ACTA ORTHOPAEDICA SCANDINAVICA
Supplementum No. 149

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

GROWTH AND REMODELLING OF THE RIBS IN NORMAL AND SCOLIOTIC PIGS

by

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MUNKSGAARD
Copenhagen 1973

ISBN 87 16 01397 2

Vammala 1973, Vammalan Kirjapaino Oy

ACKNOWLEDGEMENTS

I wish to express my gratitude to Professor Anders Langenskiöld, M.D., Head of the Department of Orthopaedics and Traumatology of the University Central Hospital, Helsinki, who suggested the subject of the present study to me. I am very grateful to him for his support and advice in the course of my work.

Thanks are due to Mr. Risto Pellinen, Ph.Lic., who helped me in the choice of methods for a quantitative presentation of the results.

I wish to thank Mr. T. Ratsula, B. Agr., for assisting in the arrangement of the animal experiments and my friend Mrs. Saimi Mustakallio for placing part of the test animals at my disposal.

During my work I had two technical assistants, in the beginning Miss Lempi Mikkola and later on Mrs. Eila Pohjola. I wish to thank both of them for their aid. Furthermore, I am obliged to the personnel of the mechanical workshop and the prostetic shop of the Invalid Foundation for assistance and technical advice during the moulding, milling and photography performed in the course of my work.

The figures in my work were planned by my wife, architect Helmine Snellman and drawn by architect Jukka Aittola in his very special way. I wish to extend my warm thanks to both ot them.

I am also very grateful to my friend Dr. Clyde Nash Jr., M.D., Cleveland, Ohio, for his critical reading of the English manuscript.

My study was translated into English by Mrs. Taina Stenman, M.A. I thank her for good co-operation. I also wish to thank Mr. Kingsley Hart, M.A., for revising the translation.

Finally, I wish to express my gratitude to all the persons not mentioned by name who helped me in different ways during my work.

The present study was financially supported by the Sigrid Jusélius Foundation and the Scientific Fund of the Invalid Foundation and Invaliidisäätiön Kannatusyhdistys Mrs. Kosti Foundation.

Helsinki, May 1973.

O. S.

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PREFACE

Idiopathic scoliosis is one of the essential problems of orthopaedics since its aetiology is still unknown. Problems associated with idiopathic scoliosis have been investigated experimentally for fifteen years at the Research Laboratory of the Orthopaedic Hospital of the Invalid Foundation under the leadership of Professor Anders Langenskiöld. On his initiative, methods for inducing progressive scoliosis in test animals have been developed.

The subject of the present study is the rib. Deformity of the ribs and lateral bending of the spine are the most distinct signs of scoliosis, and together these deformities produce the appearance of a »ribhump».

Hueter (1878) was probably the first to investigate the growth process of ribs. He assumed that the sternal end grew more than the vertebral end, since this seemed natural considering the total growth of the thorax. Since no comprehensive description of the normal development of the rib could be found in the literature, an experimental analysis of the normal growth of ribs forms a part of the present work. A rib apparently grows in a way similar to other long bones, and thus continuous three-dimensional remodelling through apposition and resorption seems to take place during its growth.

The vertebral end of the rib has an epiphyseal line from which the bone could be expected to grow longitudinally. Michelsson (1964) made certain interesting observations concerning the growth of the sternal end during his investigations of the methods for inducing scoliosis. He discovered that a metal wire placed in the sternal part of the rib receded from the sternum during the growth. This observation has also stimulated a more detailed study of rib growth.

The remodelling of each bone may also be influenced by external forces changing the drift.* Nature also tends to preserve the original

* »As areas of a bone become sequentially relocated during longitudinal growth, changes in size, shape, and axis occur. These changes are accomplished by a »drift» of the cortex into the new positions. This remodeling process

pattern of growth, which may result in self-correction, for example, during the healing process of fractures in a growing child's long bones.

In the present work the investigation of the remodelling process of the rib of a normal and a scoliotic test animal is performed macroscopically. Pigs were used as test animals. The methods used for the investigation of the growth were metal marking and tetracyclin labelling. As the three-dimensional method of investigation of bones used in the present work does not, to the author's knowledge, occur in the literature, the method will be discussed in detail.

Some preliminary results of this investigation were presented by Langenskiöld at the Second Scoliosis Proceedings in London, 1968.

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involves the appositional increase of bone on certain local surfaces, either periosteal or endosteal or both, together with corresponding resorptive removal from other local surfaces. By these means, parts of a bone become reshaped and resized in a manner which corresponds to their new positions in the bone.» (Enlow, 1963)

METHODS USED IN THE STUDY OF THE GROWTH AND REMODELLING OF BONES

Orthopaedic surgery is not so much concerned with the microscopic structure of bones as with their macroscopic structure and total growth. A knowledge of the pattern of growth and the fastest growth periods make it possible to choose both clinical and research procedures directed to the right place at the right time.

The history of our knowledge of the growth of bones contains numerous observations dating back over the last 250 years. Our present conception of the growth of bones is based on these observations.

Hales (1727) drilled two holes in the tibia of a young chicken and found that after growth the holes were no further apart, which proved that the bone grew at the ends. Duhamel (1739—1743) used silver pins and a dye (alizarine) in his experiments on pigeons and dogs. He discovered that after the dye feeding was stopped a light area appeared at the end of the bone. The dye was easily discernible and the light area indicated the longitudinal growth of the bone. In the same way the light bone deposited on the surface of the bone in the diaphysear area indicated the increase in diameter. Neither Hales nor Duhamel could explain the nature of the growth, but they considered interstitial growth possible.

John Hunter (1837) repeated the earlier experiments performed by Duhamel and Hales with metal markers (lead shots). He proved that two basic processes took place during the increase of the diameter of a bone. One was the deposition of new bone, apposition, as in the diaphysis, the other was resorption at the inner surface of the bone marrow. He also assumed that resorption took place in the metaphysis during the longitudinal growth of the bone. Hunter was perhaps the first to realize the multi-dimensionality of bone growth. He made the observation that living bone is constantly changing its matter, referring thus, probably for the first time, to the remodelling process. Later on, the significance of the epiphyseal plate to the longitudinal growth of bones was recognized (Humphry 1858, among others). At the end of the 19th century the Law of Bone Transformation was presented and published by Julius Wolff (1896), who also applied the metal marking method. He investigated the growth of the mandible by using a metal wire tied around the jaw (Wolff 1888). He discovered that the distance between the wires had remained unchanged during the growth of the test animal and that growth of new bone had occurred after the insertion of the markers.

In the investigation of the growth of bones measurements performed in the bones have also been used. Hueter (1878) investigated the longitudinal growth of bone by measuring the changes in distance from the tuberculum costae to the ends.

Duhamel (1739) and Ollier (1867) had already observed that the longitudinal growth was not uniform at the ends of the bone. In 1867 Ollier presented an experimental investigation on the growth of bone, also containing clinical applications. He used rabbits, pigeons and hens as test animals. The long bones of their upper and lower extremities were marked with metal wire. By observing the way the markers receded from the bone ends during growth he was able to formulate a rule for the rate of growth at the ends of long bones.

Payton and Brash made summaries of the growth of long bones by using alizarine and explained their own observations on the rate of growth at the ends of the bones (Payton 1931, Brash 1934).

After the introduction of X-rays there have also been observations on other kinds of »marks». The most significant ones are the »Harris lines» (Harris 1926) and the compounds of heavy metals like bismuth or metal compounds given to the child as medicine or in cases of poisoning. Vahlquist (1943) used »lead lines» as marks when performing measurements of long bones.

In addition to the classical methods, some new marking methods have been introduced during recent decades. Lomholt (1930) was apparently the first to use radioactive isotopes in his investigations by labelling bones with radium isotopes. After the Second World War new applications of different isotopes appeared. Leblond et al. (1950) introduced radioactive phosphorus. They paid special attention to the growth at the ends of bones. The use of radioisotopes allows the observation of bone growth and the uptake of minerals into the bone tissue.

About 20 years after the introduction of isotope investigations in biology it was found that a recently discovered antibiotic, tetracycline, was deposited in the part of the bone where the most active ossification took place (Milch et al. 1957 and 1958). Tetracycline appears to be bound into the growing bone tissue as a complex apatite salt forming a compound that produces yellowish fluorescence in ultraviolet light. This method is at present commonly accepted. As yet, the reaction induced by tetracycline in bone and its permanence are not fully understood. Various tetracycline derivatives have been used for labelling. In addition to these, new labelling methods have been introduced. For instance, hepatoporphyrine, RNA fluorescein and tetracycline given at short successive intervals, produce distinctly different colours of fluorescence in bone. (Olerud & Lorenzi 1970). In this way serial observations on the osteoblastic and osteoclastic processes can be made.

Tetracycline and the aforementioned substances have the drawback of disappearing when bone is demineralized. Therefore, Zak (1963) developed the lead-acetate method used earlier by Okada et al. (1958) in the investigation of teeth. Labels induced into bone by lead stay there, although the bone is demineralized. On the basis of these labels (Scheiman—Tagger & Brodie 1964), conclusions on the growth of the details of bone can be made on the microscopic level.

In general, bones have been found to have different growth patterns in their various parts, specific to each bone. The remodelling proceeds towards the form of a fully-grown bone through continuous apposition and resorption (Enlow 1963).

MATERIAL AND METHODS USED IN THIS INVESTIGATION

A. THE CHOICE OF METHODS

The methods used in the present investigation were chosen in order to obtain an overall picture of the main features of the growth process and to clarify the process in more detail. A knowledge of the growth pattern of a normal rib was necessary for the study of the growth of a scoliotic rib.

The metal marking method was chosen for the study of the longitudinal growth and the approximate growth pattern. This method is based on the principle that the distance between the markers inserted around the bone remains unchanged during growth. During his investigations on scoliosis Michelsson (1965) discovered that a metal wire placed around the sternal end of the rib of a rabbit disappeared during the growth process. The wire was found in the thoracic cavity outside the bone near the ribs. One explanation is that this occurred as a consequence of the remodelling process. Bearing this in mind, the metal marking method was only used during the period of fastest growth and a sufficiently short growth period was used to make sure that the metal markers would still be in the rib.

No description of the three-dimensional growth of an individual bone could be found in the literature. It is apparently impossible to find a definite answer descriptively, as some of the points observed disappear completely due to resorption during the growth process. By using serial transverse sections at short distances, at least a relative conception of the growth process during a short period can be obtained. When a bone is marked with Oxytetracycline (OTC),* growth is indicated by the zone around the OTC-labelling in a transverse section of the bone. For the definition of the total growth a method based on the displacement of the centre of the cross-section was used (see page 23).

* (Shortening, OTC — Johnson 1964).

The method was especially developed for the present work. Sections of bone milled at certain distances were photographed. The part of the bone sections labelled with OTC could be observed to define the growth pattern.

During preliminary experiments with approximately one hundred rabbits, these animals were found unsuitable because exact observations on the growth of their bones are difficult to make due to the coarseness of cancellous bone. At the Research Laboratory of the Orthopaedic Hospital of the Invalid Foundation pigs had been used as test animals earlier (Langenskiöld & Michelsson 1961, Karaharju 1967). Because of these positive experiences, pigs were chosen as test animals. Pacher (1939) and Ottander (1963) also used pigs in their experimental investigation of scoliosis.

B. MATERIAL

Forty test animals were used and altogether 90 different ribs. See Table I. More detailed presentation appears in following chapters.

TABLE I. *Material.*

	Normal	Scoliotic	Total
Animals	18	22	40
Ribs	37	53	90

C. DESCRIPTION OF METHODS

Anatomy of the rib

A pig has 14—15 pairs of ribs, and the last 7 are not attached by cartilage to the sternum (Nickel et al. 1968). The attachment of the ribs to the spine at the vertebral end is approximately the same as in the human body. Most of the rib of a fully-grown pig is slightly curved, with only its vertebral part more curved. The rib of the growing animal (Fig. 1) has a head (capitulum costae) with an epiphyseal growth plate. The surface of the head is cartilaginous, due to joint articulation. The rib is also articulated to the transverse process. In the sternal direction from the head there is the angular part (angulus costae), which is not definitely outlined. Between these there is the rib neck (collum costae) and the tuberculum costae with an uneven articular facet. In the angular part there is the sulcus costae for blood vessels and nerves.

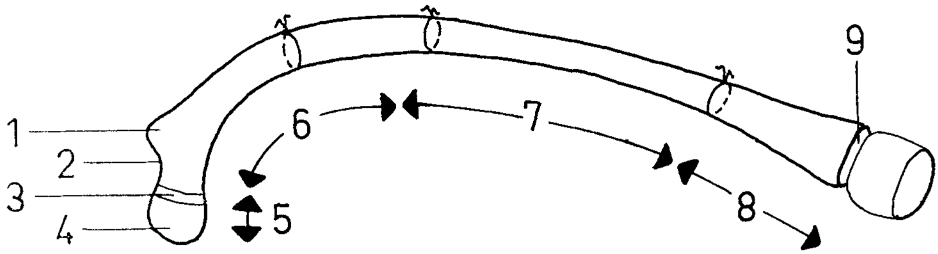


Figure 1. The placement of the metal markers around the rib. The distance between them is known, likewise the distance of the more sternal marker from the costochondral line.

1. *tuberculum costae*
2. *the neck*
3. *epiphyseal plate*
4. *the head*
5. *epiphysis*
6. *the angular part*
7. *corpus costae*
8. *the sternal extremity*
9. *the costochondral junction*

In the sternal direction from the angular part the rib continues as corpus costae, the diameter of which increases towards the costochondral junction. At the sternal extremity of the rib, there is no epiphyseal nucleus or epiphyseal plate as in other long bones, but a cartilaginous growth zone corresponding to a growth plate. Each rib has its typical longitudinal axis, which is complex. The following abbreviations will be used to identify sections of the rib:

— sternal	— st
— vertebral	— ve
— caudal	— caud
— cranial	— cran

Moreover, a rib has a surface towards the skin and one towards the lungs, abbreviated as follows:

— pulmonal	— pulm
— cutaneal	— cut

Metal marking

The ribs of the pigs chosen were marked subperiostally with stainless steel wire placed around the bone (Fig. 1, 9 and 10). The distance between the metal markers was measured with an accuracy of one millimeter. The distance of the most sternal marker from the costochondral junction was easy to measure.

The pigs were anaesthetized by means of an open mask, using trilene without premedication. Two assistants participated. One of them gave the anaesthesia and the other assisted at the operation, performed according to a normal aseptic operative technique. The operation area was cleaned with amisept (Lääke Oy®). The wounds were covered with nobecutan (Nobecutan, Bofors) after stitching. 50 mg/kg OTC (Terramycin-Pfizer®)* was administered parenterally 2—3 days before the operation, since some of these normal pigs were used as comparitive material. The wounds were sprinkled with streptomycin powder after stitching. No infection occurred. The wires were inserted in one or two ribs. The pigs were allowed to grow in order to find out the rate of growth during the various phases of the actual growth period. No metal markers were inserted in the scoliotic pigs.

At regular intervals after the operation, the pigs were killed. The ribs with metal markers were carefully detached from the thorax and from the soft tissues. The ribs were kept in a freezer to prevent damage to the tissue, as the treatment of the material took several months. After removal each rib was X-rayed in the cran-caud and the pulm-cut direction. The distance between the metal markers was measured from the radiographs.

Oxytetracycline labelling

The test animals administered 50 mg/kg OTC were divided into two groups. One consisted of the animals in which scoliosis had been induced operatively and the other of the normal control animals, some of which had been marked with metal. The pigs were operated 1—2 days after they had been given OTC. OTC was administered intramuscularly on three consecutive days, which was considered to bring about a sufficiently strong fluorescent line in UV-light.

Embedding of the rib in acrylic resin

When the animals had been killed after a predetermined time, the thorax was removed and X-rayed. The curvature of the scoliosis was determined using Cobb's method (Cobb 1948). After this the ribs were

* The author is much indepted to the Pfizer Corporation for supplying the Terramycin for this study.

Figure 2. A photograph of the mould used for imbedding the ribs in acrylic resin. The walls are made of steel and they are demountable.

carefully detached and the soft tissues were removed. All the ribs selected for the investigation were X-rayed and then kept separately in the freezer.

Each cleaned rib was embedded in acrylic resin using a special mould which was constructed so as to be easily dismantled. It was made of steel because it had to be rigid enough to ensure the uniformity of the embedding (Fig. 2). The ribs were placed in the mould as analogously as possible. Therefore, the rib was fixed with a needle through a hole filled with cork (Fig. 3). Polymeric methyl acrylate (Araldite, Ciba®) was used for the casting and H.Y.956 (Ciba®) as a hardener in the proportions of 100/18—20. The hardening process took about 24 hours. In this way the heat liberated in the hardening process did not damage the OTC-labels in the bone. The casting was performed in two identical moulds to save time. A black paste, made especially to be used with Araldite (Aralditfarbenpaste 07) was used for the dyeing of the acrylic. Thus the rib could be clearly discerned against the dark background. The embedding was performed slowly to avoid air bubbles. The mould

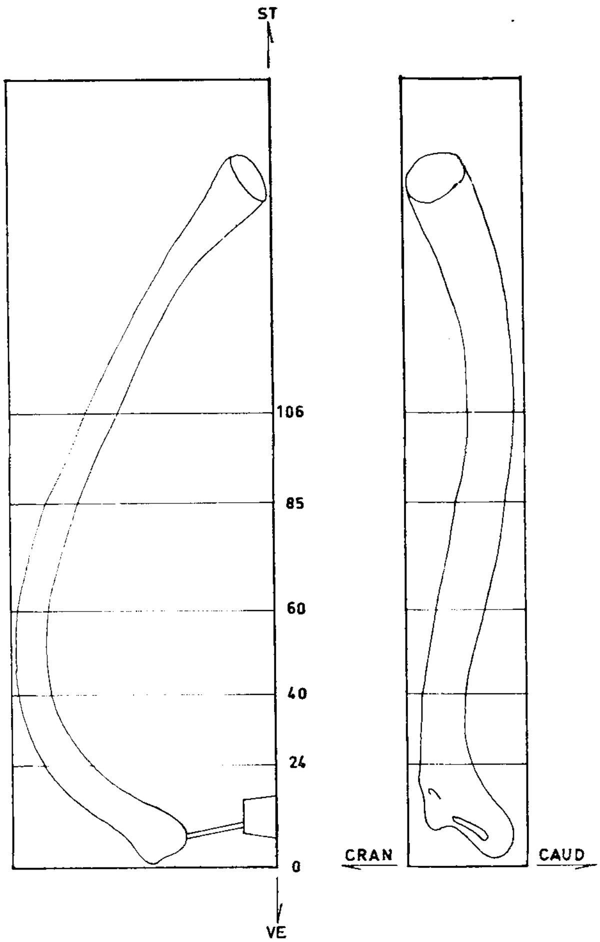


Figure 3. The positioning of the rib in the mould. Drawn according to an X-ray of the casting.

was kept vertical in order to let the air out through the open upper end. To facilitate the dismantling of the mould, the walls were covered with a thin layer of colourless wax to prevent the metal from sticking to the casting. This was important in order to preserve the coordinate system adopted for the measurements planned. The direction of the position of the axis of the system was determined by the walls (Fig. 4). (pulm-cut, cran-caud and st-ve directions). The castings were stored in a freezer. In all, 53 ribs were embedded using this method.

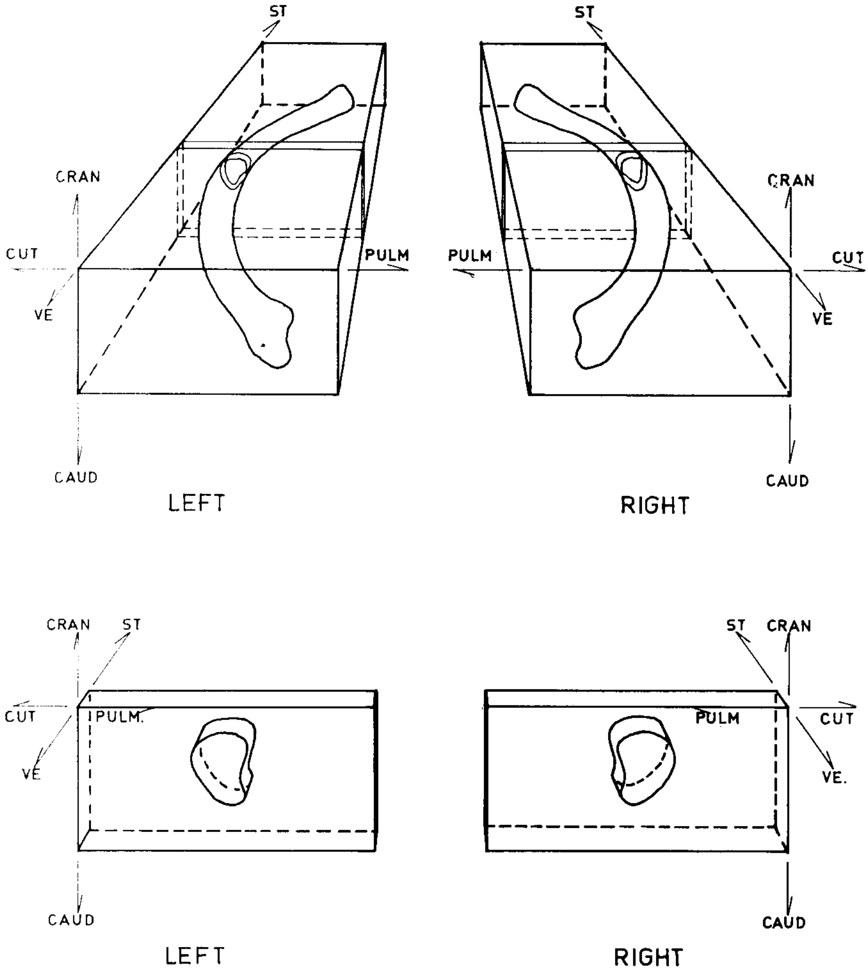


Figure 4. Schematic presentation of the coordinate system and the treatment of the right and left side of the rib illustrating the three-dimensional nature of the study.

Filing of the rib by milling machine

Each rib casting was X-rayed. In order to expose and examine successive cross-sections of the rib, parts of the ribs were filed off using a milling machine. The rotational speed of the cutter was 540—600 rpm and the feed was approximately 4 mm/second. The casting was kept rigidly fixed and the same direction in filing off sections was always used to preserve the orientation of the coordinate system adopted. The filing-off was begun from the vertebral part and the direction was perpendicular to the longitudinal axis of the casting, i.e. the ve-st direction. The length of the rib was measured from the X-ray of the casting (Fig. 3). The filing-off was performed at intervals of 1—5 mm depending on the accuracy needed and on the part of the rib. Thus, the intervals were longer in the corpus and shorter in the angulus. The casting was removed from the machine and in order to preserve the proper direction of each surface exposed, the edges were marked during photography in the same manner with a yellow colour mark. The surface was then photographed (Fig. 5) and the photographs could be oriented with the aid of these control marks. The photography was performed in the scale 1 : 1 with a Leitz Leica Aristophot apparatus with Agfacolor daylight film CT 18. Two Osram UV-lamps (HBO 200 W, spectral range 3300—5000 Å) were used for illumination. Between the lamps and the casting UG 1 filters were used as exciter filters. In front of the camera lens a Kodak Wratten 2B filter and a Kodak colour compensating filter CC2OR were used. With these filters the yellowish fluorescence of OTC could be seen very clearly. The exposure time was 1—3 seconds depending on the intensity of the fluorescence. During the filing-off process and the photography the positions of the appearance and disappearance of the OTC-labelling were recorded.

A total of 53 ribs (15 normal and 41 scoliotic) were prepared in the described manner. 1910 photographs were taken representing about 35 photographs of each rib.

Study of displacement of the centre of the cross-section of the rib

The photographs were analyzed by projecting the slides on paper, on which the contours of the sections of the ribs and the OTC-lines were drawn. In this way the sections could be drawn on the same paper. The area between the inner and outer curve indicated the amount of growth. The centre of the cross-section for the inner and outer curve in each curve was determined by cutting the projected figure out of the paper, and suspènding it from three different points, drawing a vertical line through each point of suspension separately. Thus the centres of the curves were determined by determining the corresponding centres of gravity of the paper. The straight line between the centre of gravity

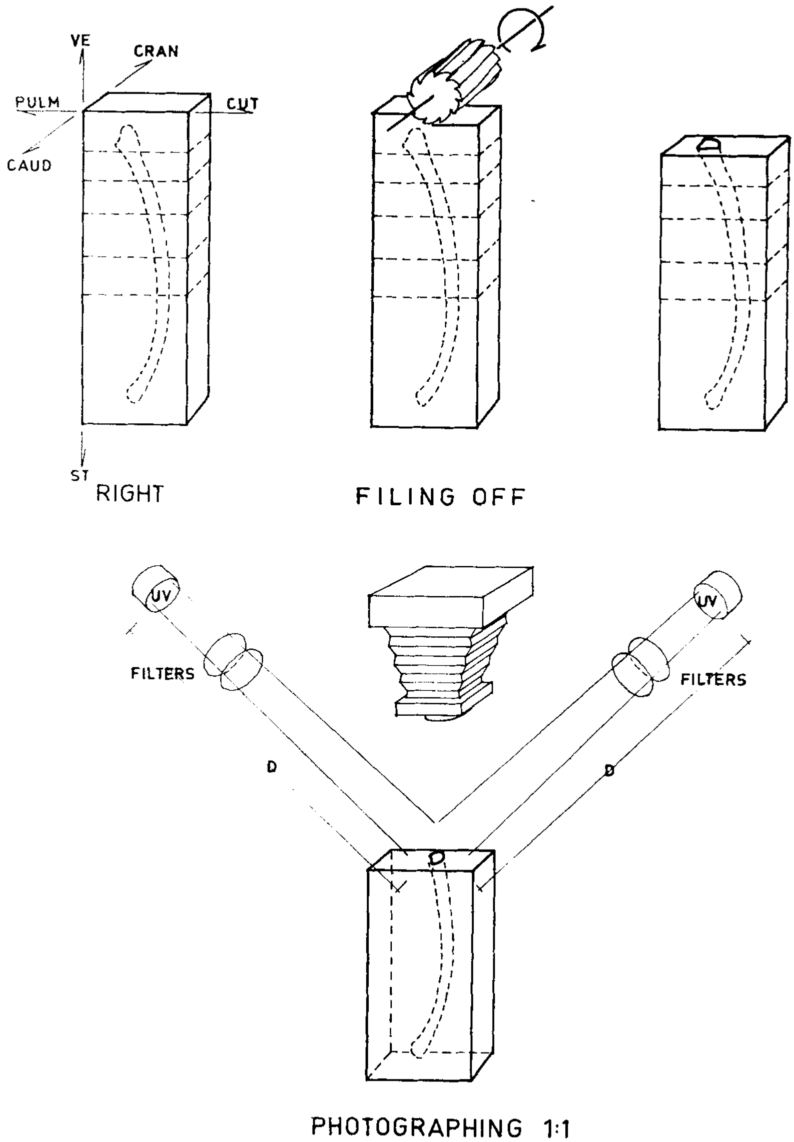


Figure 5. The filing of the surface of the cast and the photographing of the exposed surface. The filing off was begun from the vertebral end. The figure presents the right side rib. The filing off was performed perpendicularly to the st-ve axis.

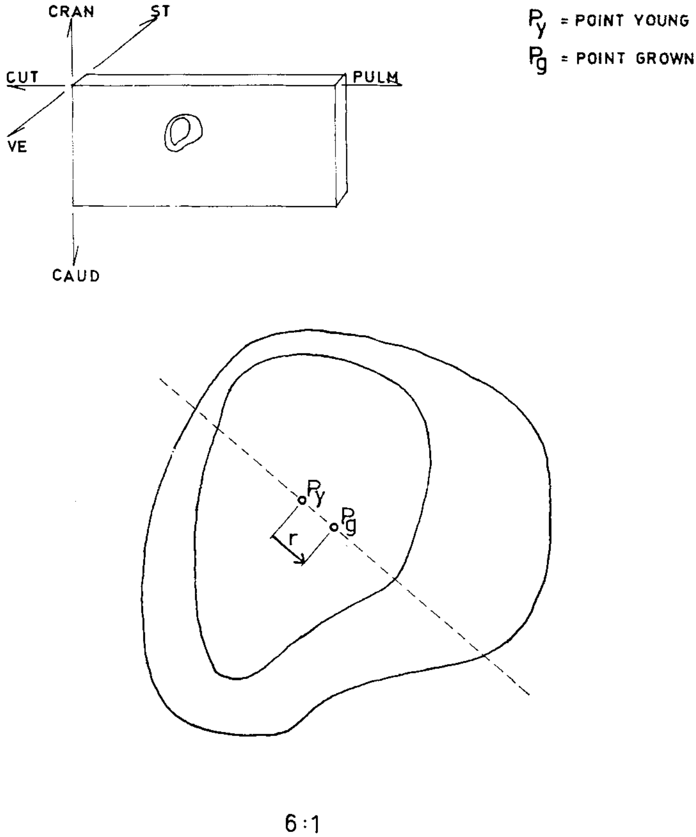


Figure 6. The resultant of the displacement of the centre of the cross-section i.e. the resultant of the growth in the section.

of the two curves represented the resultant of the growth in the section in question. This was a direct measure of the displacement of mass, and it also indicated the drift of the growth. As the coordinate system was preserved during the casting, filing-off and photography, the total resultant of growth of a rib could be determined. The centres of cross-sections representing the two stages of growth were determined in this way in 28 ribs (8 normal and 20 scoliotic). Care was taken to preserve the coordinate system on the paper used for drawing the sections. The growth resultant was divided into components along the pulm-cut and the cran-caud directions using trigonometric functions.

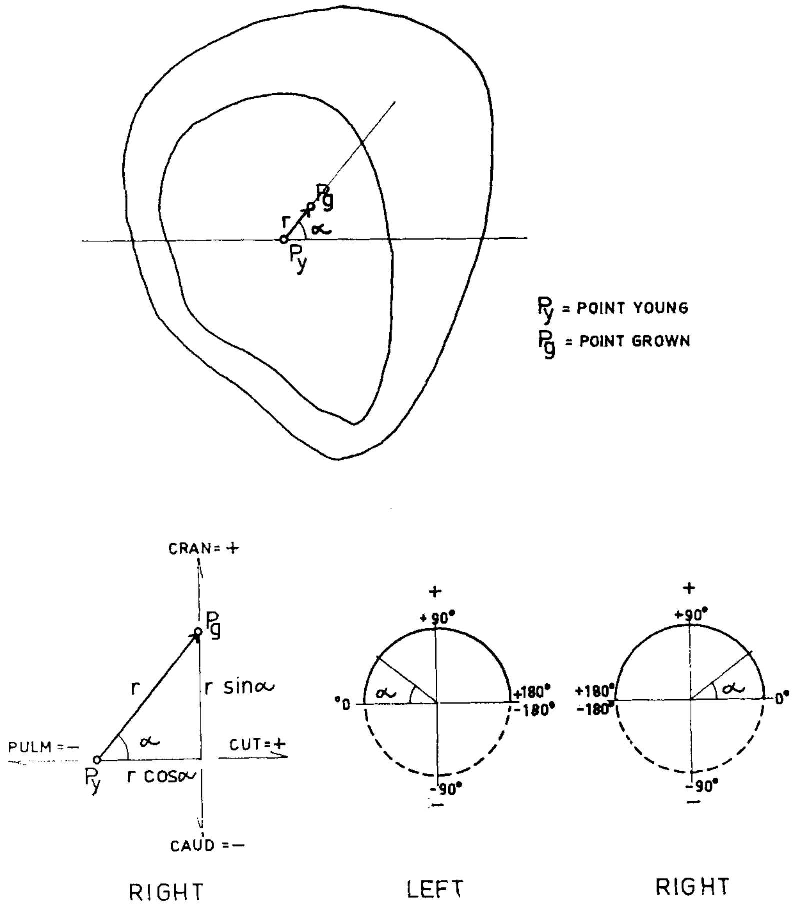
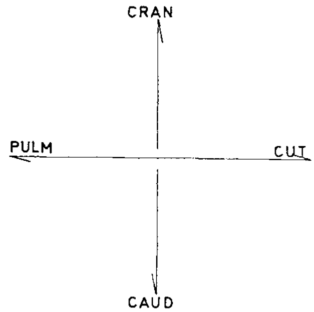


Figure 7. The division of the resultant into components. The length of the resultant was measured. The direction angles were defined, as in the figure to the right and to the left, using the pulm-cut axis as a reference.

The direction angles of the resultants were measured (Fig. 7 and 8). For this purpose the longitudinal axis was chosen as the reference axis. The distance of each section from the vertebral end along this axis was known. The growth in the directions pulm-cut and cran-caud could then be determined as a function of the resultants. Graphical representations of these quantities are presented in Figs. 13. With the aid of these curves quantitative evalutions could be drawn on each rib separately.

P_yn P_gn	ST	r	
n		LENGTH	ANGLE
1	16 mm	8 mm	−91°
2	20 mm	4 mm	−87°
3	30 mm	1 mm	88°
4	45 mm	6 mm	−11°
5	60 mm	6 mm	11°
6	75 mm	16 mm	−28°
7	90 mm	12 mm	−23°

P_y = POINT YOUNG
P_g = POINT GROWN



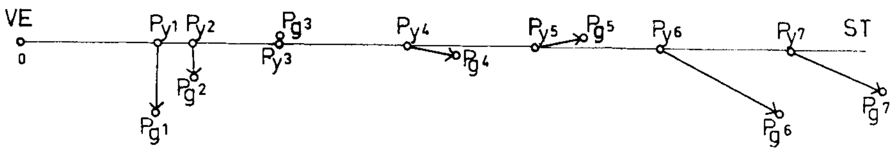


Figure 8. The definition of the direction angles on the ve-st axis. The distance was measured from the vertebral end. Normal 13th rib.

D. DISCUSSION OF THE PRESENT METHODS

Due to the complexity of the methods used in the present investigation the possible sources of error and their effect on the accuracy of the results should be discussed.

The purpose of this investigation is to elucidate the changes in the shape of the rib on a macroscopic level in a qualitative manner during the period of fastest growth. The methods aimed at analysing the remodelling of the rib during normal growth and the longitudinal growth of the rib. A conception of the drift and the amount of the longitudinal growth was obtained by the simple metal-marking method. For the treatment of the observations made with the OTC-method it was necessary to present the observations in a quantitative form to illustrate the growth process. The purpose of the work was to create a total picture of the period of fastest growth, but only during the part of the growth process when OTC-labelling made observations possible. The transverse sections of the parts of the rib containing no OTC-labels due to longitudinal growth, i.e. the ends of the bone, had to be left out. In earlier investigations a partial reconstruction was used to illustrate the remodelling of long bones (Leblond et al. 1950, Tomlin et al. 1953, Ham 1969, Enlow 1963). However, no method for attaining a three-dimensional picture of the total growth and the remodelling of bones was presented by these authors. It is also possible to use the present method in investigations of the details of bone growth in general.

The following fallacies in the above technique must be taken into account:

a) If the distance between the metal markers changes by their displacement into soft tissue during the growth of the bone, the method cannot be used. No such changes occurred during the present investigation.

b) In some cases metal markers caused a periostal reaction in the diaphysis, which disturbed observations locally, but this can hardly be considered to have had any effect on the observations of longitudinal growth.

c) It is obvious that an exact reconstruction (Figs. 9 and 10) is impossible, because parts of the young rib, into which the marks were originally inserted, disappeared due to the remodelling process. For a complete reconstruction the young bone must be taken from another animal of the same age and size.

d) OTC-labelling represents a modern, commonly accepted labelling method. OTC has been found to have an injurious effect on bone during the embryonal stage, when given over a long period (Saxén 1966), but it is not known to have any effect on the longitudinal growth of postnatal bone when given for a short time, hence no sources of error concerning this part of the investigation should be expected. Kaitila (1971) draws the same conclusion in his work. The line caused by a preoperative dose of OTC, given to the test animals during 2—3 days, was not too thick to prevent an accurate measurement. During photography the fluorescence of the deeper parts of bone softened somewhat, affecting the accuracy of determining the OTC-line. Some practice was needed before the line could be discerned. This disadvantage was somewhat diminished by the installation of the UV-lamps at a suitable angle. At the sternal end, weakness of the OTC-lines did not occur, but the labelling was found to »stretch». The disturbance was not noteworthy, as the contours of the OTC-line were sufficiently distinct.

The thickness of the OTC-lines in the angular part possibly caused some minor inaccuracy as a consequence of the length of the section. In those sections the OTC-line was drawn in the centre of the fluorescence. This was not considered to disturb observations, since they were of a qualitative nature.

e) The slight dissimilarity of the curvature of the ribs could also be a source of error when the rib was fixed into the mould. Therefore the fixing of the rib was performed as analogously as possible. However, when calculating the error, there was hardly any effect on the quality of the final results. The exposed surfaces were found to be uniform, and no »burning» due to the rotation speed was observed. The cutter did not »move» the structure of the bone marrow and the filed surface was clear enough to be photographed.

f) Aberration, caused by the optics of the projector, was kept in mind when projecting the sections from photographs to paper. The sections were placed in the middle of the projected area to minimize aberration. The magnification was controlled in two phases. The exposed surface was first controlled during photography and then during the projection of the photograph on paper. The variations in weight of the different parts of a paper of uniform thickness was ignored as the measurements were performed at three different points.

g) The peripheral line of the rib might have changed due to too violent detachment of the periosteum, which might have effected the amount of growth, too. Particular attention was paid to this factor during the operation.

Thus, all the possible sources of error having an effect of some kind on the aforementioned measurements can be eliminated due to the sufficiently short distances between the sections. In the present investigation the significance of the fallacies can be considered theoretical since no absolute quantitative evaluations could be attained and the methods were only used to illustrate the growth process qualitatively.

NORMAL GROWTH AND REMODELLING OF THE RIB

A. INTRODUCTION

Gray's textbook of anatomy mentions that postnatal growth obviously takes place at the sternal end of the rib (Gray 1967). Swoboda (1969) states that there is an epiphyseal plate at the vertebral end. This statement is to be found in most textbooks of anatomy. In addition, he states »Die sternalen Rippenenden sind Metaphysen mit intensivem Längenwachstum . . .». Rickets and scurvy are mentioned, as histological changes at the sternal end of the rib have been observed as a result of these diseases. The literature dealing with rickets contains investigations of the vigorous cell proliferation at the costochondral junction towards the rib deformed by this disease (Park 1964). In this part of the rib, cartilage tissue is replaced by bone. Swoboda points out that the sternal part of the rib acts as a metaphysis, which would refer to the existence of an epiphyseal line at this junction (Swoboda 1969). It was not until the introduction of the OTC-method that investigations on the sternal end of the rib were begun. There are numerous microscopical publications on the growth and remodelling of the rib (Klein et al. 1965, Epker & Frost 1966, Landeros & Frost 1966, Taylor et al. 1966, Marotti et al. 1968, Frost et al. 1969 etc.). By microscopical investigations it was discovered that growth at the sternal end of the rib mostly occurred in the cutaneal direction. In a microscopical investigation on the growth of the bone tissue, Landeros and Frost proved the occurrence of a vigorous drift of the sternal part in the cutaneal direction, which increases towards the sternal end. This was presented in the form of a schematic figure (Landeros & Frost 1966). Epker and Frost state on the basis of their OTC-investigations that strong apposition in the cutaneal and resorption in the pulmonal sides takes place at the sternal end of the bone (Epker & Frost 1966). Emery and Kalpaktsoglou expressed their conception of the rate of growth at the sternal end by saying »Thus the costochondral junction should really be considered more like a slowfiring multibarrelled rocket!» thus referring to the rapidity of cell proliferation at this point. They assumed the rate of growth to be equal at either end of the rib without presenting any proof of it. In the human embryo the growth at the ends of bones would be at least 0.22 mm a day according to their calculations. In an investigation of the fifth and the sixth rib in man, Emery and Kalpaktsoglou (1967) proved that the actual rate of growth at the costochondral junction was about 0.43 mm a day.

Hueter measured the growth of rabbit ribs from the costal tubercle in the vertebral and sternal directions and found that the rib increased more in length in its sternal part (Hueter 1878). In his book, Rubin (1964) mentions that growth at the sternal end of the rib occurs in the cutaneal and cranial directions and that longitudinal growth takes place mostly at the sternal end of the rib. According to him, constriction or absorption probably occurs from the inferior surface, and apposition of new periosteal bone takes place superiorly (Rubin 1964). The figure on page 70 in the aforementioned book presents the relative rate of growth at the ends of the rib and the author claims that longitudinal growth is faster at the sternal end of the rib and much slower at the vertebral end. The amount of growth is not mentioned. Neither is there any mention of where these observations were made, and therefore the schematic figure probably has to be regarded as an observation based on X-rays. Although Emery and Kalpaktsoglou (1967) mention the rib as the ideal bone for studying linear growth, the rib has been used very little in macroscopical investigations. In spite of the fact that the bone is situated near the skin and is easily accessible to operative marking, it is not easy to detach it as a whole from a living animal, due to the relatively complex anatomy of its vertebral end.

B. EXPERIMENTAL SERIES

Two methods were applied to the investigation of normal growth. The metal marking method was used to obtain a conception of the nature of growth and its drift and quality. The purpose of the OTC-labelling method was to investigate the process of remodelling taking place in the rib. This method permitted the reconstruction of an overall picture of the remodelling and the growth process. For a more detailed investiga-

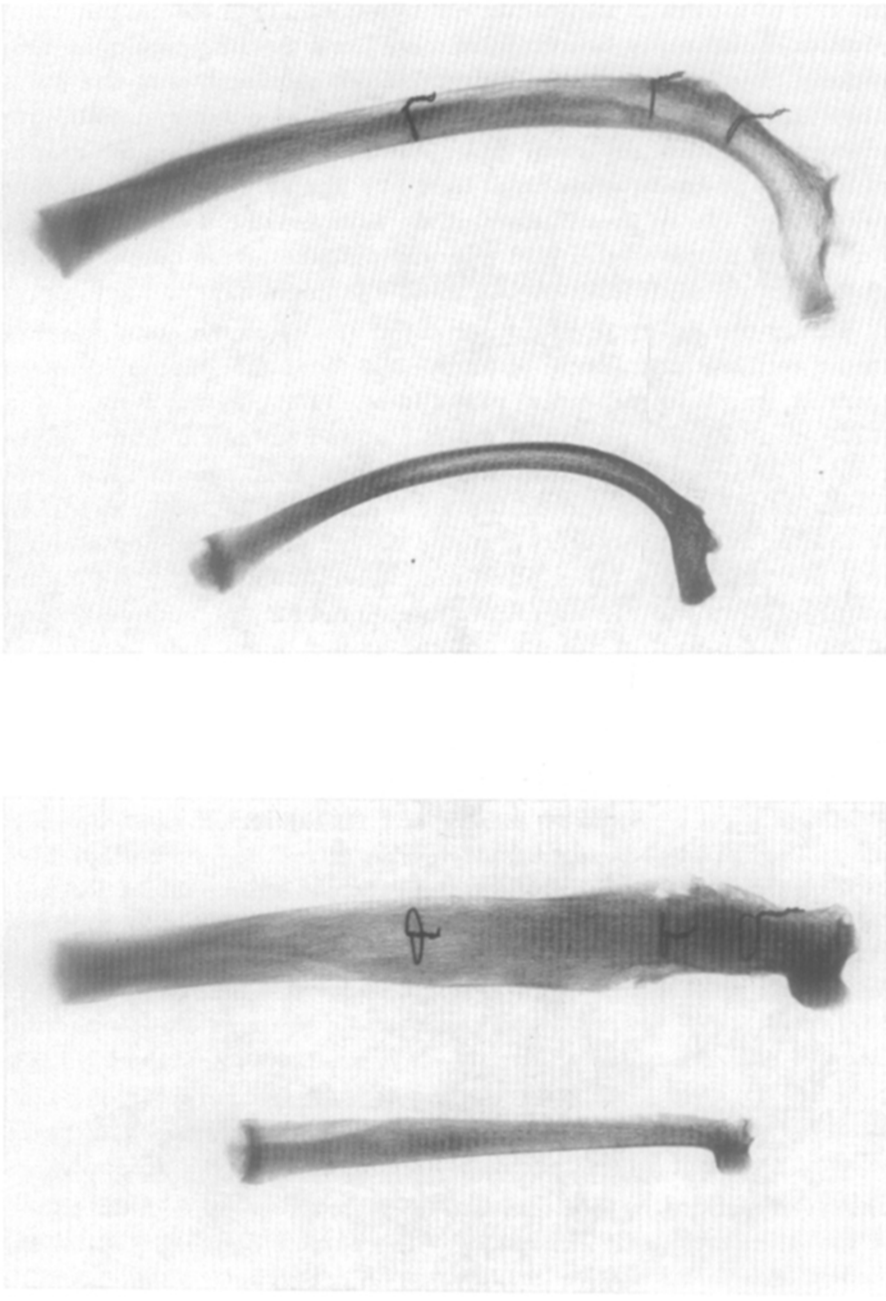


Figure 9. The position of the metal markers in »older bone». The lower radiograph shows the size of the rib at the time of labelling.

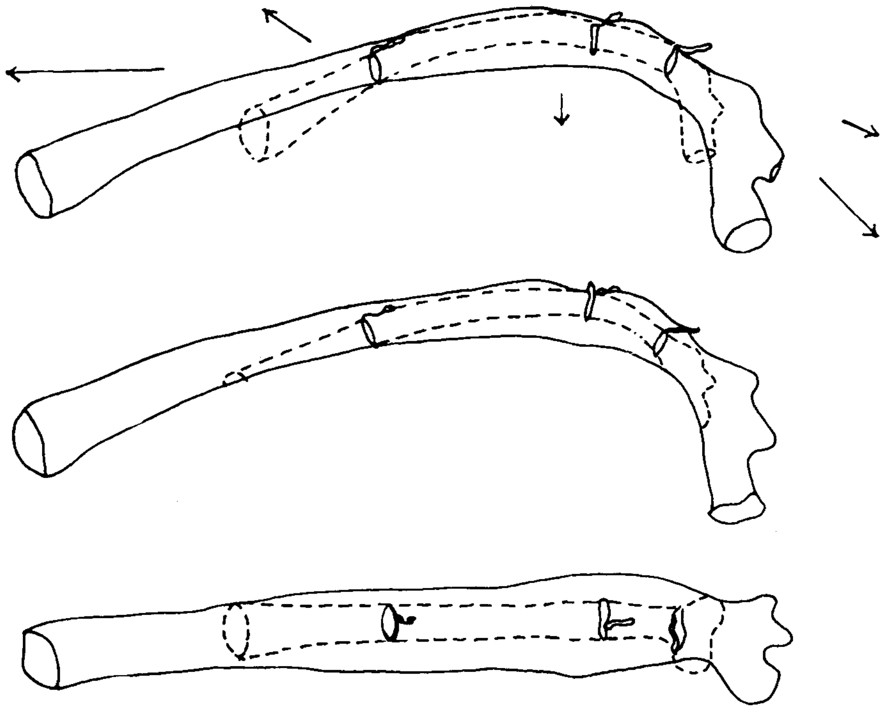


Figure 10. Knowing the distances between the markers in the »younger bone» a graphic reconstruction, indicating the drifts of the growth, was made. Notice the vigorous growth of the sternal end in the cutaneal and sternal directions.

tion the aforementioned marking of the centres of the cross-sections was used to observe the drift in relation to the pulm-cut and cran-caud directions.

Metal marking

The ribs of 5 pigs were marked subperiostally with stainless metal markers under anaesthesia using the aforementioned operative technique in aseptic conditions (see Figs 1 and 9). The age of the pigs was 21—70 days at the time of operation. They were allowed to grow to an age of 112—113 days. Altogether 7 ribs were used.

OTC-labelling

No attention was paid to a possible asymmetry of the right and left side of the normal animals. Only the ribs of the right side were used.

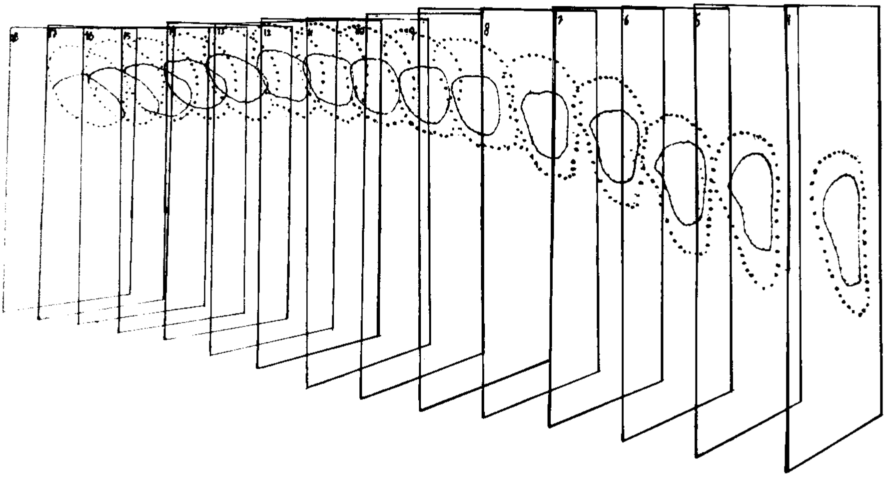


Figure 11. The positioning of the sections at certain distances from one another on the basis of OTC-labels gives a reconstruction of the course of growth of a normal rib in the area that can be observed by OTC-labels.

Neither was it the purpose to observe the growth process in each rib separately. Three pigs were used in this normal series and 15 ribs were investigated in all. Cross-sections of the most curved angular part were studied at short intervals, while those of the less curved sternal part were examined at longer intervals.

The sections of normal ribs chosen for the investigation of the displacement of the centres of the cross-sections were chosen mainly at the same points as the sections of scoliotic ribs used for qualitative comparison. According to the OTC-method a reconstruction illustrating the course of growth was made by magnifying (x 12) a number of sections from the area marked with OTC on transparent plastic sheets. The sheets were placed in a frame constructed according to the coordinate system used, so that the intervals of the sections corresponded to their relative intervals in the rib. A schematic figure (Fig. 11), obtained by photography gives an idea of the increase of the diameter of a normal rib. Eight ribs of normal pigs marked with OTC were used for the investigation of the centres of cross-sections. Seven of these were chosen for the final illustrative presentation.

C. RESULTS

Metal marking

When the pigs were killed, the distance between the metal markers in the ribs was measured, and it was found to have remained almost unchanged during the growth process (Fig. 12). The metal markers are represented by the vertical lines in the diagram. The upper lines of the pairs in the histograms indicate the ribs of young animals and the lower the ribs of grown animals. The shaded areas indicate longitudinal growth. The table was obtained by using the corresponding bone of a pig of the same age. The diagram of the growth process could be reconstructed by placing the rib of the young animal (YA) »inside» that of the grown animal (GA) with the aid of the metal marking (see Figs. 9 and 10). By measuring the distance between the old and the young bone ends, it was possible to obtain certain values for the growth at the sternal and vertebral ends. The values indicate that the rib grows distinctly more at the sternal than at the vertebral end. Thus, the longitudinal growth at the vertebral end of the bone is only about one fourth of that at the sternal end. In all, 5 young pigs were used for the measurement. The ribs of the normal pigs were chosen to correspond to the ribs of the scoliotic experimental animals situated by the apex.

OTC-labelling

During the successive exposure of different cross-sections and photography, the points at the vertebral end where OTC-labels appear in UV-light and at the sternal end the point where the labels disappear were noted first. In general, the labels appear, depending on the age of the test animal, about 10—20 mm from the vertebral end and disappear about 90—100 mm from the vertebral end. The resultant of the direction of growth in each section could be defined by using the method of the displacement of the centre of a the cross-section and by combining these, the total growth process of the ribs could be determined. When the numerical values of the components of the growth resultants in these successive sections have been determined by trigonometrical functions, as described on pages 21, 23 and 24 (see Figs. 7 and 8) a diagram for graphic presentation can be obtained (Fig. 13). The patterns of the diagrams of normal ribs show a certain distinct similarity due to normal physiological asymmetry. The diagrams of the left and

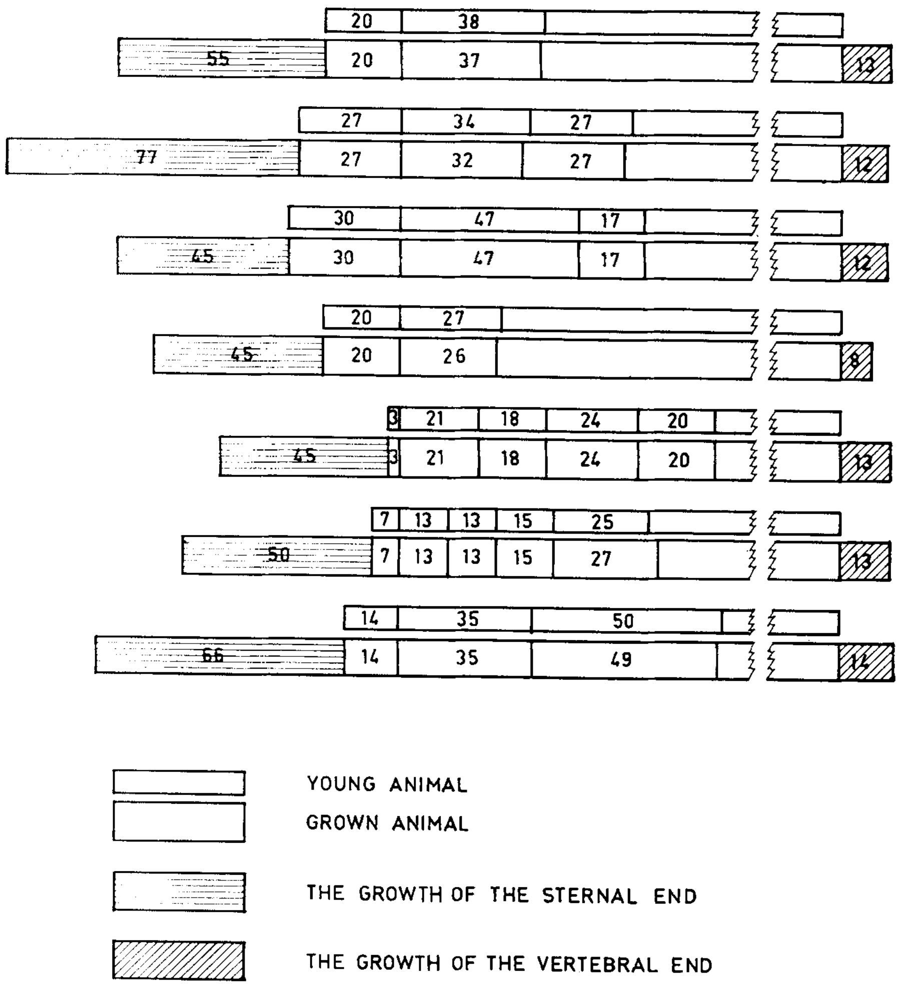


Figure 12. Indicates schematically the change in the position of the markers. The distance between them was unchanged. The growth at the sternal end can be estimated as four times faster than at the vertebral end. Measurements in millimetres (mm.)

right 8th ribs of a normal pig in the control series were almost identical both in the pulm-cut and the cran-caud direction (Fig. 14 and 15). This observation proves that the description of the qualitative process of growth can also be presented quantitatively.

The following observations on the modelling of the ribs of the normal pig can be made, starting from the 8th rib (Figs. 13 and 16). In the

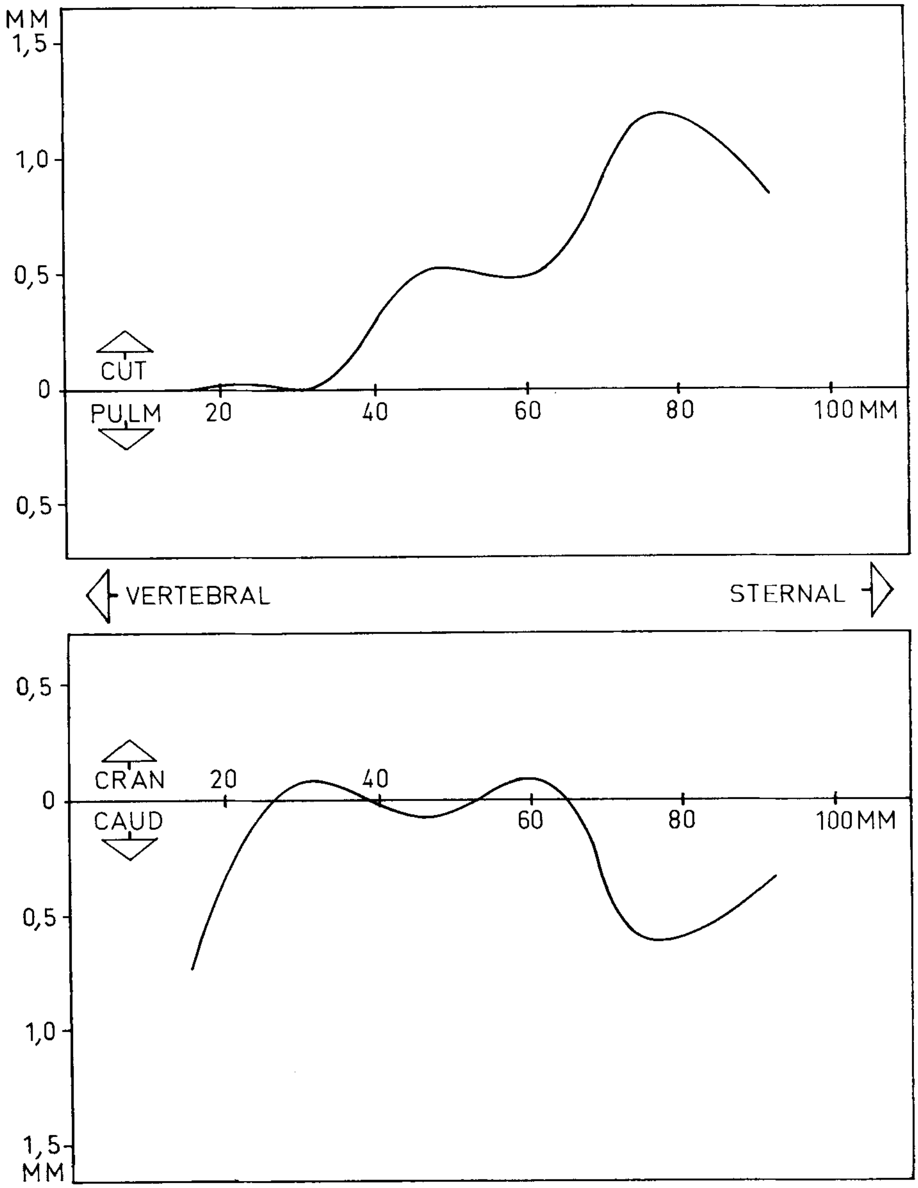


Figure 13. Growth pattern of a normal 13th rib. The upper diagram presents the growth in the cutaneal-pulmonal direction and the lower in the cranial-caudal direction. Growth period 38—78 days (OTC-labelling-killing).

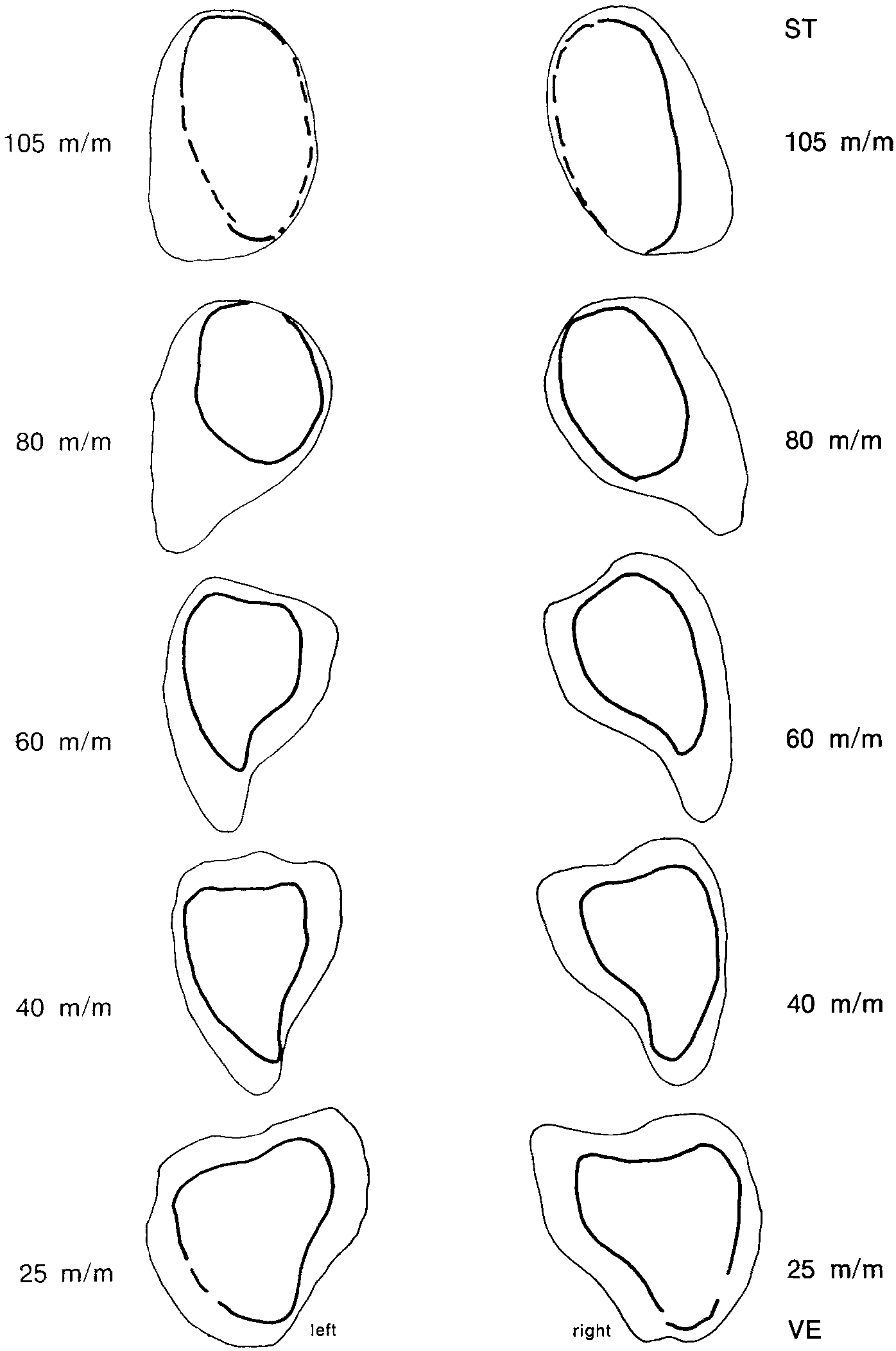


Figure 14. Series of sections presenting the similarity of the right and left side on the basis of OTC-lines. A normal rib.

diagrams a similar drift was observed at the vertebral and sternal ends of all ribs. At the sternal end, closer to the sternum, the drift changes from the cutaneal to the pulmonal direction. Correspondingly, the drift of the growth in the caudal direction decreases towards the sternal end. A similar tendency can be observed at the vertebral end. Near the vertebral end, growth occurs in the cutaneal direction but decreases considerably around the 30 mm section from the vertebral end, from where more growth in the pulmonal direction can be observed. In the lower diagram, growth at the vertebral end occurs first in the caudal direction, and around the 30 mm section the tendency approaches the cranial direction. These diagrams of each rib are very similar, the form of the diagrams depending on where the rib is situated in the thoracic cage (Fig. 16). Thus, for example, the 13th rib obviously looks different from the 8th rib in these diagrams. Furthermore, it is obvious that the growth process of various ribs must be different because their anatomic shape and their position in the thorax are different.

D. CONCLUSIONS

An investigation of normal ribs with the metal marking method indicates the approximate drift of growth. The distance between the metal markers remains unchanged throughout the growth process. By placing the contour of the rib of the young animal (YA) inside the contour of the rib of the grown animal (GA) with the aid of metal markers it can be established that the bone grows distinctly more at the sternal end than at the vertebral end. The metal marking method is classical and its significance lies in its usefulness in the investigation of longitudinal growth. Observations with metal markers were also made by Wolff 1888 and Kornew 1929. Harris 1926, Brash 1934, Payton 1931 and Rubin 1964 observed markers left in bones or induced into them. Partial reconstruction was also applied, e.g. Enlow (1963). These investigations gave results on the amount and rate of the longitudinal growth of different bones.

In the present investigation, performed with the metal marking method, the angular part of the vertebral end was found to straighten out somewhat during the growth process (see arrows in the reconstruction of the growth of the rib, Fig. 10). Vigorous longitudinal and appositional growth directed to the surface of the body is observed at the sternal end, which leads to the straightening of the angular part. At

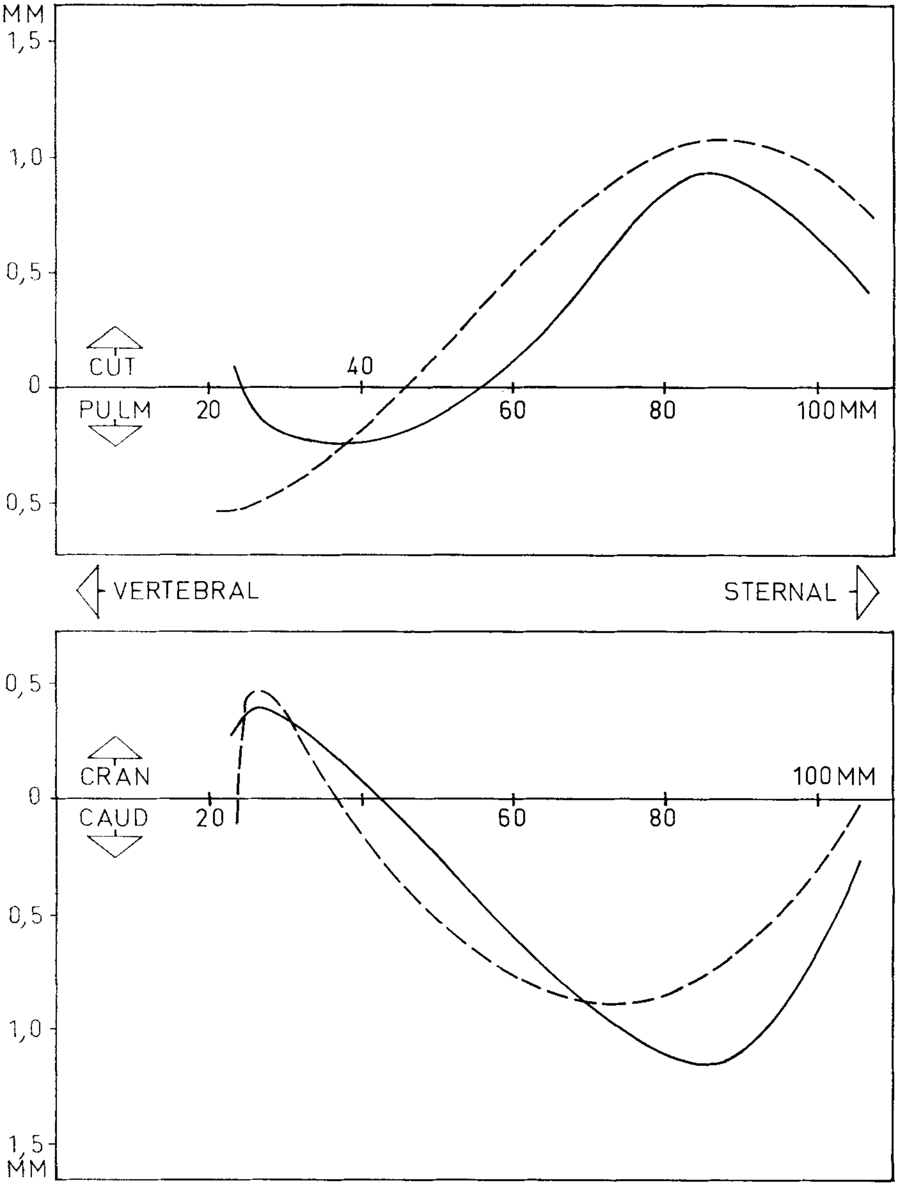


Figure 15. Growth pattern of the 8th rib of a normal pig on the right and the left. The upper diagram presents the remodelling in the cutaneal-pulmonal direction, the lower in the cranial-caudal direction.

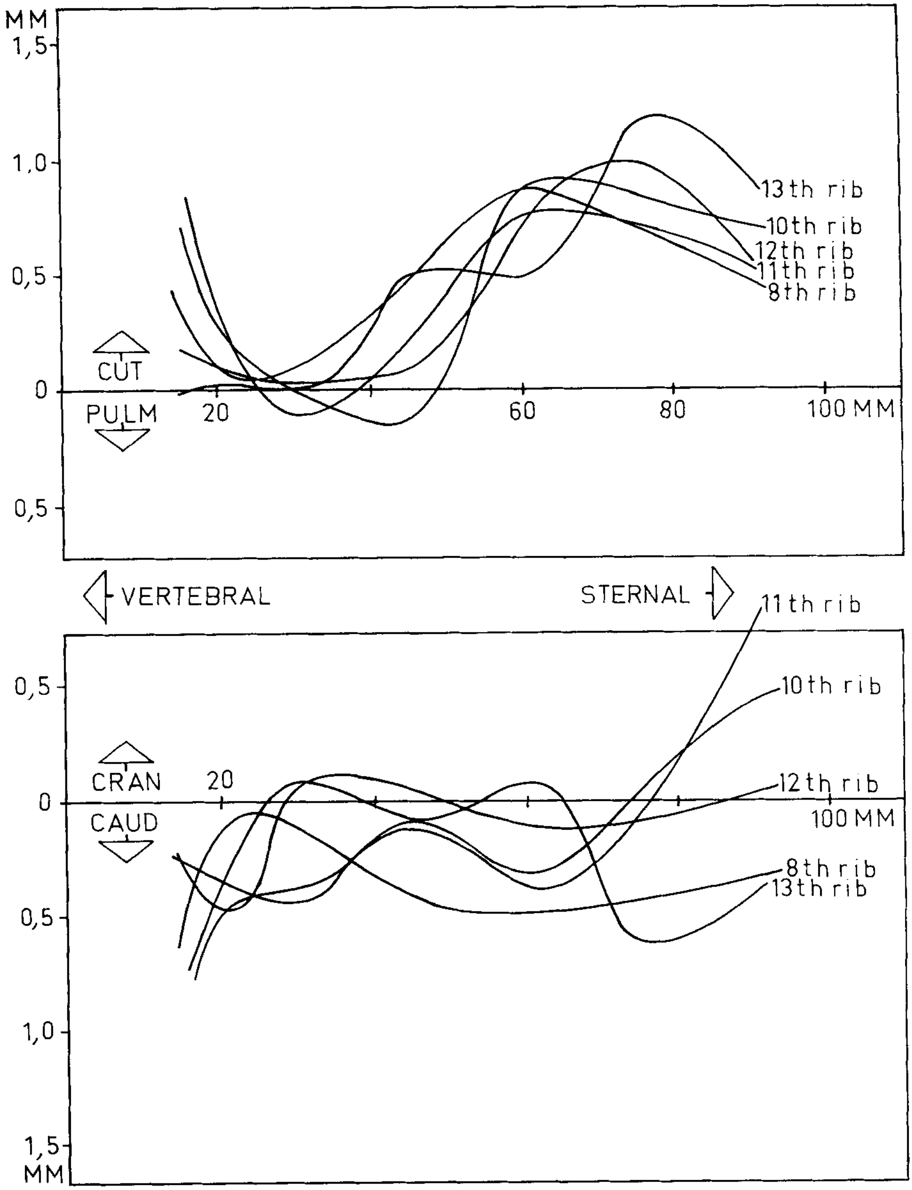


Figure 16. Specific curvature of various ribs of the same normal pig. The curves are similar in the cutaneal-pulmonal direction, but somewhat deviating from each other in the cranial-caudal direction, especially in the sternal end of the rib.

the sternal end there is also more growth in the caudal direction in cranially located ribs. In this respect the observation differs from Rubin's assumption that in the sternal end growth would occur generally in the cranial direction (Rubin 1964). Rubin's observations seem to have been made on the human body.

According to Karaharju's experimental investigation of pigs, longitudinal growth in the spine of a pig takes place almost at the same rate in the two end plates of the vertebra (Karaharju 1967). The same observation was made earlier by Haas 1939, Bick & Copel 1950, Gooding & Neuhauser 1965. They found that vertical growth in the vertebral body was uniform in both end plates. The remodelling of the thoracic cage is known to occur from round into oval (Meyer 1866, Swoboda 1969). These investigations support the observation made during the present work that bending of the rib decreases during the growth process and that growth in the cran-caud direction occurs in relation to the longitudinal growth of the vertebral body at the vertebral end of the rib. In addition to this there is remodelling depending on the specific growth in each rib and on the position of the rib in the thorax.

The concept of the growth process obtained from the metal marking method was complemented by the more detailed OTC-method, by which diagrams of growth could be drawn using the method of the displacement of the centres of cross-sections. These diagrams indicate the direction of growth at every point in the cutaneal-pulmonal and cranial-caudal directions. The normal diagrams of many ribs showed very distinct similarities. This proved the accuracy of the method to be sufficient for an illustrative presentation of the qualitative and even quantitative pattern of growth. This was also justified by the fact that the diagrams of the left and right sides of a normal pig were almost identical. Likewise, the corresponding diagrams of the different ribs of the same animal showed similarity. On the other hand, the minor dissimilarities in the behaviour of the diagrams may depend on the specific anatomic difference of the ribs and on the influence of the sternum on the growth process of the whole thoracic cage. This is also proved by the cranial drift of the sternal parts of the caudal ribs.

No detailed description of the normal growth of the rib could be found in the literature. An account of the remodelling during the fastest period of growth was therefore necessary for the presentation of the differences in the growth of the ribs of a normal and a scoliotic test animal. The remodelling of the rib obviously follows the drift of the total growth of the thorax. The most significant observation on the growth of the normal rib was the more vigorous growth in the sternal end than in the vertebral end. An investigation of a normal pig also shows that the drift of growth varies somewhat in the different parts of the rib depending on its position in the thorax. The dominating influence of the sternum seems to be a significant factor in the remodelling of the rib.

GROWTH PATTERN OF THE RIBS IN EXPERIMENTAL SCOLIOSIS

A. INTRODUCTION

Scoliosis is one of the most difficult orthopaedic problems in children and the etiology of its idiopathic form is not yet known. The history of the investigation of this crippling disease is long. Valentin uses one fifth of the 287 pages in his book (Geschichte der Orthopedie) for an account of its history (Valentin 1961). No other orthopaedic disease has been the subject of such eager study. For example, there is a monograph containing 478 references from 1538 to 1885 (Fischer 1885). Idiopathic scoliosis still remains a mystery, while other causes for this disease such as poliomyelitis, rickets and tuberculosis are known. Paralytic scoliosis has taught us the role of muscle imbalance as a factor provoking scoliosis, and this may also play a part in the etiology of idiopathic scoliosis (Carey 1932, Langenskiöld & Michelsson 1961, Liszka 1961). The primary cause of this imbalance is still unknown.

Research in the field of scoliosis has two main purposes: the clarification of its etiology and the discovery of an adequate method of treatment. The discovery and the use of polio vaccination at the end of the 1950's have decreased one of the factors provoking scoliosis leading to a rapid decrease in the incidence of paralytic scoliosis.

von Lesser (1884) made an attempt to provoke scoliosis by the resection of the phrenic nerve, but although the operation was successful, he was not able to provoke any considerable changes in the spine. He considered the vertical position of man to be one of the factors provoking scoliosis. However, in numerous publications, idiopathic scoliosis has been described as occurring naturally in several species of animals such as pigs (Schulthess 1901, Hartel 1909), goats (Ottendorf 1903), hens (Chlumský 1924) and fish (Eckhardt 1934, Snellman 1966). The fact that idiopathic scoliosis is found in fish, birds and the quadrupeds tends to refute the statement that the vertical position of man would be a main factor in provoking idiopathic scoliosis. As to the other theories on the etiology of scoliosis, reference can be made to Brunk's thesis (1951) dealing with the part played by rickets as a factor causing scoliosis and to the etiological division presented in a publication by Liszka (1961). In his book Brunk deals thoroughly with the theories of the origin of idiopathic scoliosis through the centuries.

During his measurements of post-mortem specimens, Meyer discovered that in very severe dextro-scoliosis, the difference in the lengths of the ribs on the concave and convex sides was very small (at most 9 mm), while the overall length of the ribs was 240 mm (Meyer 1866). In his opinion this proved that the ribs could not provoke scoliosis. Hueter (1878) presents a different opinion, stating that the growth of the thorax is a consequence of the vigorous growth process in the sternal end. He used rabbits in his experiments, removing cartilage from the sternal part of 2—3 ribs (3rd—6th ribs), which brought about a change in the growth of the rib. On the basis of this he claimed that scoliosis results from a decrease in pressure on the concave side. Wullstein (1902) described the deformity of a scoliotic thorax in a comprehensive publication of 213 pages presenting 200 references from 1880 to 1902. He used dogs as experimental animals. Wullstein was probably the first to provoke scoliosis in animals. He tied the front and hind legs of dogs with leather bands. Later on, there were numerous attempts by other investigators to provoke scoliosis in test animals, but the resulting scoliosis was too slight to allow any comprehensive conclusions and the experimental material was generally limited.

The methods developed at the Orthopaedic Hospital of the Invalid Foundation in Helsinki and other institutions have enabled the experimental investigation of scoliosis and its possible corrective treatment (Manning 1968, Nash 1969, Burwell 1970, James 1970). Michelsson mentions numerous earlier experimental studies, but few of them were successful in provoking progressive scoliosis (Michelsson 1965). Michelsson's thesis contains a review of earlier experiments and a description of his own methods. Langenskiöld and Michelsson (1961) stated that resection of the vertebral ends of ribs and hemilaminectomy regularly provoked scoliosis, and that the most significant scoliosis-provoking factor was the loss of function of the costovertebral ligaments. Later on, Manning (1968) and Piggott (1971) applied the same methods in provoking scoliosis. Liszka (1961) used a method similar to that used by Langenskiöld and Michelsson (1961) in his experiments on rabbits. Pigs were used as test animals by Pacher (1939) and Ottander (1963), among others.

The ribs attached to the spine are deformed adaptively as a consequence of the scoliosis. As proved earlier by many investigators (Fischer 1885, Schulthess 1905, Kleinberg 1951, Steindler 1964), a twist like the one in the schematic figure occurs in the human body as a consequence of this. Roaf describes his own concept of the movement of the ribs during the breathing process and the change in this movement in scoliosis (Roaf 1966). Michelsson proved a similarity in the deformity of ribs in rabbits and pigs in comparison to human ribs.

In his investigation of the pathological conditions of bones under compression and tension, Maas also deals with the deformation of ribs in idiopathic scoliosis (Maas 1902 and 1924). According to him, compression and tension have no organic effect on the growth of bone, but they do have an effect on the direction of growth by increasing and decreasing the amount of growth through apposition and resorption. On the concave side in the vertebral end of the rib, the growth in diameter decreases while longitudinal growth increases. On the convex side there is less longitudinal growth and more increase in diameter. Tension occurs on the concave and compression on the convex side. Maas did not investigate the longitudinal growth at the sternal end, but he assumed that longitudinal growth in the sternal part of the concave side decreases, while it increases in the convex part. In the same way there would be less increase in diameter in the sternal end and more on the concave side. He drew the conclusion that the total amount of resorption and apposition does not change, only the direction and the location.

Dorsally on the concave side of scoliosis, the ribs are pressed down and correspondingly there is a separation on the convex side. On the concave side of the ventral thorax there is also a ribhump, slighter than on the convex side. Lovett already drew the conclusion that lateral bending cannot occur without simultaneous rotation (Lovett 1905). This principle was best described by Steindler (1964). According to him the deformation of the rib begins when the lateral deviation has reached the stage where the stretch of the joints articulating the ribs to the vertebrae and of the costovertebral and costotransversal ligaments becomes so tight that the ribs exceed their normal range of movement. Thus, in scoliosis the ribs change both actively and passively, as they are attached to the spine. These processes are so dynamically connected that the part played by the spine and the ribs in scoliosis cannot be dealt with separately.

B. EXPERIMENTAL SERIES

In the method used for provoking scoliosis, it was essential to preserve the rib undamaged for investigation, but such a method did not always provoke sufficiently severe scoliosis in the pigs. For this reason, partial rib section and fixation of the ribs to the spinal processes were also used. Thin-walled teflon tube was used for the fixation on the left side. These methods did not allow the investigation of all ribs. The operative methods are explained both in the works of Langenskiöld & Michelsson (1961) and Michelsson (1965) and partly in the investigations of Karaharju (1967). According to their principles scoliosis was always provoked convex to the right, because human idiopathic scoliosis is mostly convex to this side. Table II and III contains a list of the methods used in this investigation.

TABLE II. *Methods:*

I	Dissection of costotransverse ligaments	3
II	Hemilaminectomy and resection of three intercostal (medial) nerves	5
III	Hemilaminectomy and resection of three intercostal nerves + fixation	1
IV	Hemilaminectomy and resection of vertebral ends of ribs	5
V	Resection of vertebral ends of ribs and fixation of ribs to the spinal processes	8
	together	22

Hemilaminectomy and the resection of the intercostal nerves proved difficult because damage to the spinal cord easily caused paraplegia due to the movements of the pig when the intercostal nerve was resected. Three pigs were lost for this reason later on. They were not included in the material. All operations were performed on growing pigs and scoliosis was always provoked convex to the right. The observations on the curves were performed on the basis of X-rays and the scoliosis was measured by Cobb's method (1948). No attention was paid to the sex of the animal. Pigs of approximately the same weight and size from almost similar litters, were chosen for the investigation. Feeding and treatment were the same for all. The pigs operated on were allowed to live quite normally. The scoliosis-provoking operations were performed at the age of 6—9 weeks (Table III).

The ribs of the scoliotic pigs were not marked with metal wire. The observations on changes during the growth process were made on the basis of OTC-labels. The scoliotic ribs were embedded into acrylic

TABLE III. *Ages of the scoliotic test animals at the time of operation, the scoliosis measured from the X-rays (according to Cobb's method), and ages when killed. The methods by which scoliosis was provoked are divided into five different groups.*

	Method	Pig No.	Age at time of operation (days)	Scoliosis in degrees	Post-operative time (days)	Scoliosis in degrees	Age when killed (days)	Post-operative time (days)
I	Ligament release on the right. Transsection of the costo-transverse ligaments at five levels (8—12)	1	43	35°		18°	104	71
		2	53			12°	104	51
		3	43			14°	104	71
		4	57	10°		10°	120	63
II	Hemilaminectomy on the right and resection of 3 medial intercostal nerves	5	57	5°		7°	120	63
		6	60			17°	275	
		7	71	10°	43	6°	147	76
		8	65	0°		0°		
III	Hemilaminectomy (8—12) and resection of 3 medial nerves on the right and fixation with dacron thread between the rib and the spinal process on the left	9	87	31°	15	16°	198	111
IV	Resection of the vertebral ends of the ribs on the right (6—11 or 8—12)	10	56	29°	7	15°	144	83
		11	66	11°	57	5°	144	78
		12	74	21°	21	21°	143	69
		13	74	14°	21	18°	143	69
		14	67	0°	0	21°	165	98
V	Resection of the vertebral ends of the ribs on the right and fixation with dacron thread (as in method III) on the left	15	56	83°	48	84°	171	115
		16	56	102°	48	90°	171	115
		17	55	53°	27	42°	137	82
		18	55	35°	85	37°	173	118
		19	59	38°	15	47°	128	69
		20	59	50°	15	39°	131	62
		21	87	13°	15	26°	198	111
		22	35	48°	26	32°	192	137

resin in moulds in the same way as the normal ones. 53 ribs of 22 scoliotic pigs were used altogether. Some of the ribs were investigated in order to obtain a general picture, and 41 ribs were chosen for more detailed investigations. Some of these were used for the investigation of the amount of growth based on the appearance and disappearance of the OTC-lines. In all, 20 ribs of 8 pigs, undamaged due to fixation or costal resection, were used to obtain transverse sections of the cranial and caudal parts of the apex. These ribs were examined by using the method of the displacement of the centres of the cross-sections.

In 15 of the pigs the degree of scoliosis was slight (less than 30°), in 5 moderate (31—50°) and in 2 severe (more than 50°).

TABLE IV.

	Ribs	Animals
Scoliotic ribs used for investigation	53	22
» » » » detailed investigation	41	8
» » » in the study of displacement of centres of the cross-sections	20	8

C. RESULTS

Immediately after the operation slight scoliosis with the convexity on the operated side was generally observed. In group I the primary scoliotic curve was slight and measurements could not be performed on the sections of the ribs of the pigs alone (observations on the differences between the right and left side). There were, however, slight changes in the curves and a certain consistency in the remodelling process could be observed. In group II the changes observed on the basis of the sections were likewise fairly slight, but more distinct than in group I. With the aid of the curves obtained on the basis of the components of the growth resultant much more distinct changes could be observed. In group V distinct changes could already be observed on the basis of the sections, when comparing the different sides with each other, and likewise on the basis of the curves. In the test animals of group V scoliosis could be observed immediately after the operation, since the bending of the animal was artificially increased by twisting the thorax manually during the fixation.

When a scoliotic rib pair of one of the test animals was compared to a normal one, a ribhump in its angular part could be observed on the right, i.e. the convex side, and correspondingly a ventral, but a much slighter ribhump on the left, i.e. the concave side, near the sternal part.

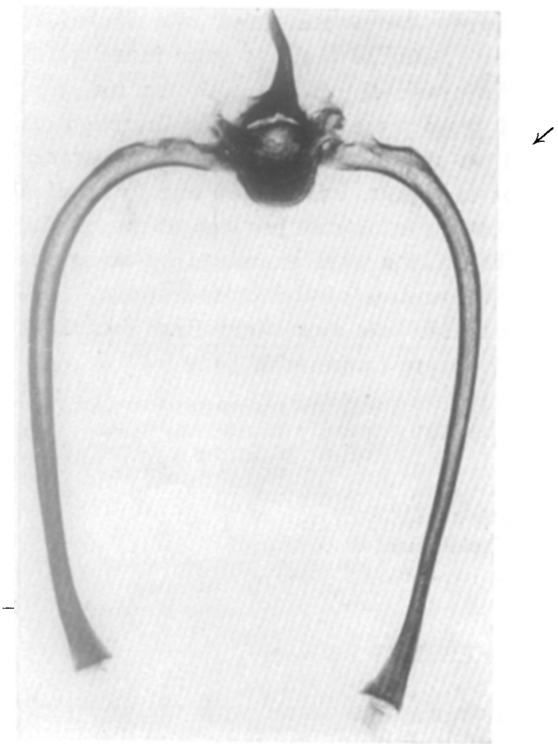
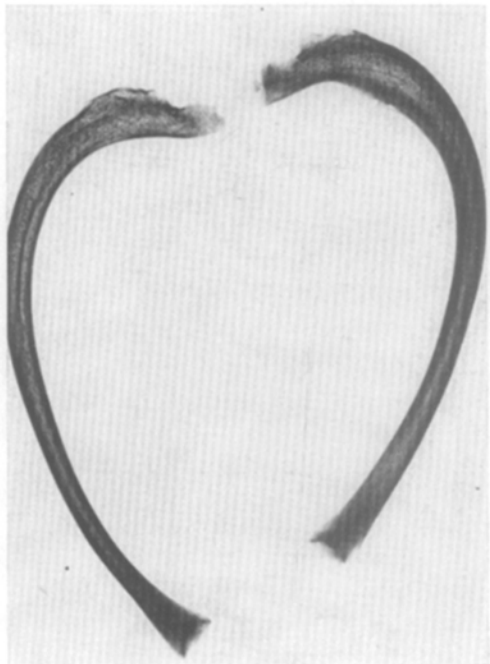


Figure 17. Pig No. 10 (slight scoliosis, under 30°) the 12th rib pair. A slight ribhump can be observed on the right in the vertebral end of the rib and a slight ventral ribhump (arrows) on the left.

It seems as if the corpus and the sternal parts of the rib on the concave side were in general thinner than the same parts of the rib on the convex side (Fig. 17). In severe scoliosis (over 50°) the ribs in the ribhump area were distinctly thicker than those in the corresponding area on the concave side (Fig. 18). Measurements of the distance between the epiphyseal line and the tuberculum costae in the X-rays seem to prove that less growth in the vertebral part occurs on the convex side. Correspondingly, the sternal part of the rib on the concave side grows more slowly. The concept of the growth of the sternal end, obtained by studying the photographs also indicates that more longitudinal growth occurs on the convex side, as the distance between the costochondral junction and the last sternal OTC-label was somewhat greater on the convex side according to the observations.

In severe scoliosis the distinct observations on the sections of the ribs indicate the occurrence of a corrective remodelling during growth.



sin dx

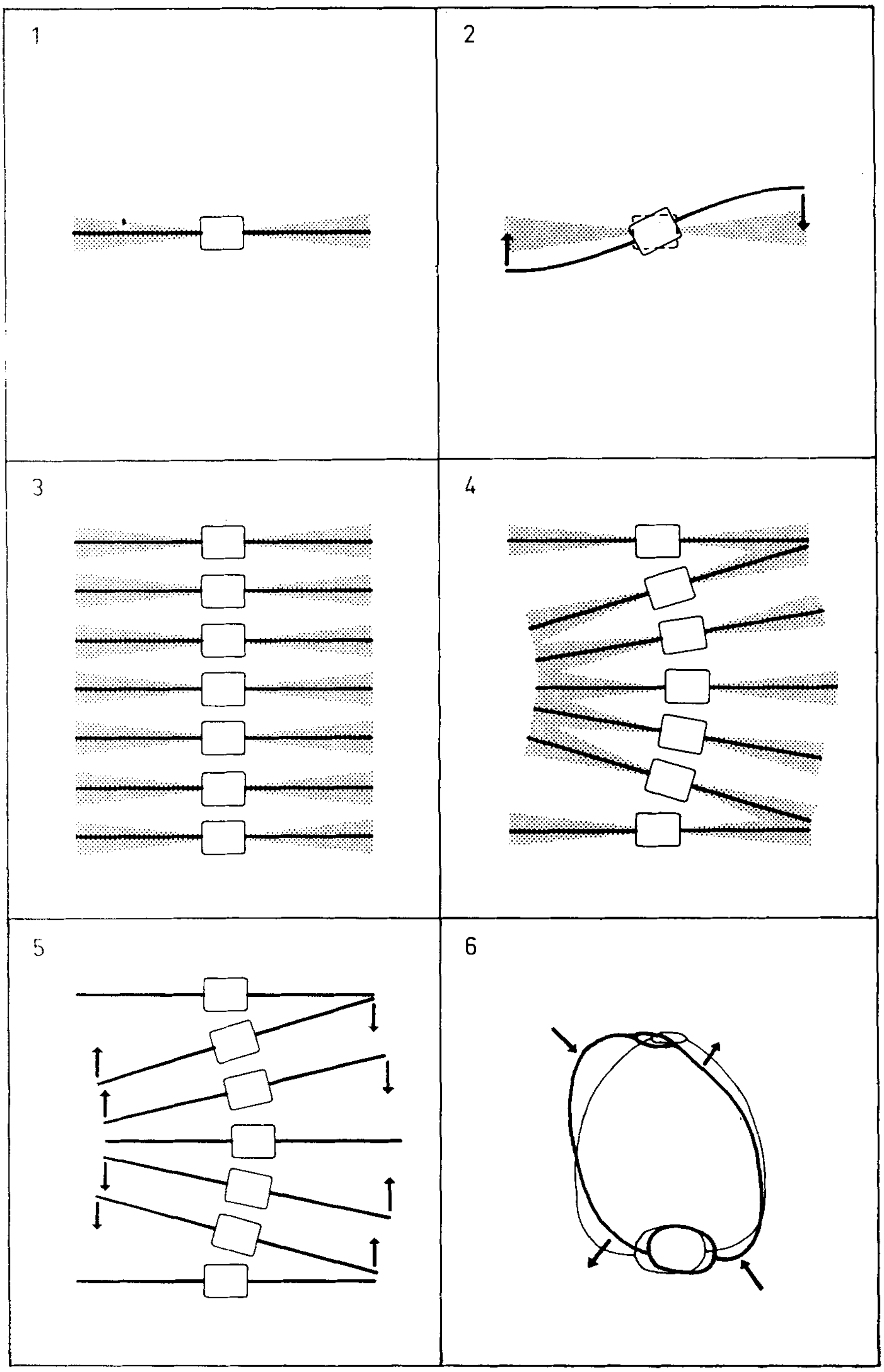
Figure 18. The ribhump clearly discernible in severe scoliosis (over 50°) on the right and the ventral ribhump (arrows) in the sternal end of the rib. The difference in diameter is distinctly discernible in this projection. Pig No. 17 and the 8th rib pair.

The correction of the scoliotic curve by apposition and resorption of bone indicates a similar tendency (Table V). A schematic reconstruction of the remodelling process during the growth of the ribs was made on

TABLE V. *Test animals in which correction could be observed during growth according to the measurements.*

Pig. No.	I	II
1	35°	18°
7	10°	6°
9	31°	16°
10	29°	15°
11	11°	5°
15	105°	84°
16	102°	90°
17	53°	42°
20	50°	39°
22	48°	32°
Total:	10 pigs	

Correction	10
Progression	3
No progression } Uncertain	> 9
Total:	22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2
3
4
5
6

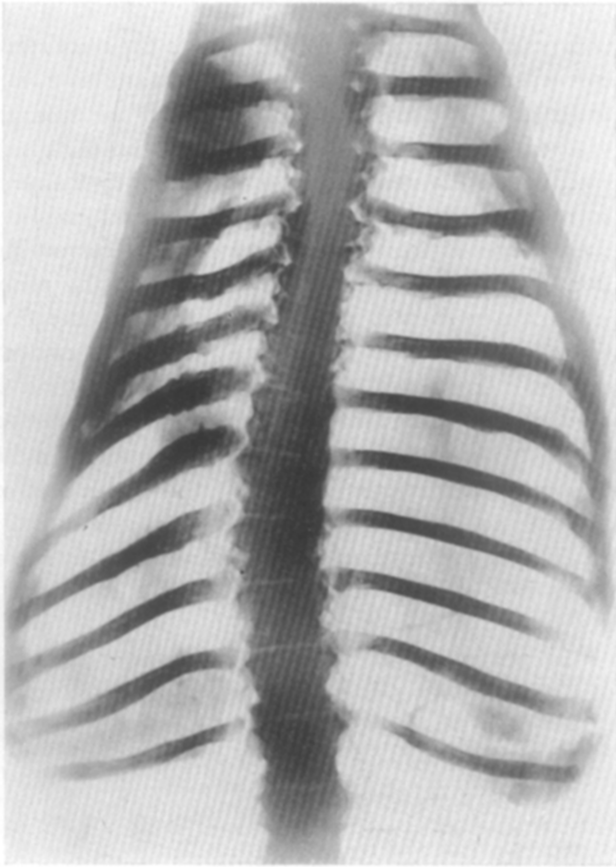

Figure 20. X-ray of slight scoliosis. Pig No. 1. Correction from 35 to 18 degrees. Age at the time of operation 43 days. Growth period after the operation 71 days. The picture was taken of the specimen.

the basis of these observations (Fig. 19). According to this, in the cranial part of the curve correction of the ribs towards the cranial direction occurs on the concave side of the scoliosis and towards the caudal direction on its convex side. In the caudal part of the curve correction in the rib on the concave side occurs towards the caudal direction and in the rib on the convex side towards the cranial direction. According to the

←

Figure 19. Diagram based on observations made during the investigation, on the basis of which the remodelling due to correction in the ribs is presented. 1: schematic presentation of the normal specific range of movement of the rib. 2: the normal range of movement is exceeded and deformation occurs in the rib due to scoliosis. 3: normal spine. 4: scoliotic spine. 5: the arrows indicate the direction of the correction in the ribs. 6: correction of the rib in the vertical plane, the arrows indicating its directions at the various points.

observations or severe scoliosis and to the reconstruction of the drift of the correction, in the ribhump on the convex side vertical correction occurs towards the pulmonal direction and in the sternal part of this rib more vigorously towards the cutaneal direction than in the rib on the concave side, where the ventral ribhump (in the sternal part of the rib) would be corrected towards the pulmonal direction. In the sternal part of the rib the changes differ from one another, the correction in the cutaneal direction being larger on the convex than on the concave side.

In the vertebral and angular parts of the ribs on the concave side the changes caused by scoliosis would be corrected more towards the cutaneal direction, whereas by the dorsal ribhump correction would occur in the pulmonal direction. Thus, the vertebral and angular parts of the rib straightened on the concave side would be corrected towards the cutaneal direction. During the correction of the scoliosis during growth the remodelling on the cranial side of the apex would, however, be different from that on its caudal side. In the schematic figure, however, they have been marked as if the correction occurred in the same manner.

To prove the very clear correction tendency, further investigations of different degrees of scoliosis were made and examined as follows:

— slight — (under 30°)
— medium severe — (31°—50°)
— severe — (over 50°)

This definition of the degree of scoliosis is artificial. It is only a relative definition used in the present work.

Slight scoliosis. The curves of the right and left sides of the 8th rib pair of pig No. 1 are clearly different from each other. The scoliosis was originally 35°, but in about two months it was corrected to 18° measured from the preparation. The curve of the change (Figs. 20 and 21) in the cran-caud direction on the left indicates growth in the caudal direction between 40—60 mm, followed by a turning towards the cranial direction (Fig. 22). On the right there is first vigorous growth in the caudal direction, followed by a turning towards the cranial direction nearer the sternal end. This remodelling may partly depend on the growth in the cranial direction observed in the sternal end in the specific curvature of the rib of a normal test animal. Thus, remodelling towards the cranial direction can be observed both on the right and on the left side closer to the sternal end, but the phenomenon is more distinct

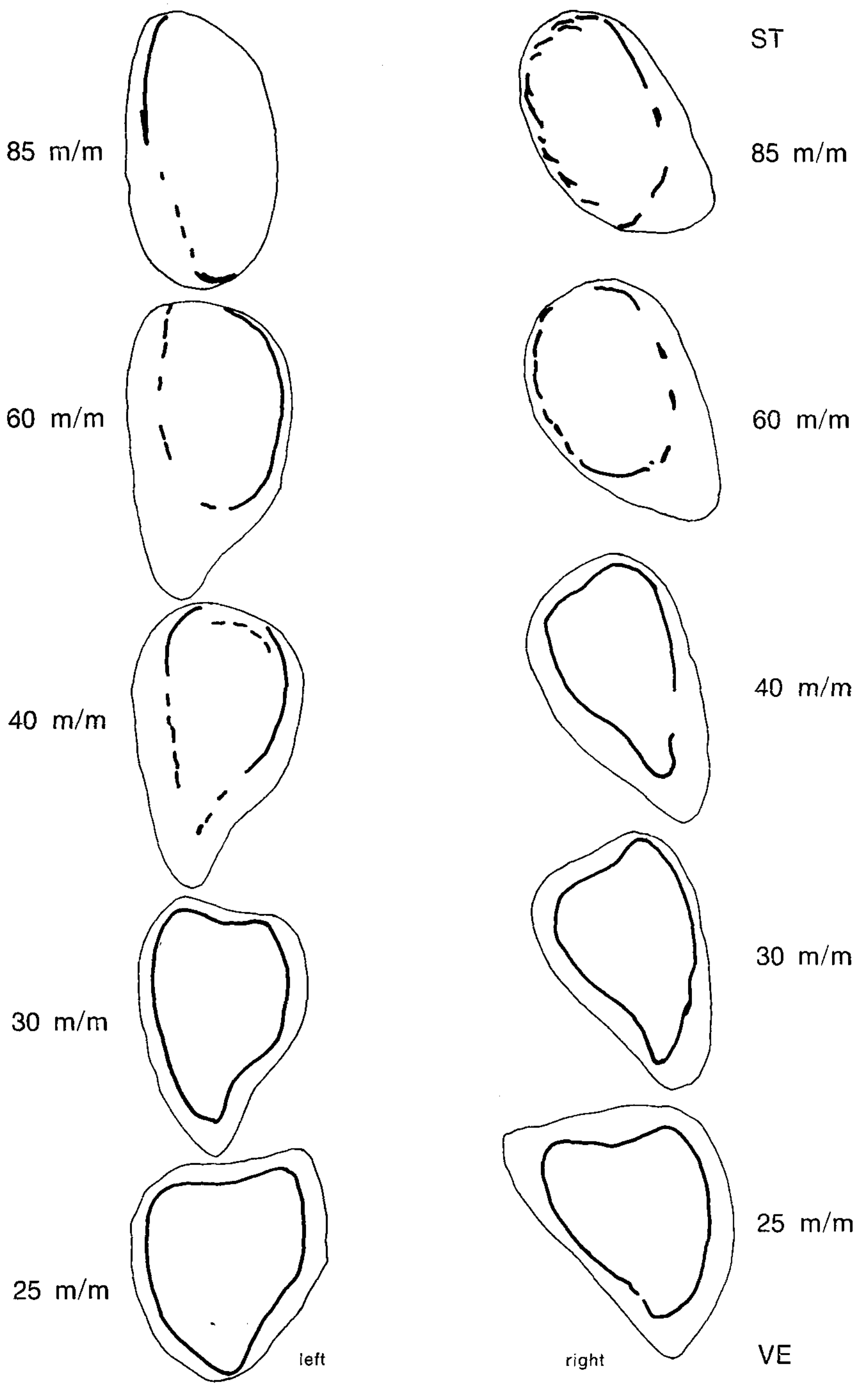

Figure 21. The sections of the 8th rib pair illustrating the remodelling process. Measurements taken from the vertebral end. The inner circle present the OTC-labelling. Pig No. 1. Slight scoliosis. The same as in Fig. 20.

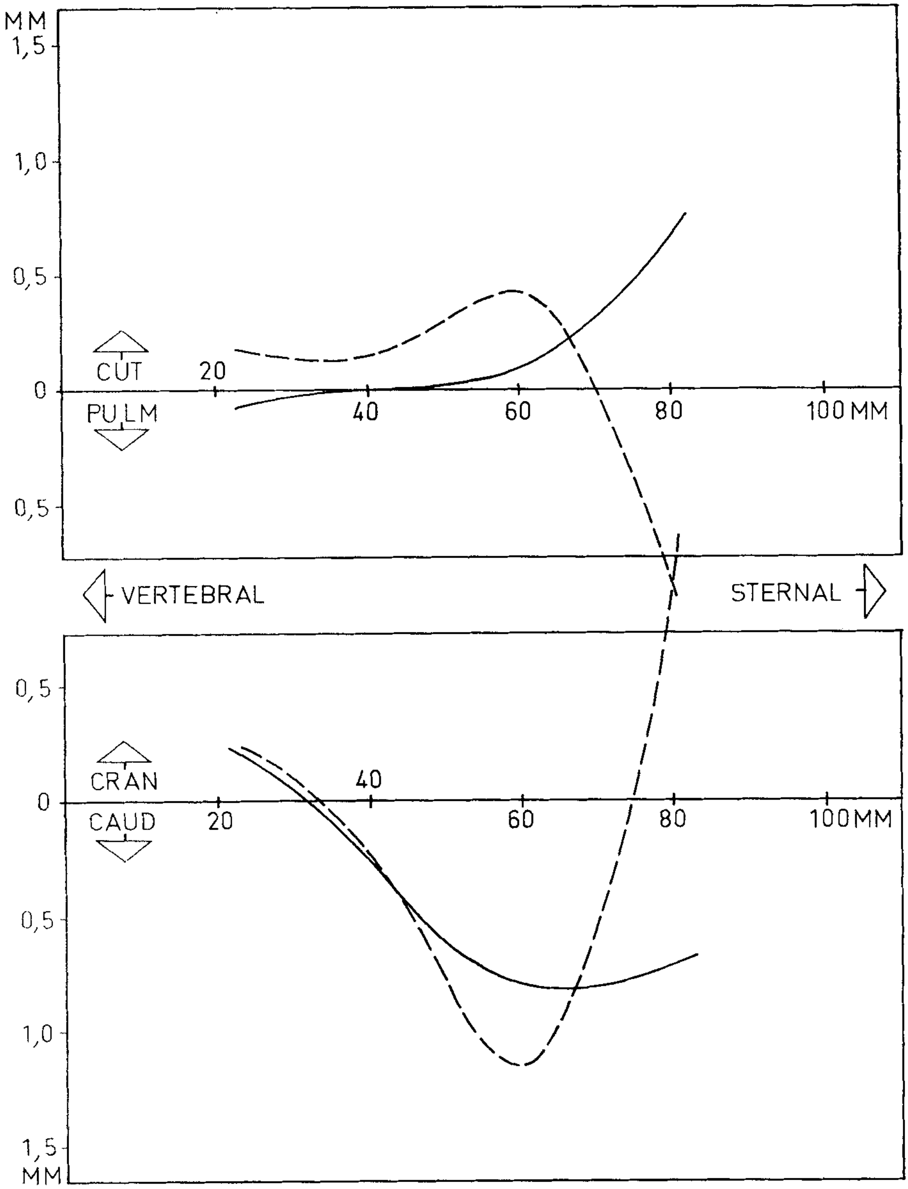

Figure 22. Diagrams presenting the changes of the right and left side ribs in the cutaneal-pulmonal and cranial-caudal directions, based on the numerical values of the components of the growth resultants determined from the sections. The diagram marked with a dashed line presents the right or convex side. The figure presents the rib pair situated cranially in relation to the apex of the scoliosis.

on the right. By examining the function in the cut-pulm direction, remodelling (or correction) on the left can be observed quite concentrically up to about 60 mm, where it suddenly turns towards the cutaneal direction. On the right, or convex side, remodelling towards the lungs can be observed nearer the sternal end. This may indicate that here the correction of the ribhump by the remodelling process would occur in the pulmonal direction, correcting this ribhump during growth, which is in accordance with other observations.

The curves changing in the cran-caud direction (pig 10/9th rib) indicate that on the right the curve goes towards the caudal direction, turning some 40 mm more towards the cranial direction (Fig. 23). The peak on the left in the caudal direction is reached by this curve around 60 mm, remaining constant and then turning towards the caudal direction. This curve also corresponds to the 8th rib pair of pig No. 1 in the same way as the pulm-cut curve. The correction by remodelling of the cran-caud curves during growth is in accordance with the other observations. The tendency towards the caudal direction is more vigorous on the right than on the left. The growth in the cut-pulm direction is first observed to be vigorous in the cutaneal direction on both sides. However, the curves are different: the left side is first constant, while the right side starts to turn towards the cutaneal direction. Here the curves recede from one another intersecting once again nearer the sternal part, after which the growth in the cutaneal direction decreases on the right, while it increases on the left. When this pig is compared to pig No. 1 (18°) and its 8th rib pair, the cut-pulm growth curves are found to be almost alike, with dissimilarities especially in the sternal end. The specific tendency of the curves is, however, alike. Nearer the apex of the scoliosis the remodelling in the cut-pulm direction seems to occur in the same way as in a normal rib. However, the observation on this concerning the apex is uncertain. On the other hand there is much remodelling in the pulmonal direction on the right by the ribhump in accordance with the observations concerning the remodelling on the convex side. It is obvious that the behaviour of the sternal end of the curves is also significant corrective remodelling, because this part of the ribs joins them to the sternum. The same phenomenon can be observed in almost all the curves when the sternal end is examined. Around the middle of the curves the remodelling in the cran-caud direction is found to occur in the caudal direction on the left and in the cranial direction on the right. The growth on the right is distinctly more vigorous than on the left, the correction

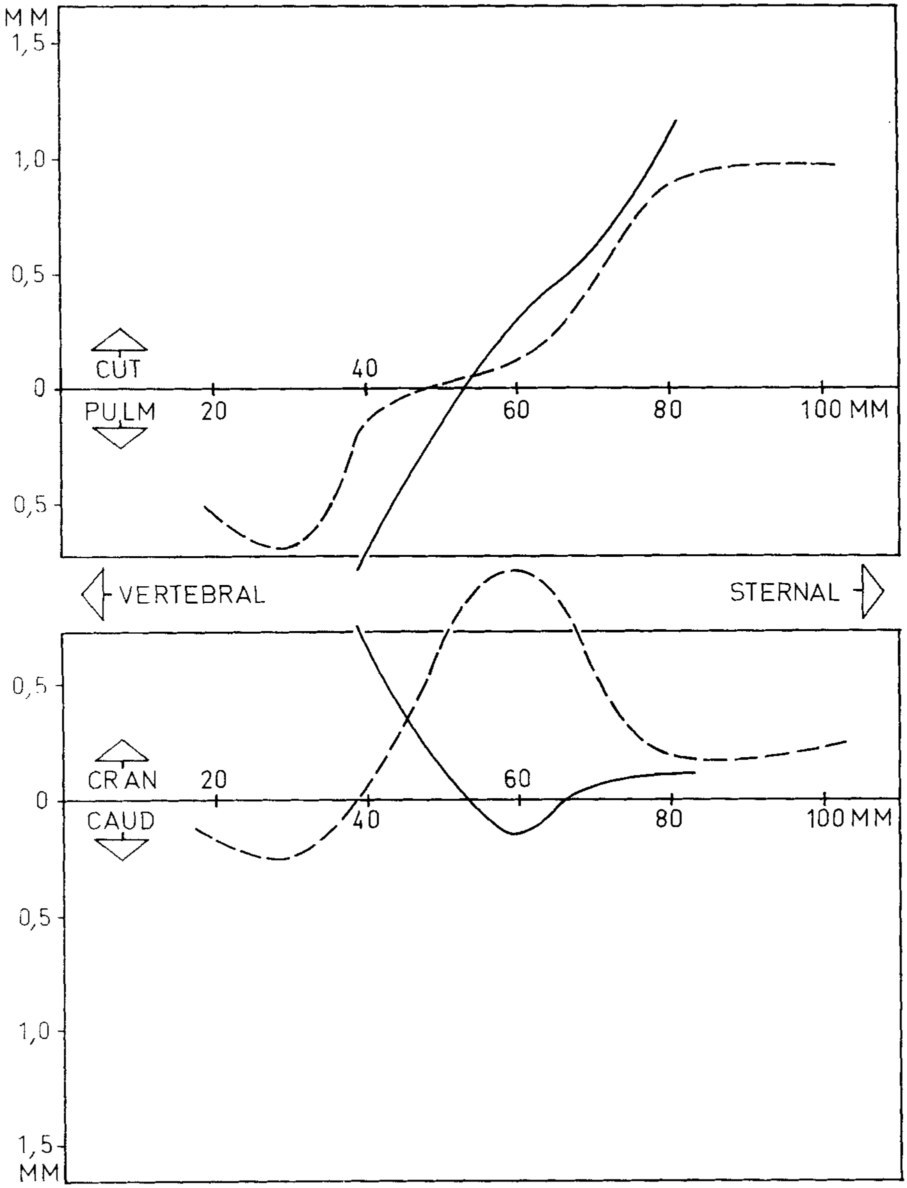

Figure 23. Diagrams obtained from the sections of the 12th rib pair of pig No. 10. The age at the time of operation was 56 days and the growth period 83 days. Scoliosis was corrected from 29 to 15 degrees. The rib pair is situated caudally in relation to the apex of the scoliosis. The dashed line presents the right side.

tendency being thus in accordance with the other observations. The curves in the cut-pulm direction have an almost similar tendency on the right and on the left. Nearer the sternal end growth is quite vigorous in the cutaneal direction, this tendency being a little stronger on the left, however. Remodelling similar to the normal growth pattern of the rib can again be observed in the sternal part.

Medium severe. The scoliosis of pig No. 20 was corrected from 50° to 39° in two months. The remodelling of the curve of the 8th rib in the cran-caud direction on the left was almost completely transferred to the positive side of the middle or 0-line (sine values positive), to a position quite different from the normal (Figs. 24 and 25). This scoliotic curve is found to resemble the normal curve of the corresponding 8th rib of the normal pig, No. 7, but in the scoliotic pig No. 20 the curve was transferred to another position. Attention is paid to the amount of growth and to where it takes place compared to the behaviour of the normal curve. The similarity between these curves is evident, however. Observations on this material would also prove that during growth the rib tends to be corrected to its normal shape. This is also in accordance with the other observations, as on the left growth occurs first more in the cranial, but on the right more in the caudal direction, followed by turning on both sides, closer to the sternal end, towards the cranial direction. In accordance with other facts the dissimilarity in the remodelling of the curves in the cran-caud direction is quite distinct. The curves in the cut-pulm direction are found to be different. Between 40—60 mm on the left there is first remodelling in the pulmonal direction, but around 60 mm the curves are almost alike on either side. Thereafter both curves turn somewhat towards the pulmonal direction, but growth as a whole continues in the cutaneal direction. Once again the influence of the sternum is significant. When this curve is compared to that of the normal pig, the specific curvature is found to be alike as a whole, but due to scoliosis the position of the occurrence of remodelling in the curve is different. This re-occurrence of the specific curvature of the same rib pair in scoliosis of varying degrees, and also in comparison to the normal curve, is an additional proof of the usefulness of the method.

Severe scoliosis. The scoliosis of pig No. 15 (14th rib) was 84° measured from the preparation, having been 102° at its worst (Figs. 26 and 27). The growth period was 115 days, i.e. about four months. Scoliosis was in this case provoked by ribresection and fixation of the spinous processes to the ribs. The cran-caud curve indicates a very distinct

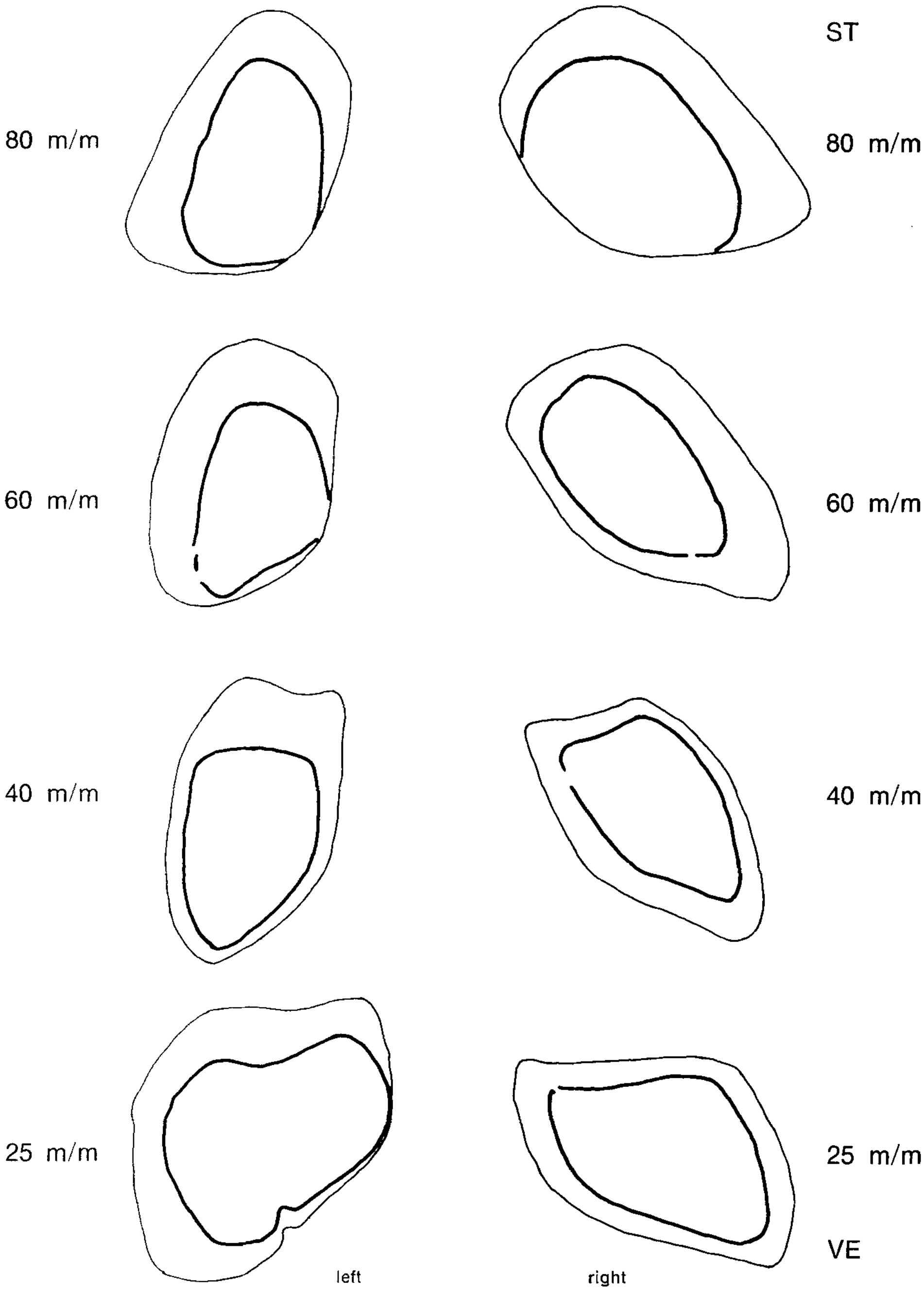

Figure 24. A selection of sections of the 8th rib pair in medium severe scoliosis. The distances of the sections were measured from the verebral end. Pig No. 20. The age at the time of operation 59 days. The growth period 62 days after operation. Scoliosis was corrected from 50 to 39 degrees.

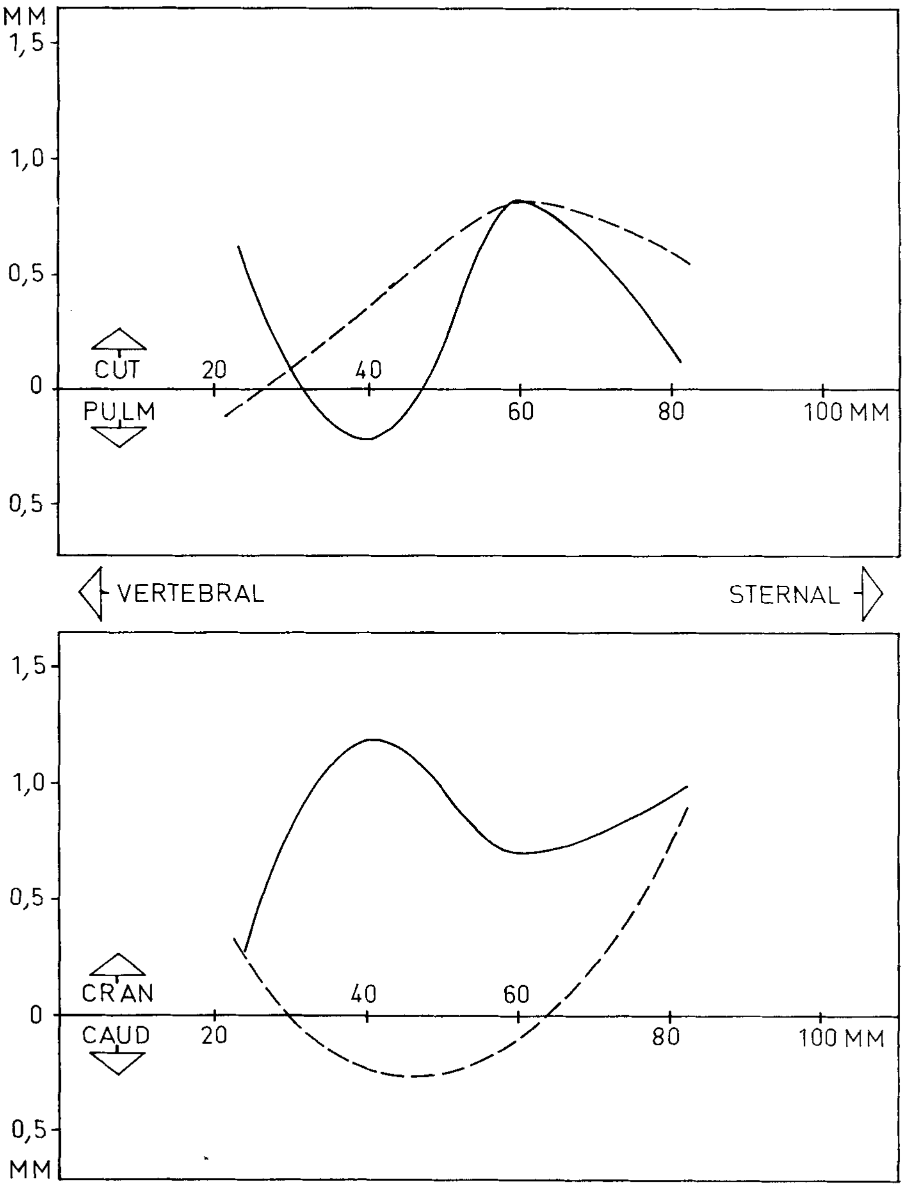

Figure 25. Diagram based on the numerical values of the components of the growth resultants in the sections. On the basis of the form of the diagrams, correction can be observed in the caudal direction on the right and in the cranial direction on the left. The dashed line presents the right side.

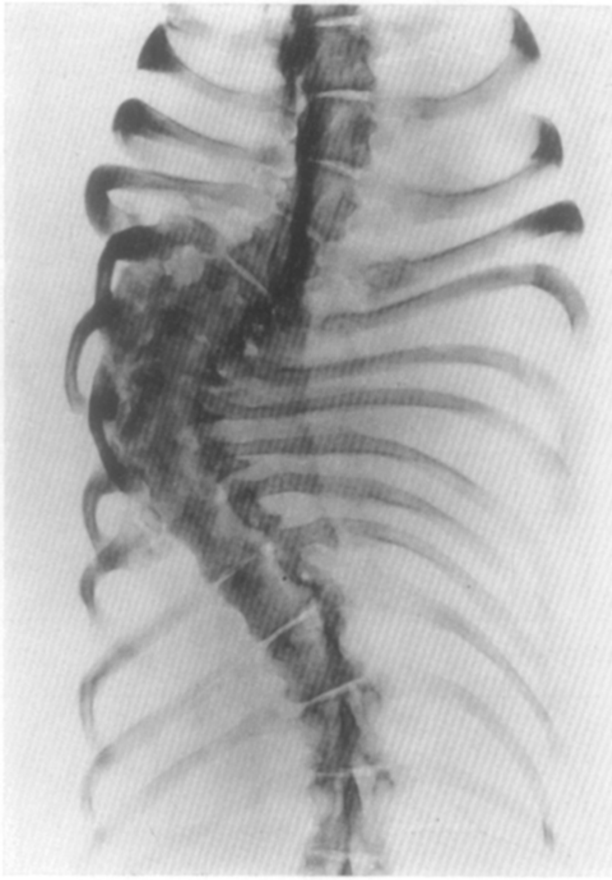

Figure 26. X-ray of severe scoliosis. Pig No. 15. Correction from 102 to 84 degrees. Age at the time of operation, 56 days. Growth period after the operation, 115 days. The picture was taken of the specimen.

correction in the cranial direction on the right and vice versa on the left (Figs. 28 and 29). This is completely in accordance with the other experimental observations. Vigorous growth in the cutaneal direction nearer the sternal end can be observed in the curve, which means that even in severe scoliosis the growth pattern resembles that of normal growth.

When the 14th rib pair of pig No. 17 is examined it can be observed that in this case the scoliosis was 53°, which was corrected to 42°, measured from the preparation (Figs. 30, 31 and 32). About the same, but slighter changes can be observed as in the 14th rib of the previous pig. On

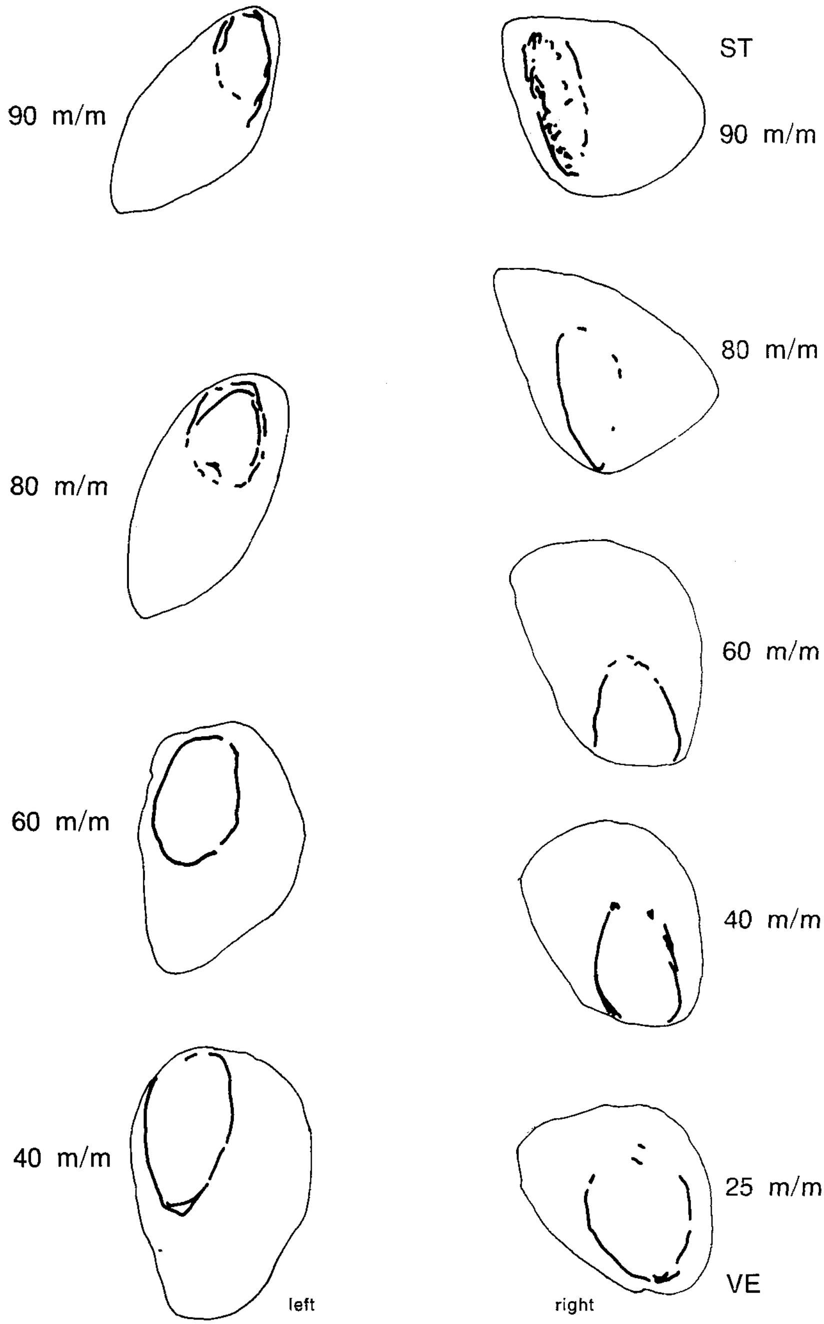

Figure 27. Sections chosen of severe scoliosis, in which the remodelling and its direction can be observed. The position of the section was measured from the vertebral end. See also the colour picture, page 87. Pig No. 15.

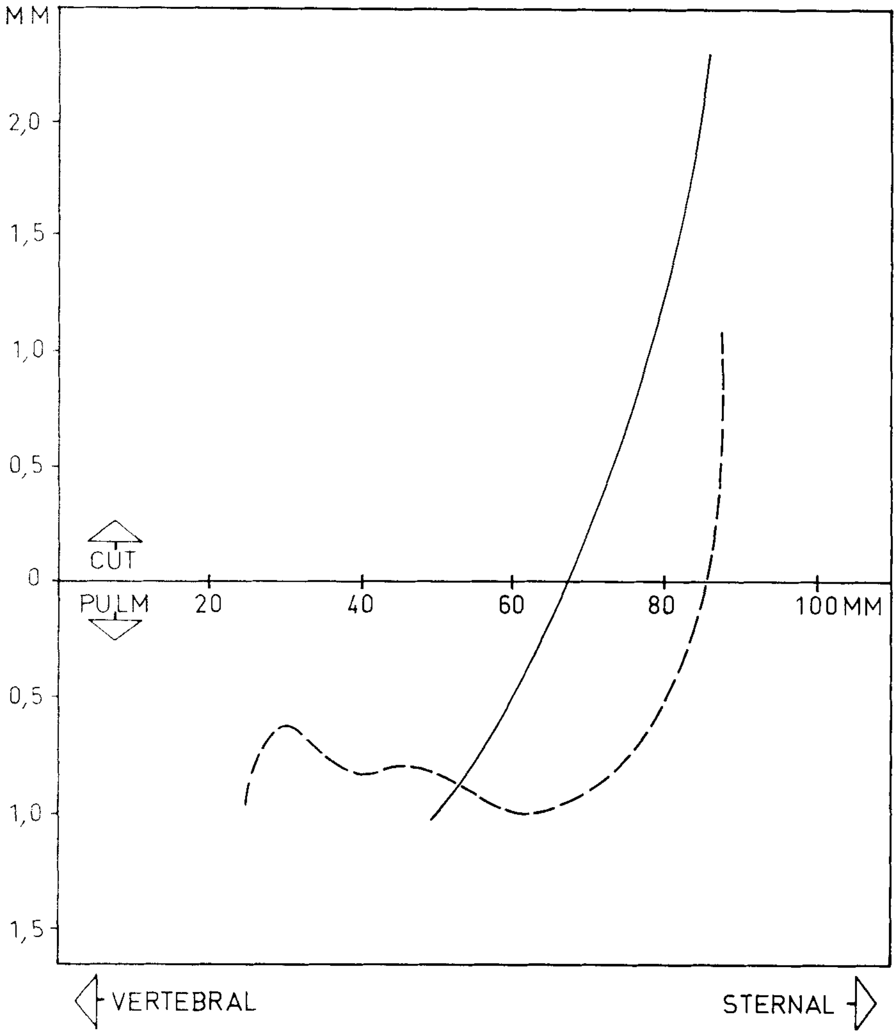

Figure 28. Correction in the cutaneal-pulmonal direction only; pig No. 15. See preceding pictures. Further explanation in the text. Pig No. 15.

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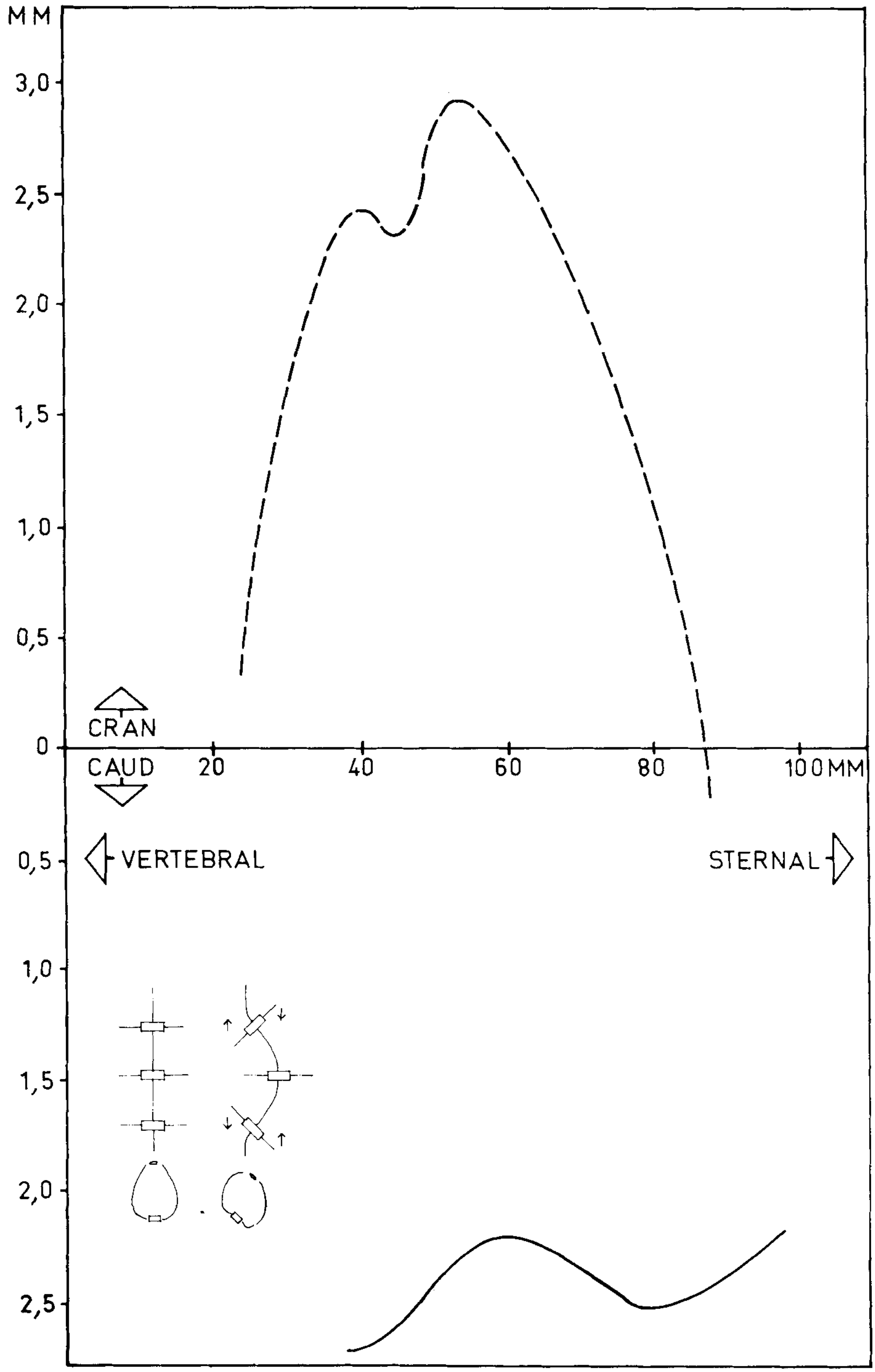
Figure 29. Correction in the cranial-caudal direction; pig No. 15. See earlier pictures of the same pig. Further explanation in the text.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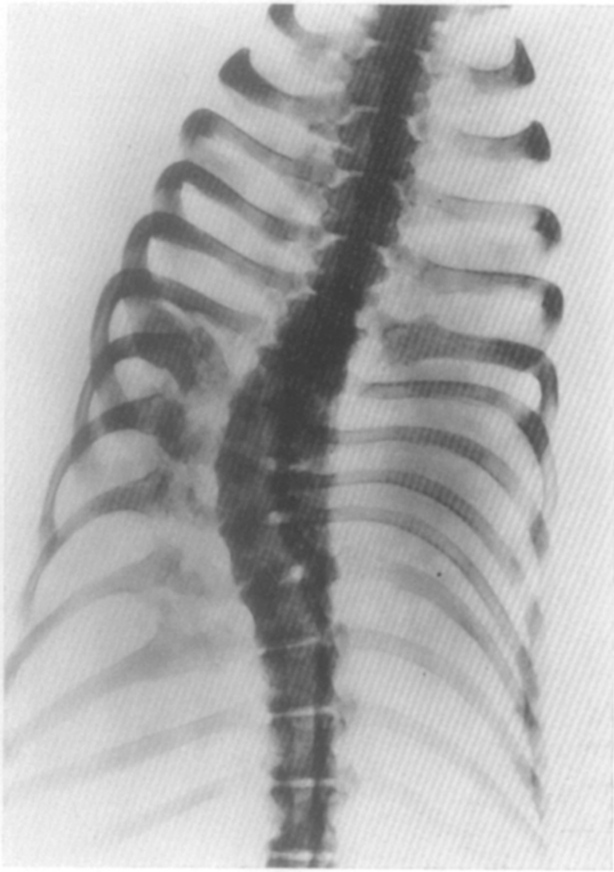

Figure 30. X-ray of severe scoliosis. Pig No. 17. Correction from 53 to 42 degrees. Age at the time of operation, 55 days. Growth period after operation, 82 days. The picture was taken of the specimen.

the right considerable correction in the cranial direction can be observed in the cran-caud curve, while on the left it is found to occur in the caudal direction, which is once again in accordance with other findings.

In the cut-pulm direction the curve shows dissimilarity 24 mm from the vertebral end, but thereafter the drift of the growth distinctly turns towards the cutaneal direction on both sides. This, however, takes place in different ways, an observation made on every rib almost without exception, whatever the degree of scoliosis.

In addition to the curves of scoliosis of different degrees, a number of sections taken at a certain distance from the vertebral end are presented. Direct conclusions could not always be drawn on the basis of these sections. Nevertheless, in the serious form (pig. No. 15, 14th

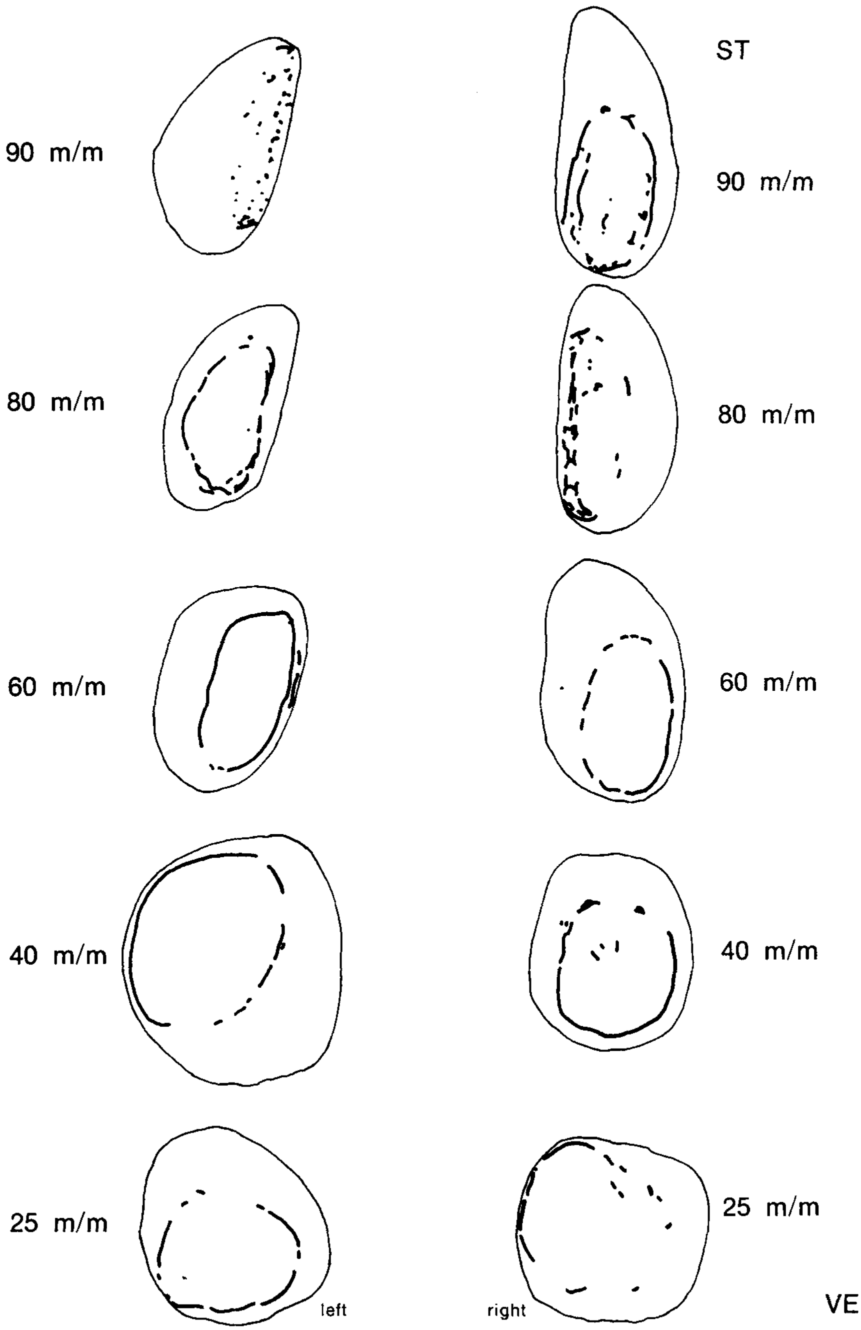

Figure 31. Sections chosen of the 14th rib pair. The distances were measured from the vertebral end. The sections indicate the drift of the correction. On the right, correction in the cranial, on the left in the caudal direction. The differences are not quite as distinct as in pig No. 17.

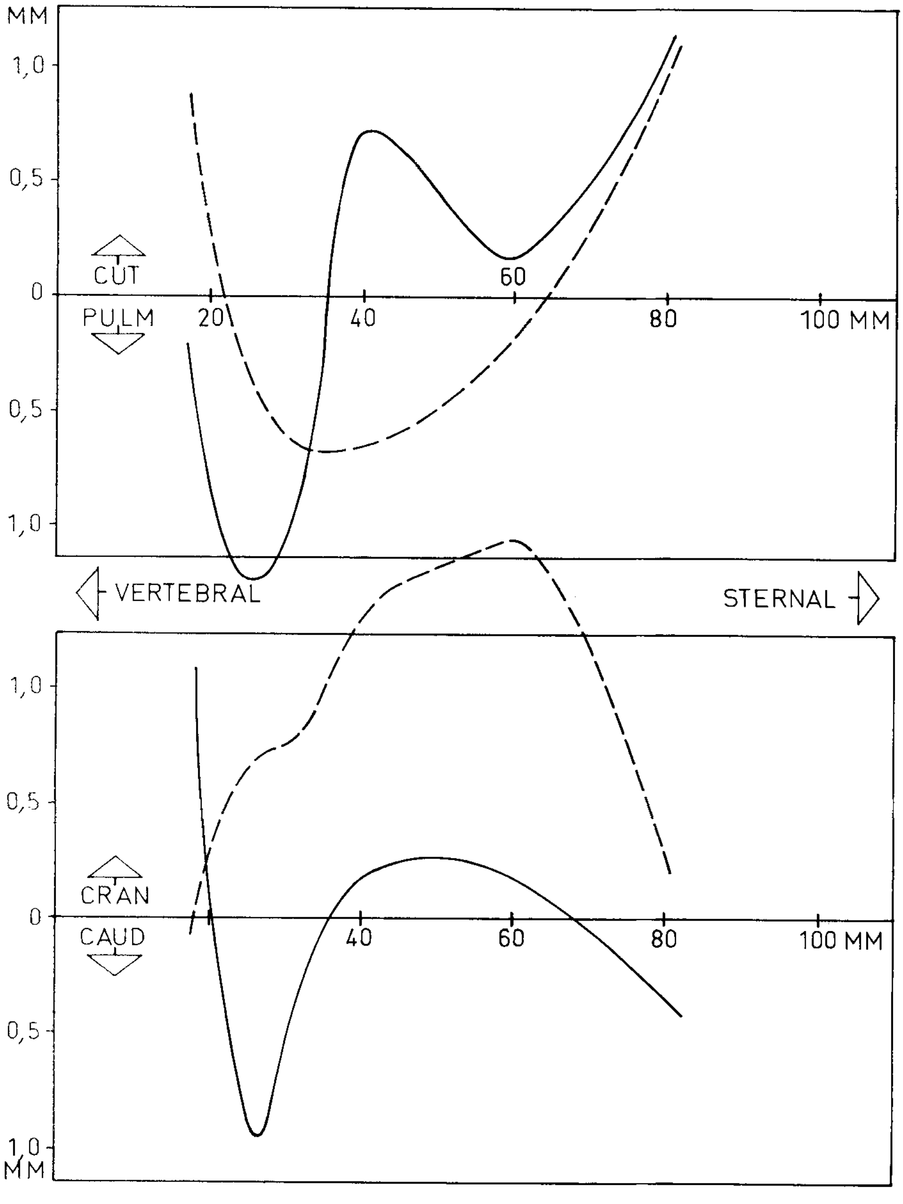

Figure 32. Diagram based on the numerical values of the components of the growth resultants obtained from the sections. The dashed line presents the right side.

pair) distinct remodelling could be observed when the right and left sides were compared to each other (Fig. 27). A few colour photographs of these examples have been enclosed (see the page 87).

The section of the 14th rib on the left or concave side 55—60 mm from the vertebral part distinctly indicates the occurrence of apposition on the caudal, and resorption on the cranial side of the section. Correspondingly, there is even more distinct apposition towards the cranial direction on the convex side and resorption on the caudal side of the section. The same observation can be made in slighter cases of scoliosis. The differences between the right and left sides are difficult to observe with the naked eye and therefore the comparison must be made mostly by using the curves obtained on the basis of the numerical values of the components.

D. CONCLUSIONS

The methods used give a picture of the remodelling process observed in ribs during the progression of scoliotic curves in pigs. It can be established that the remodelling in the cranial-caudal direction is almost regularly a process of apposition and resorption correcting the shape of the thoracic cage towards the normal. Correction during this process occurs cranial to the apex, towards the cranial direction on the concave side and towards the caudal direction on the convex side. The degree of the correction varies depending on the degree of scoliosis and on the position of the rib in relation to the apex. The correction of the position of the rib of a scoliotic test animal always occurs towards the normal growth pattern. The correction tendency in the cut-pulm direction occurs in accordance with the phenomenon observed concerning the spine by Langenskiöld & Michelsson (1961 and 1962), Karaharju (1967), but it is more difficult to observe this in the sections and, likewise, in the curves. The correction around the ribhump is worth special attention. The vertebral end is obviously a kind of »joining» part, as the changes there are smallest and the forces having an effect on it also seem to be in balance. The growth towards the cutaneal direction observed almost regularly in the sternal part on the basis of all the curves is another significant factor in the remodelling of the rib. The direction and the amount of growth varies, however, somewhat depending on the degree of scoliosis and, as proved to be the case in a normal rib, the amount of growth seems to vary depending on the position of the rib on the thorax. Thus, the sternum obviously plays a significant role in the remodelling process of a scoliotic thorax and in its growth. It can also be established that the bending of the rib and obviously also the gradual change in the rotated position of the vertebrae in the various parts of the curve is directed in a somewhat different manner to the right and left sides of the rib pair (White 1969). The purpose of the curves is to illustrate these processes in a quantitative manner. The appearance of the curves of a scoliotic animal and a normal test animal is similar enough to allow sufficient conclusions, especially concerning the growth tendency of the vertebral and sternal parts of the ribs.

Finally, it can be established that the concept of the deformation of a rib pair in scoliosis, and of the correction tendency in the test animals during growth, proves that the remodelling takes place as shown schematically in Fig. 19.

GENERAL DISCUSSION

The main function of the thorax is to protect the vital organs and to participate in the breathing together with the muscles. In this function the rib is movable, being attached to the spine by joints and ligaments and to the sternum by its cartilaginous part. During growth it also participates in the remodelling of the thoracic cage. Idiopathic scoliosis is a disease of young growing people, causing deformity of the ribs, which together with the lateral bending of the spine displaces the organs inside the thorax from their normal positions, decreasing their functions and possibly also shortening the life of the patient. (Eckhardt 1927, Stracker 1938, Zorab 1969).

According to Kleinberg (1951), functional scoliosis is »curable», but structural is not. Doubt about the truth of this statement may have initiated the development of methods for provoking experimental scoliosis in animals (Langenskiöld 1964). According to James it has been an extraordinarily difficult deformity to induce in animals and he admits that for decades this was one of the primary problems in the experimental investigation of idiopathic scoliosis (James 1970). Langenskiöld and Michelsson succeeded, however, in inducing scoliosis of varying degrees in test animals through selective resection or trans-section of different structures in the spine or its vicinity (Langenskiöld & Michelsson 1961). Few references to the postnatal growth of the human rib can be found in the literature. The rib was known to have an epiphysis at the vertebral end where its growth was expected to occur. Yet Hueter (1878) already mentioned that the growth of the sternal end was vigorous on account of the growth of the thorax. Swoboda (1969) also supposed that most of the growth took place in the sternal end and that this process was similar to that in the meta-physis of a tubular bone. The metal marking method used in the present work also indicates that most of the growth of the rib occurs in the sternal end, which seems natural considering the total growth of the thoracic cage. It was proved that the growth of the vertebral body in the lateral direction is concentric and that no noteworthy remodelling in the transversal directions takes place (Haas 1939, Bick & Copel 1950, Gooding & Neuhauser 1965, Karaharju 1967). Likewise, the growth of the rib in the cranial-caudal direction in its vetebral part seems to be accompanied by an equal amount of growth beginning from the epiphyseal end plates.

The metal marking method used in the present work is a classical one. It is based on the observation that the distance between two markers in the bone does not change. The observations made by using the metal marking method, indicate the main drifts of growth. The longitudinal growth in the vertebral end was found to be only one fourth of that in the sternal end. The sternal end grows vigorously in the cutaneal direction leading to the widening of the thorax. The drifts shown by the metal marking are approximate and do not allow any other conclusions except on the rough directions of growth. The investigation was therefore completed by the OTC-method. On the basis of the yellow fluorescence of OTC the peripheral growth in the transverse sections could be observed. These two methods were combined by using the resultant of the total growth and its direction. Figs. 6, 7 and 8 were obtained by measuring these sections. The diagrams, based on the numerical values of the components of the growth resultant, indicate the direction and amount of growth in each rib. The illustrative figure shows the fast growth of the sternal end and its drift in the cutaneal direction. The growth of the rest of the rib from the angular part to the sternal end occurs in the cutaneal direction. Marotti et al. found a corresponding increase in the growth at the sternal end when investigating the transverse section of the osteon with the OTC-method (Marotti et al. 1968). The drift in the cranial-caudal direction is somewhat dissimilar in the diagrams of normal ribs, due to the specific bending of each rib. The dissimilarities seem to correspond to the somewhat varying functions of the different ribs on the thorax, each rib being remodelled in its various parts into its own final form. In the present work no attempt was made to present the total growth of the thoracic cage. On the basis of the above results there are, however, reasons to suppose that the pattern of the total growth of the thoracic cage follows a pattern of remodelling in the sternal and cutaneal directions. (Figs. 33, 34 and 35).

The methods used in the investigation of bone growth presented in the literature are two-dimensional, although a few three-dimensional ones could be found (Cohen & Harris 1958, Scheiman—Tagger & Brodie 1964). Cohen and Harris's work on the description of the osteon was based

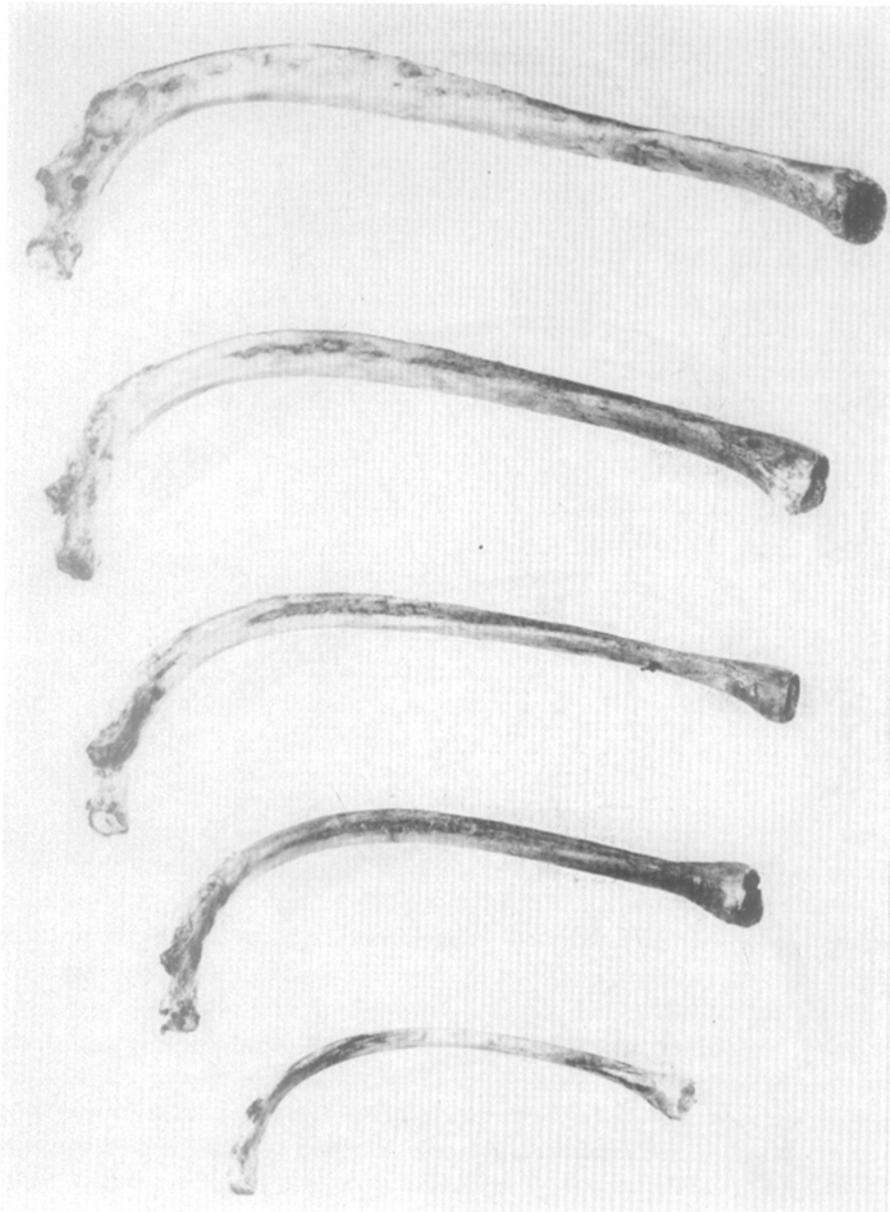

Figure 33. Series of the 8th ribs of pigs of different ages. The rib is remodelled from round to more oval. The ages from the bottom 42, 75, 108, 133 and 166 days.

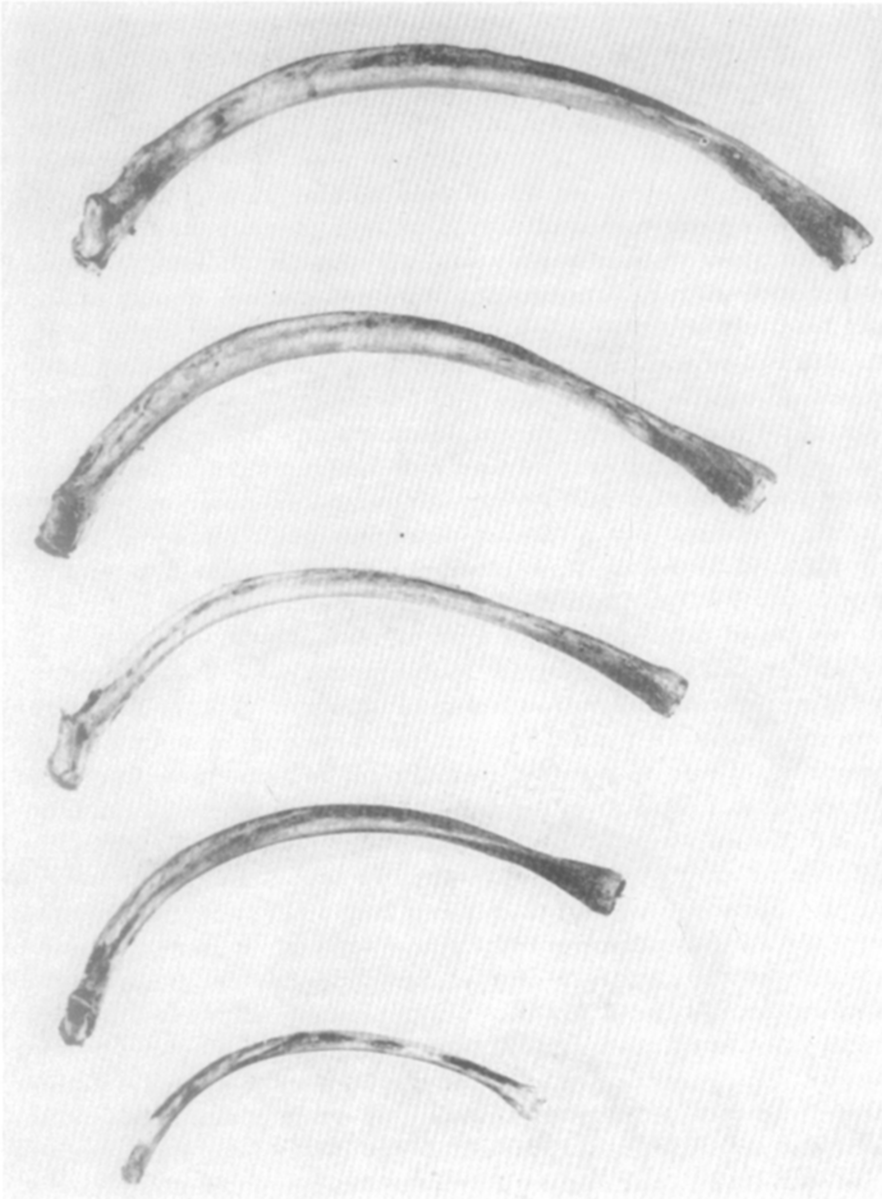

Figure 34. The 12th ribs of the same pigs. The same observation as in the previous figure can be made on the basis of this series.

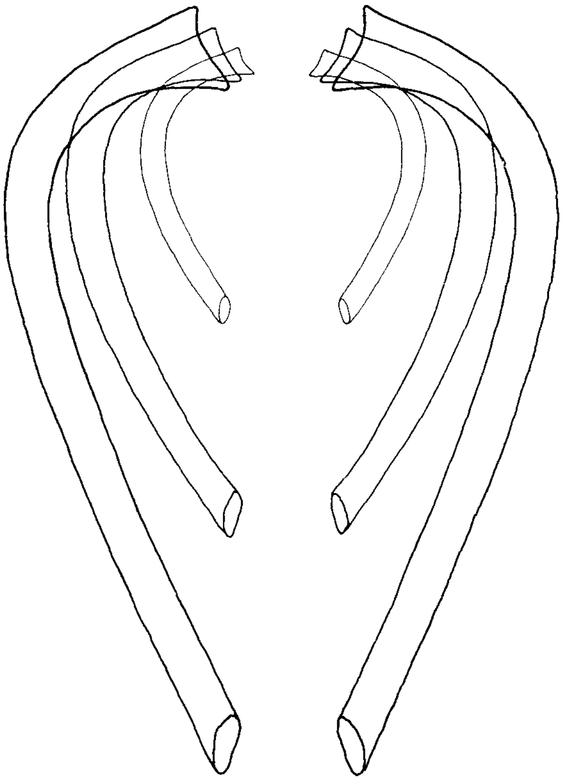

Figure 35. Remodelling drift during growth drawn schematically according to the previous figures and to the observations of the growth in the vertebral and sternal end.

on microscopic serial sections, and Scheiman—Tagger and Brodie only refer to the possibility of applying a three-dimensional method when using lead acetate, which does not disappear in this method when the bone is demineralized. The earlier descriptions of the growth of bone were obtained separately by observing serial sections and they probably give a correct picture of the expected drift of growth only (i.a. Leblond et al. 1950, Enlow 1963, Rubin 1964, Ham 1969). The method applied in the present work is not obviously quite exact as to the observations on the amount of growth. However, it facilitates the description of the total growth of bone on the macroscopic level. The method used for the description of the three-dimensional nature of the growth process is presented on pages 20—27 together with an evaluation of the possible sources of error. According to this, the growth process can be roughly presented as a diagram, based on the numerical values of the components of the growth resultants. The method does not allow a comparison of various ribs except in an approximative manner. Thus, a few dissimilarities and similarities can be observed in them, for example, by studying the right and left side of a scoliotic rib pair.

In the investigation, scoliosis was provoked convex to the right as this disease mostly occurs convex to the right in human idiopathic scoliosis. This was not done in order to draw conclusions on the etiology of scoliosis provoked in pigs compared to humans, but because the similarity in the structural changes might give information of value for research on the treatment of human idiopathic scoliosis.

The comparison of the scoliotic ribs was performed between three pigs with a scoliosis of different degrees. For this purpose the rib pairs of three test animals were chosen so that the deformity of the caudal and cranial part to the apex of the thorax could be compared.

The rib is articulated to the vertebra and the transverse process. Due to their articulation the ribs have a limited range of movement (Steindler 1964). They are connected by the intercostal muscles, which also have a function in the breathing process. Muscles participating in the bending of the spine are also attached to the ribs. Severe disturbances in the function of these muscles change the shape of the thorax. This can be observed in paralytic scoliosis, caused by poliomyelitis. In idiopathic progressive scoliosis, the process of deformation apparently does not begin until the normal balance of the muscles is so disturbed that the normal range of movement of the ribs is exceeded and they are thus forced to bend and are gradually deformed (Steindler 1964).

The diagrams as well as the photographs of the transverse sections were used as examples of the remodelling. In the comparison of various scoliotic rib pairs and the ribs of the left and the right side, an almost regular drift towards a correction of deformity was observed. The observations of the modelling in the cranial-caudal direction can be understood on the basis of the schematic figure of the correction toward the normal position of the rib (Figs. 36 and 37). Likewise, the figure illustrates the changes in the pulmonal-cutaneal direction. One of the factors which made the interpretation of the observations easier was the correction of the lateral bending of the spine observed in pigs, mentioned by Langenskiöld and Michelsson (1961 and 1962) and by Karaharju (1967). The scoliosis in the pigs was first very distinct and progressive, but later on a decrease of the bending could be observed. Correction was so obvious in the slighter cases that it was difficult to observe any actual scoliosis in these pigs. However, on the basis of the transverse sections, the formation and correction of scoliosis during the growth

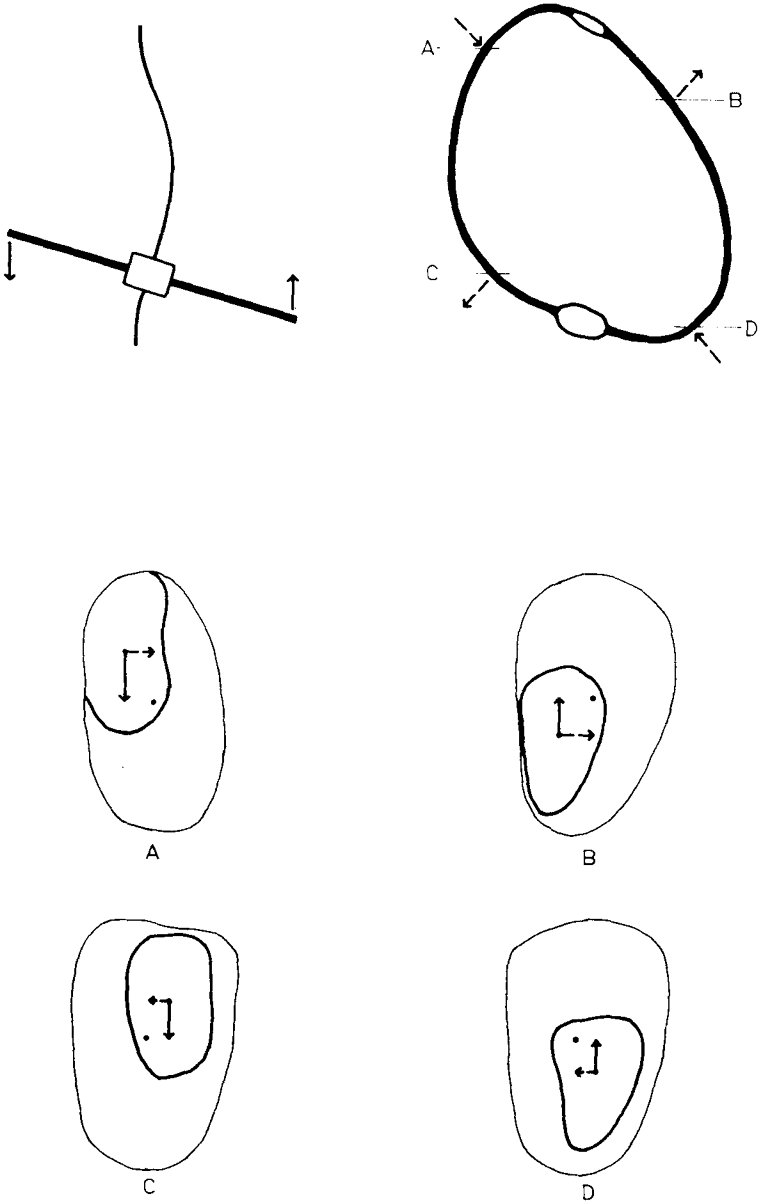

Figure 36. Remodelling taking place in relation to the apex in a caudal rib pair of a scoliotic test animal.

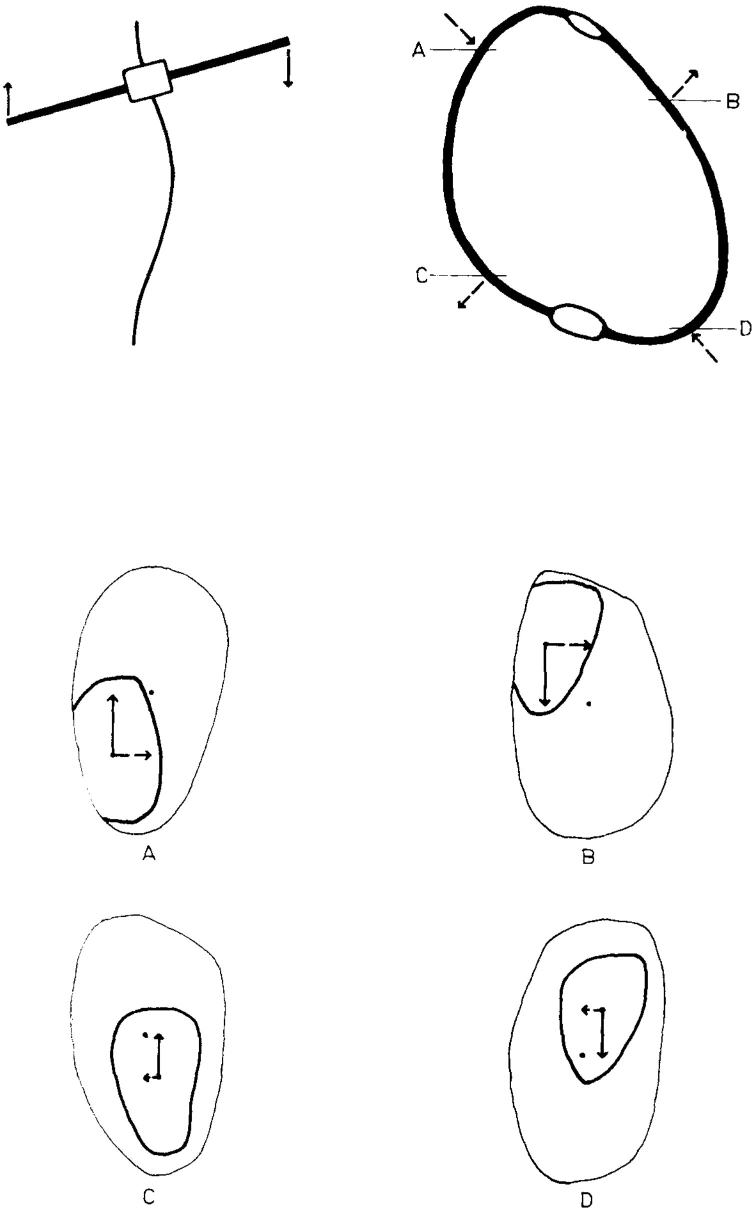

Figure 37. Remodelling in relation to the apex in a cranial rib pair of a scoliotic test animal.

process could be observed. Correction seemed to occur when the normal range of movement of the ribs was exceeded. The correction was obvious in the transverse sections of the scoliotic ribs, too (Figs. 36 and 37).

The spontaneous correction observed in some of the pigs gives reason to think that correction could be provoked by applying prophyllactic operative procedures to children with progressive idiopathic scoliosis, if the treatment could be started at a suitably early stage of growth. Yet it must be taken into consideration that experimentally produced scoliosis and human idiopathic scoliosis are distinctly different, a fact also referred to by James (1970), according to whom the role of experimental conditions is too hypothetical as far as scoliosis in the human body is concerned.

The spontaneous correction of scoliosis in pigs after progression and the tendency of correction of the ribhump gives us reason to hope that structural scoliosis in growing children may be curable.

Conclusions:

1. *Normal Growth:*

a) The longitudinal growth of a normal rib occurs mainly in the sternal end. According to the present investigation the longitudinal growth in the vertebral end is only one fourth of that in the sternal end.
b) The growth pattern of the ribs seems to depend on their position in relationship to the thorax.
c) The growth pattern of the total growth of the rib of a young pig indicates that the shape of a transverse section of the thoracic cage is remodelled from a half-circular into an oval shape during growth.

2. *Experimental scoliosis:*

a) Some of the test animals exhibited progressive, later on decreasing scoliosis. These observations indicate that spontaneous correction of scoliosis occurred in the test animals investigated.
b) Correction of the deformity of the ribs of the scoliotic pigs occurred in accordance with the facts found to be valid for the scoliotic spine in corresponding experiments. It occurred in a different manner on the right and left sides and also in the cranial and caudal parts of the scoliotic curve (Figs. 36 and 37).
c) The methods used in the present investigation proved useful in the study of three-dimensional growth of bones in general.

SUMMARY

The purpose of the present study was to clarify the course of growth in normal ribs and to study the changes occurring in the growth processes of the ribs of animals during the progression and the spontaneous correction of an experimentally provoked scoliotic curve.

The process of longitudinal growth of normal ribs of pigs was studied by the metal marking method. The processes of apposition and resorption of bone associated with the growth in width and the remodelling of the ribs during growth were studied by the tetracycline method.

The process of longitudinal growth in normal ribs was studied by implanting metal markers in seven ribs of five normal pigs and following the change in site of the markers during certain periods of growth. Normal growth in the vertebral end of a rib was found to be only about one fourth of that occurring in the sternal end. The ribs seem to grow in length mainly from a growth zone at the junction between the bony rib and the rib cartilage. The cartilage close to this junction is comparable to the epiphyseal cartilage in a long bone.

When the OTC-labelling method was used the pigs were given given daily 50 mg oxytetracycline per kilogram in one single dose during 2—3 days before the operation. When normal ribs were studied the pigs were allowed to grow for about two months. A total number of 37 normal ribs were studied by the tetracycline method. In order to preserve the possibility of studying the details of the change of the topography of the rib during the period from the apposition of tetracycline containing fluorescent bone to the moment when the animal was killed, each rib was cast in an acrylic mould. This allowed the reconstruction of the mutual position of the numerous transverse sections made of the bone and gave a clear picture of the growth of the rib as a whole (Fig. 11). The series of sections of the ribs were photographed in ultraviolet light. In each section two closed curves could be seen, each of them representing the surface of the bone at the moment the animal was killed, the inner, fluorescent

curve represented the bone laid down by apposition at the surface of the bone about two months earlier. The distance from the fluorescent bone to the actual surface of the bone of the killed animal represented the amount of apposition of bone in every individual bone and in any different part of it. The mutual position of a fluorescent curve and the area surrounded by it in relation to the whole section of the bone indicated the »drift» of the bone during a period of about two months. In order to study this phenomenon of »drift» and its variations in different regions of the ribs, the centre of the cross-section of the rib of the areas surrounded by the fluorescent ring on the one hand and the centre of the cross-section as a whole on the other hand were determined. The line connecting these centres indicated the direction and amount of »drift» of the bone in the area in question during the two-month period of growth. To facilitate the estimation of the growth of the rib as a whole the »drift» seen in each section was divided into two components, one pulmonal-cutaneal component and one cranial-caudal component.

Since the main direction of appositional growth in every section of the rib was known, numerical values for pulmonal-cutaneal growth and cranial-caudal growth could be calculated and diagrams could be drawn on the basis of them. The drift of a normal rib caused by apposition and resorption of bone was found to occur mainly in the cranial direction in the vertebral end of the rib (Figs. 10 and 13). Towards the sternal end the drift in the cutaneal direction is more and more marked (Figs. 10 and 13). Although all ribs mainly behaved in the same manner, each rib was found to have its specific shape and growth pattern depending on its anatomical position. The normal process of growth of ribs was studied by OTC-labelling in about 300 sections of 8 ribs in 3 pigs.

For the purpose of studying the growth of ribs during progression and the spontaneous correction of an experimentally produced scoliotic curve, twenty-two pigs were used. By using the same methods used for the study of the growth of normal ribs it was found that *in the cranial part of a progressing scoliotic curve, remodelling of the ribs in the cranial direction was seen on the concave side and a drift in the caudal direction was seen on the convex side of the curve.* Correspondingly, *in the caudal part of the curve correction in the cranial direction occurred on the convex side and in the caudal direction on the concave side* (Figs. 19, 36 and 37). The change of the growth pattern of each rib was thus different, depending on its position in relationship to the apex of the curve.

In accordance with facts based on earlier studies on experimental scoliosis published from the same laboratory, correction of the ribhump both on the dorsal and ventral side of the thorax was produced by the processes of apposition and resorption of bone during progression of a scoliotic curve. On the concave side near the vertebral part a drift occurred towards the cutaneal direction and, correspondingly, a drift in the other direction occurred in the sternal ends on the convex side.

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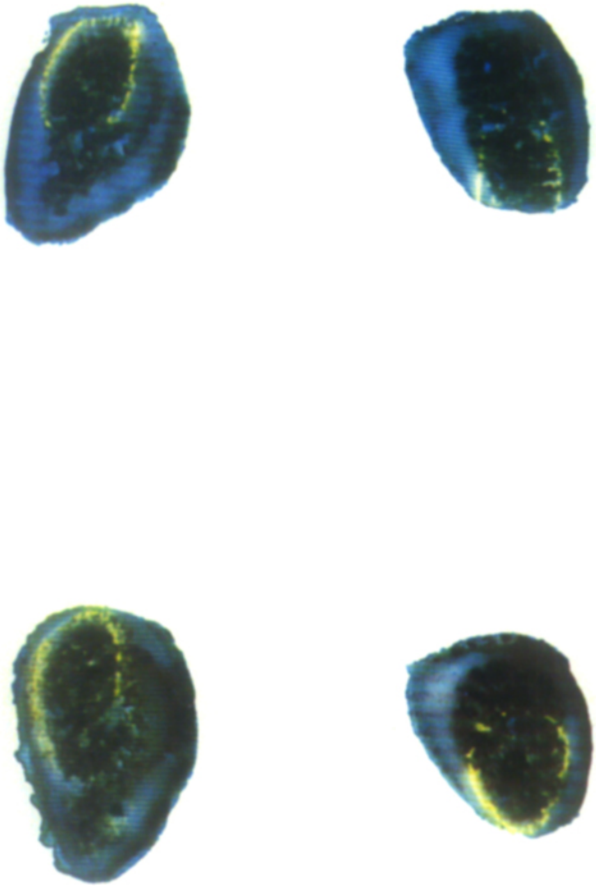

The cross sections of pig. No. 15 (see page 61). See also Fig. No. 26.

ERRATA

Page 13 line 20: for »patterns» read »pattern»
Page 17 line 8: for »(Lääke oy®)» read »(Amisept, Lääke oy®)»
Page 17 line 9: for »(Nobecutan, Bofors)» read »(Nobecutan, Borfors®)»
Page 20 line 2: for »filing off» read »filing-off»
Page 20 line 5: for »filing off» read »filing-off»
Page 33 line 9, and line 10 and page 37 line 20 and 21 »(YA)» and »(GA)», abolished.
Page 33 line 32: for »patterns» read »pattern»
Page 61 Figure 27: for »87» read »85» and for »Pig No. 15» read Pig No. 15, 14th rib pair
Page 65 Figure 31: for »17» read »15»
Page 67 line 3: for »87» read »85»
Page 81 Carey, E. J.: for »rotary» read »rotatory»
Page 85 colour picture: for »sections of pig» read »sections of 14th rib of pig»

ERRATA

Page 15 line 27: for "crease" read "an increase"

Page 40 line 28: for "2p 0.05" read "$2p < 0.05$"

Page 101 line 12: for "to 15^{o}" read "15^{o}"

Page 112 text to fig.: for "percentage" read "degree"

Page 155 line 2: for "diminished" read "increased"

Page 176 last line: for "61" read "6"