliosis. J. Thorac. Surg. 4, 435—442.

Bisgard, J. D., Musselman, M. M. (1940) Scoliosis, its experimental production and growth correction: Growth and fusion of vertebral bodies. Surg. Gynec. Obstet. 70, 1029—1036.

Bouillet, R., Vincent, A. (1967) La Scoliose idiopathique. Acta orthop. belg. 33, 93—366.

Bradford, D. S., Oegema, T. R., Brown, D. M. (1977) Studies on skin fibroblasts of patients with idiopathic scoliosis. Clin. Orthop. 126, 111—118.

Butterworth, T. R. Jr., James, C. (1969) Electromyographic studies in idiopathic scoliosis. Sth. med. J. (Ala) 62, 1008—1010.

Cobb, J. R. (1948) Outline for the study of scoliosis. The Am. Academy of Orthop. Surg.: Instructional course lectures. 5, 261—275. Ann. Arbor. Mich. Edwards.

Cowell, H. R., Hall, J. N., McEwen, G. D. (1972) Genetic aspects of idiopathic scoliosis. Clin. Orthop. 86, 121—131.

Crawford, G. N. C. (1972) The effect of temporary limitation of movement on the longitudinal growth of voluntary muscle. J. Anat. 111, 1, 143—150.

Crawford, G. N. C. (1973) The growth of striated muscle immobilized in extension. J. Anat. 114, 2, 165—183.

Davenport, H. K., Ranson, S. W. (1930) Contracture resulting from tenotomy. Arch. Surg. 2, 995—1014.

Davenport, H. K., Ranson, S. W., Stevens, E. (1929) Microscopic changes of muscle in myostatic contracture caused by tetanus toxin. Arch. Pathol. 7, 978—992.

Davis, P. R. (1968) Compression resistance in the vertebral bodies and discs. Proceedings of a second symposium on scoliosis held in London 1967. Ed. by P. A. Zorab, pp. 44—45. Livingstone, Edinburgh and London.

Eccles, J. C. (1944) Investigations on muscle atrophies arising from disuse and tenotomy. J. Physiol. (Lond.) 103, 253—266.

Edholm, P. (1967) Instrument for measuring angles from roentgenograms. Acta radiol. (Diagn.) (Stockh.) 6, 156—166.

Eisenhauer, J., Key, J. A. (1945) Studies on muscle atrophy. A method of recording power in situ and observations on effect of position of immobilization on atrophy of disuse and denervation. Arch. Surg. 51, 154—163.

Engel, D., Richer, A. (1939) Experiments on the production of spinal deformities by radium. Am. J. Roentgenology 42, 217—234.

Farkas, A. (1954) The pathogenesis of idiopathic scoliosis. J. Bone Jt Surg. 36-A, 617—654.

Ferguson, A. B., Vaughan, L., Ward, L. (1957) A study of disuse atrophy of skeletal muscle in the rabbit. J. Bone Jt Surg. 39-A, 583—596, 624.

Frey, E. K. (1922) Die Entstehung der Dorsalskoliosen und Möglichkeiten ihrer chirurgischen Behandlung. Dtsch. Z. Chir. 169, 13—150.

Fröhlich, A., Mayer, H. H. (1920) Über Dauerverkürzung der gestreiften Warmblütermuskeln. Arch. exp. Pathol. Pharmakol. 87, 173—188.

Goldstein, L. A., Waugh, T. R. (1973) Classification and terminology in scoliosis. Clin. Orthop. 93, 10—22.

Gruca, A. (1958) The pathogenesis and treatment of idiopathic scoliosis. A preliminary report. J. Bone Jt Surg. 40-A, 570—584.

Haas, S. L. (1939) Experimental production of scoliosis. J. Bone Jt Surg. 21, 963—968.

Hakkarainen, S. (1973) Growth disturbance of muscle — a possible factor in the pathogenesis of scoliosis. Experimental study. Acta orthop. scand. 44, 101—103.

Hakkarainen, S., Langenskiöld, A. (1971) Lihaksen kasvuhäiriö — idiopaattisen skolioosin etiologinen tekijä? Duodecim 87, 1344.

Harrington, P. R. (1962) Treatment of scoliosis. Correction and internal fixation by spine instrumentation. J. Bone Jt Surg. 44-A, 591—610.

Harrington, P. R. (1977) The etiology of idiopathic scoliosis. Clin. Orthop. 126, 17—25.

Hirano, S. (1972) Electron microscopic studies on back muscles in scoliosis. J. Jpn. Orthop. Assoc. 46, 47—62.

Hoppenfeldt, S., Spiro, A. (1973) Histochemical findings in the paraspinal muscles of patients with idiopathic scoliosis. J. Bone Jt Surg. 55-A, 435.

James, J. I. P. (1967) Scoliosis. Livingstone, Edinburgh and London.

James, J. I. P. (1970a) The orthopaedic surgeons and research. The second R. I. Harris lecture. J. Bone Jt Surg. 52-B, 14—28.

James, J. I. P. (1970b) The etiology of scoliosis. J. Bone Jt Surg. 52-B, 410—419.

Kane, W. J., Moe, J. H. (1970) A scoliosis prevalence survey in the state of Minnesota. J. Bone Jt Surg. 52-A, 403—404.

Kane, W. J. (1977) Scoliosis prevalence: A call for a statement of terms. Clin. Orthop. 126, 43—46.

Karaharju, E. O. (1967) Deformation of vertebrae in experimental scoliosis. The course of bone adaptation and modelling in scoliosis with reference to the normal growth of the vertebrae. Acta orthop. scand. Suppl. 105.

Keim, H. (1976) The adolescent spine. Grune et Stratton, New York.

Kiviluoto, O. (1976) Use of free fat transplants to prevent epidural scar formation. An experimental study. Acta orthop. scand. Suppl. 164.

Knowlton, G. C., Hines, H. M. (1936) Kinetics of muscle atrophy in different species. Proc. Soc. Exp. Biol. Med. 35, 394—398.

Knutsson, F. (1961) Growth and differentiation of the postnatal vertebra. Acta radiol. 55, 401—408.

Knutsson, F. (1966) Vertebral genesis of idiopathic scoliosis in children. Acta radiol. (Diagn.) 4, 395—402.

Kyselka, R. (1965) Biochemische Vorgänge in Zusammenhang mit der progredienten Skoliose. Beitr. Orthop. Traumatol. 12, 130—137.

Langenskiöld, A. (1971) Growth disturbance of muscle: a possible factor in the pathogenesis of scoliosis. Scoliosis and Growth. Ed. by P. A. Zorab, pp 85—90. Livingstone, Edinburgh and London.

Langenskiöld, A., Kiviluoto, O. (1976) Prevention of epidural scar formation after operations on the lumbar spine by means of free fat transplants. A preliminary report. Clin. Orthop. 115, 92—95.

Langenskiöld, A., Michelsson, J.-E. (1960) Unpublished observations.

Langenskiöld, A., Michelsson, J.-E. (1961) Experimental progressive scoliosis in the rabbit. J. Bone Jt Surg. 43-B, 116—120.

Langenskiöld, A., Michelsson, J.-E. (1962) The pathogenesis of experimental progressive scoliosis. Acta orthop. scand. Suppl. 59.

Lexer, E. (1919) Die freien Transplantationen. 1. Teil. Verlag von Enke, Stuttgart.

Lindahl, O., Movin, A. (1968) Measurement of the deformity in scoliosis. Acta orthop. scand. 39, 291—302.

Lindåhl, O., Reader, E. (1962) Mechanical analysis of forces involved in idiopathic scoliosis. Acta orthop. scand. 32, 27—38.

Lindholm, T. S., Snellman, O., Österman, K. (1977) Scoliosis caused by benign osteoblastoma of the lumbar spine. A report of three patients. Spine 2, 276—281.

Liszka, O. (1961) Spinal cord mechanisms leading to scoliosis in animal experiments. Acta Med. Pol. 2, 45—63.

Lovett, R. W. (1891) The etiology of lateral curvature of the spine. Boston Med. Surg. 124, 6—8.

Mac Ewen, G. D., Cowell, H. R. (1970) Familial incidence of idiopathic scoliosis and its implications in patient treatment. J. Bone Jt Surg. 52-A, 405.

Matsuoka, M. (1904) Über Gewebsveränderungen der künstlich erzeugten Kyphose der Schwanzwirbelsäule des Kaninchens. Arch. Entw. d. Org. 18, 253—260.

Michelsson, J.-E. (1965) The development of spinal deformity in experimental scoliosis. Acta orthop. scand. Suppl. 81.

Miles, M. (1947) Vertebral changes following experimentally produced muscle imbalance. Arch. Phys. Med. 28, 284—289.

Moe, J. H., Winter, R. B., Bradford, D. S., Lonstein, J. E. (1978) Scoliosis and other spinal deformities. Saunders, Philadelphia.

Moll, A. (1886) Experimentelle Untersuchungen über den anatomischen Zustand der Gelenke bei andauernder Immobilisation. Virchows Arch. (Pathol. Anat.) 105, 466.

Moser, H. (1957) Experimentelle Skoliosen. Verh. Dtsch. orthop. Ges. 90, 178—180.

Müller, W. (1926) Discussion. Verh. Dtsch. orthop. Ges. 48, 186—187.

Müller, W. (1928) Skoliosen in Tierversuch. Beitr. klin. Chir. 142, 343—379.

Nachemson, A. L. (1976) Terapeutiska framsteg inom skoliosområdet. Läkartidningen 73: 953—961.

Nachlas, I. W., Border, J. N. (1950) Experimental scoliosis — The role of the epiphysis. Surg. Gynecol. Obstet. 90, 672—680.

Nordwall, A. (1973) Studies in idiopathic scoliosis relevant to etiology, conservative and operative treatment. Acta orthop. scand. Suppl. 150.

Osmond-Clarke, H. (1950) Scoliosis. Modern trends in orthop. Ed. by Harry Platt, pp. 220—247, Hoeber, London.

Österman, K. (1972) Operative elimination of partial premature epiphyseal closure. An experimental study. Acta orthop. scand. Suppl. 147.

Ottander, H. G. (1963) Experimental progressive scoliosis in a pig. Acta orthop. scand. 33, 91—97.

Pacher, W. (1939) Operative Erzeugung einer Skoliose im Tierversuch. Ztschr. f. Orthop. Chir. 69, 140—154.

Plageman, H. (1926) Skoliosenoperationen im Experiment am Tier. Verh. orthop. Ges. 48, 188—194.

Ponseti, I. V. (1957) Skeletal lesions produced by aminonitriles. Clin. Orthop. 9, 131—144.

Ponseti, I. V. (1959) Studies on the nature of skeletal lesions produced by aminonitriles. Bull. Hosp. Jt. Dis. (NY) 20, 1—8.

Ponseti, I. V. (1968) The pathogenesis of adolescent scoliosis. Proceedings of a second symposium on scoliosis held in London 1967. Ed. by P. A. Zorab, pp. 60—63. Livingstone, Edinburgh and London.

Ponseti, I. V., Baird, W .A. (1952) Scoliosis and dissecting aneurysm of the aorta in rats fed with Lathyrus odoratus seeds. Am. J. Pathol. 28, 1059—1077.

Ponseti, I. V., Shepard, R. S. (1954) Lesions of the skeleton and of other mesodermal tissues in rats fed sweet-pea (Lathyrus odoratus) seeds. J. Bone Jt Surg. 36-A, 1031—1058.

Pusch, G. (1926) Physikalisches und Experimentelles zum Skoliosenmechanismus. Verh. Dtsch. orthop. Ges. 48, 181—186.

Ralston, H. J., Feinstein, B., Inman, V. T. (1952) Rate of atrophy in muscles immobilized at different lengths. Fed. Proc. 11, 127.

Ranson, S. W., Sams, C. F. (1928) A study of muscle in contracture: The permanent shortening of muscles caused by tenotomy and tetanus toxin. J. Neurol. Psychopathol. 8, 304—320.

Risser, J. C. (1957) Scoliosis. Instruct. Course Lect. Am. Acad. Orthop. Surgeons 14, 91—105.

Ritsilä, V. A. (1969) Talipes equinovarus and vertical talus produced experimentally in newborn rabbits. Acta orthop. scand. Suppl. 121.

Roaf, F. (1958) Rotation movements of the spine with special reference to scoliosis. J. Bone Jt Surg. 40-B, 312—332.

Schultz, A. B., Larocca, H., Galante, J. O., Andriachi, T. P. (1972) A study of geometrical relationship in scoliotic spines. J. Biomech. 5, 409—420.

Schwartzmann, J. R., Miles, M. (1945) Experimental production of scoliosis in rats and mice. J. Bone Jt Surg. 27, 59—69.

Schönenberger, F., Taillard, W., Berger, H. (1961) Beitrag zur Aminosäuren Ausscheidung bei Epiphyseolysis, Pertesscher Krankheit und Skoliose. Z. Orthop. 95, 73—81.

Shands, A. R., Eisberg, H. B. (1955) The incidence of scoliosis in the state of Delaware. J. Bone Jt Surg. 37-A, 1243—1249.

Smith, J. W. (1962) The relationship of epiphysial plates to stress in some bones of the lower limb. J. Anat. 96, 58—78.

Smith, R. (1968) Aspect of collagen metabolism. Proceedings of a second symposium on scoliosis held in London 1967, Ed, by P. A. Zorab. pp. 50—54, Livingstone, Edinburgh and London.

Snellman, O. (1973) Growth and remodelling of the ribs in normal and scoliotic pigs. Acta orthop. scand. Suppl. 149.

Somerville, E. W. (1952) Rotational lordosis: The development of the single curve. J. Bone Jt Surg. 34-B, 421—427.

Spalteholz, W. (1910) Handatlas der Anatomie des Menschen. Erster Band, S. Hirzel, Leipzig.

Stearns, G., Chen, J.-Y. T., McKinley, J. B., Ponseti, I. V. (1955) Metabolic studies of children with idiopathic scoliosis. J. Bone Jt Surg. 37-A, 1028—1034.

Stilwell, D. L. Jr. (1962) Structural deformities of vertebrae. Bone adaptation and modelling in experimental scoliosis and kyphosis. J. Bone Jt Surg. 44-A, 611—634.

Summers, T. B., Hines, H. M. (1951) Effect of immobilization in various positions upon the weight and strength of skeletal muscle. Arch. Phys. Med. 32, 142—145.

Thompson, T. C. (1934) Experimental muscular atrophy. J. Bone Jt Surg. 16, 564—571.

Waugh, T. R., Riseborough, E. J .(1977) Scoliosis. Spinal disorders. Diagnosis and treatment. Ed. by Ruge, D. and Wiltse, L. L., pp. 176—192, Lea & Febiger, Philadelphia.

Willner, S. (1972) Factors contributing to structural scoliosis. Thesis. Lund 1972.

Wullstein, L. (1902) Die Skoliose in ihrer Behandlung und Entstehung nach klinischen und experimentellen Studien. Z. Orthop. Chir. X, 177—388.

Wynne-Davis, R. (1968) Familial (idiopathic) scoliosis. A family survey. J. Bone Jt Surg. 50-B, 24—30.

Yamada, K., Ikata, T., Yamamoto, H., Nakagava, Y., Tanaka, H., Tezuka, A. (1969) Equilibrium function in scoliosis and active corrective plaster jacket for the treatment. Tokushima J. exp. Med. 16, 1—7.

Yamada, K., Yamamoto, H., Ikata, T., Nakagava, Y., Kinoshita, I., Tezuka, A., Tamura, T. (1971) A neurological approach to the etiology and therapy of scoliosis. J. Bone Jt Surg. 53-A, 197—198.

Zorab, P. A. (1968) Total hydroxyproline excretion in scoliosis. Proceedings of a second symposium on scoliosis held in London 1967. Ed. by P. A. Zorab, pp. 55—57. Livingstone, Edinburgh and London.

Zorab, P. A., Clark, S., Cotrel, Y., Harrison, A. (1971) Bone collagen turnover in idiopathic scoliosis estimated from total hydroxyproline excretion. Arch. Dis. Child. 46, 828—832.

Zuk, T. (1962) The role of spinal and abdominal muscles in the pathogenesis of scoliosis. J. Bone Jt Surg. 44-B, 102—105.