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OPERATIVE ELIMINATION OF PARTIAL PREMATURE EPIPHYSEAL CLOSURE

An Experimental Study

by

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Kalevi Österman

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INTRODUCTION

In orthopaedics and traumatology of children a special problem is caused by the diseases and injuries which affect the growth zone of a tubular bone. If the epiphyseal growth plate of a tubular bone is destroyed, the longitudinal growth of the bone produced by this epiphyseal plate ceases. The operative arrest of bone growth used in leg length equalization in children is based on this observation (*Phemister* 1933).

Cessation of growth is due to the fact that a bony connection appears between the epiphysis and metaphysis. Then the size and the site of the bone bridge determine the type of deformity.

The deformities caused by bone bridges between an epiphysis and a metaphysis have generally been treated by osteotomy or epiphyseodesis.

The injuries affecting the distal femoral and proximal tibial growth plates are of special clinical significance because a considerable part of the longitudinal growth of the leg occurs in this area.

In 1967 *Langenskiöld* presented two clinical cases on this subject. In one of them the bone bridge crossing the distal femoral epiphyseal plate disappeared after an osteotomy. In the other case the bone bridge between the epiphysis and the metaphysis at the upper end of the tibia was operatively removed and the defect in the bone was filled with a free transplant of fat tissue. After the operation, correction of the deformity was observed.

Because of the great vulnerability of epiphyseal plates, surgeons have in general been cautious with regard to operative procedures. The results of the experimental investigations of these injuries have not been very encouraging (*Friedenberg* 1957, *Nordentoft* 1969).

The observations based on the two clinical cases mentioned above, however, offered encouragement for further experimental investigation of injuries to the epiphyseal plate of a tubular bone. The need for this type of investigation was particularly great because sufficient experimental investigation is required before further clinical application.

The purpose of this study was to make qualitative observations on the following items:

1) The effect of partial epiphyseodesis on the epiphyseal plate and on the growth of a tubular bone.
2) The growth of the bone and the changes in the epiphyseal plate after elimination of partial epiphyseodesis.
3) The possibilities of using different interposition materials to prevent the recurrence of the bone bridge.
4) The possibilities of elimination of partial epiphyseal closure in man.

A preliminary report on this study was presented at the meeting of the Finnish Orthopaedic Association (*Österman & Langenskiöld* 1970).

REVIEW OF THE LITERATURE

Several authors agree that in 1727 *Stephen Hales* was the first to note experimentally that the long bones grow in length only at the epiphyses. His observations were confirmed by *Duhamel* (1742) and *Haller* (1766). Enchondral ossification in the growing epiphysis was noted by *Miescher* (1836) and described in detail by *Müller* (1858).

In 1798 *John Hunter* presented the still prevailing theory of the growth mechanism of the bone by realizing that simultaneous deposition and resorption occur in the growth process and lead to modelling that controls bone growth. He also proved that bone constantly changes its matter.

Since then many authors, too numerous to mention here, have studied longitudinal bone growth in the epiphyseal plate (*Haas* 1917, 1926, *Fell* 1925, *Harris* 1926, *Gatewood & Mullen* 1927, *Payton* 1932, *Policard* 1941, *Enlow* 1962, *Ham* 1969) and vascular supply of the epiphyseal plate and its role in osteogenesis (*Trueta & Morgan* 1960, *Trueta & Little* 1960, *Yabsley & Harris* 1965, *Spira & Farin* 1967).

In spite of contrary observations, the last of them presented by *Hellstadius* (1947, 1951), the importance of enchondral ossification at the epiphyseal plate in the longitudinal growth of normal bones has been convincingly established. There is a long-standing theory that growth in width of the epiphyseal plate takes place interstitially (*Ranvier* 1889, *Keith* 1920, *Policard* 1941).

This theory is supported by some observations concerning epiphyseal growth in Ollier's disease (*Langenskiöld* 1947). Similar observations have been made after an experimental roentgen ray injury of the epiphyseal plate (*Langenskiöld & Edgren* 1949). By using radioisotope similar results have been obtained in the normal epiphyseal plate (*Langenskiöld, Rytömaa & Videman* 1967). On the other hand some investigations support the theory of appositional growth in diameter (*Solomon* 1966, *Rang* 1969).

Pioneer investigations concerning experimental injuries of the epiphyseal plate were performed by *Ollier* (1867), who in his extensive monograph states the effects of different experimental injuries on the epiphyseal plate as follows:

Small incisions into the epiphyseal plate have little influence on bone growth.

Marked excisions have a strong influence and cause shortening and deformities of the bone.

Experimental separation of the epiphysis has little influence if it is immediately replaced in a good position.

Total excision of the epiphyseal plate causes a complete cessation of growth.

In 1873 *Bidder* proved histologically that a partial lesion of the epiphyseal plate is followed by a bone bridge between the metaphysis and the epiphysis. This bone bridge causes growth retardation and degenerative changes in the epiphyseal plate starting from the side of the injured area. His observations were confirmed by *Nové-Josserand* (1893), who showed that a bony connection always follows an injury, extending from the metaphysis to the epiphysis. The size and location of the bone bridge are responsible for the type of deformity. These observations have since then been confirmed by using different types of surgical injuries to the epiphyseal plate (*Vogt* 1878, *Nakahara* 1909, *Haas* 1917, 1919, *Nunnenmacher* 1939, *Ring* 1955, *Ford & Key* 1956, *Friedenberg* 1957, *Key & Ford* 1958, *Brashear* 1959, *Campbell, Grisolia & Zanconato* 1959, *Barash & Siffert* 1966, *Nordentoft* 1969, *Salenius & Videman* 1970, *Serafin* 1970). On the other hand *Hatt* (1940) could find no growth disturbances in patients after using central cortical bone grafts which traversed the epiphyseal plate.

Growth arrest produced by a bone bridge between the epiphysis and metaphysis was put into clinical use when *Phemister* (1933) published his generally accepted method of operative arrest of longitudinal bone growth for equalization of leg length.

The effect of metal pins and wires on longitudinal growth of the bone when traversing the epiphyseal plate has been investigated by several authors (*Haas* 1945, 1950, *Siffert* 1956, *Key & Ford* 1958, *Campbell, Grisolia & Zanconato* 1959, *Kolesnikov* 1967). It has been noticed that a bony connection between the epiphysis and the metaphysis follows the removal of the metal. The growth retarding effect depends on the pin, so that a smooth pin traversing the epiphyseal plate perpendicularly causes least growth disturbance. It has also been proved that the deformity and retardation in growth correlate with the time which has passed since the removal of the metal pin.

Many authors stress the great vulnerability of the epiphyseal plate. In addition to mechanical traumata to the epiphyseal plate, many other types of damage to the plate may cause bone bridge formation between the epiphysis and the metaphysis. Temporary ischaemia of moderate duration of the epiphyseal plate results in necrotic changes in it (*Trueta & Amato* 1960, *Troupp* 1961, *Brashear* 1963, *Young* 1966). By using x-ray irradiation it has been possible to cause epiphyseal plate injuries (*Perthes* 1903, *Engel* 1938, *Reidy, Lingley, Gall & Barr* 1947, *Langenskiöld & Edgren* 1949). The ^{90}Sr isotope that accumulates in the bone has caused similar damage (*Ray, Thompson, Wolff & Laviolette* 1956). On the other hand a strontium-rich diet is able to disturb ossification and causes degenerative changes in the epiphyseal plate (*Storey* 1965). External physical changes, such as frost bite, may also cause destruction of the epiphyseal plate and growth disturbances (*Lindholm, Nilsson & Svartholm* 1968).

The longitudinal growth of a bone can be arrested or retarded by external compression and this may cause irreversible and progressive damage to the epiphyseal plate (*Haas* 1945, *Gelbke* 1951, *Strobino, French & Colonna* 1952, *Arkin & Katz* 1956, *Düben* 1956, *Siffert* 1956, *Strobino, Colonna, Brodey & Leinbach* 1956, *Trueta & Trias* 1961, *Sijbrandij* 1963, *Hall-Craggs & Lawrence* 1969). On the other hand the decompression of the epiphyseal plate causes acceleration of growth in accordance with the Hueter-Volkmann law. According to *Heřt* (1969) this acceleration of growth was only temporary because the unloaded epiphyseal plate disappeared prematurely and hence the effect of the excessive longitudinal growth was lost (delayed premature union).

Irrespective of the etiological factor causing a bone bridge it is evident that it constitutes a mechanical impediment to growth, and the size and density of the bone bridge are in direct proportion to the growth disturbance (*Ollier* 1867, *Bidder* 1873, *Nové-Josserand* 1893, *Nakahara* 1909, *Haas* 1919, *Phemister* 1933, *Ford & Key* 1956, *Friedenberg & Brashear* 1956, *Friedenberg* 1957, *Campbell, Grisolia & Zanconato* 1959, *Johnson & Southwick* 1960, *Heikel* 1961).

Small bone bridges have caused only minimal growth disturbances. In these cases the growth potential of the epiphyseal plate causes elongation of the bone bridge. The elongation is due to the formation of microscopic defects in the bone, which in fact means a certain kind of remodelling (*Johnson & Southwick* 1960).

The mechanical force caused by the growth of the epiphyseal plate is considerable. In some clinical cases staples used to control bone growth have bent or broken (*Blount & Clarke* 1949, *Blount & Zeier* 1952), so it seems natural that small bone bridges cannot arrest growth. Measurements of the growth potential of the epiphyseal plate show that the growth of the proximal tibial epiphysis was inhibited by 3 kg, or 15 g per mm^2 cross-sectional area of the plate, or 15 mg per column of cartilage cells (*Sijbrandij* 1963). The experiments by *Strobino, Colonna, Brodey & Leinbach* (1956) show that this power is 45 pounds per square inch (3.1 kg per cm^2) in the proximal tibial epiphysis of a calf.

The clinical problems connected with injuries to the epiphyseal plate have been recognized for a long time. In 1867 *Ollier* observed that resection of the tuberculous knee of a child led to a considerable loss of leg length.

Based on experimental observations *Bidder* (1873) concluded that the bone bridge between the epiphysis and the metaphysis causes growth disturbances in man, too. After these and many other sporadic observations *Poland* in 1898 published his extensive monograph on injuries to the epiphysis. Since then many authors have paid attention to this problem (*Bergenfeldt* 1933, *Aitken* 1935, 1936, 1965 a, b, *Gill & Abbott* 1941, *Abbott & Gill* 1942, *Aitken & Magill* 1952, *Blount* 1954, *Rehnberg* 1955, *Aitken & Ingersoll* 1956, *Redell* 1956, *Harsha* 1957, *Fielding, Liebler & Tambakis* 1960, *Cassebaum & Patterson* 1965, *Crenshaw* 1965, *Neer & Horwitz* 1965, *Morton & Starr* 1964, *Siffert* 1966, *Jani & Hertel* 1967, *Langenskiöld* 1967 b, c, *Rang* 1969, *Rogers* 1970).

In children under the age of sixteen 6 to 15 per cent of fractures of the long bones involve the epiphysis. Of all these injuries 25 to 33 per cent result in some shortening or deformity, of which 10 per cent are considered sufficient to interfere with function (*Rogers* 1970).

Salter & Harris (1963) reviewed these injuries in detail and classified them in five groups. According to them significant growth disturbances are found in cases where the fracture traverses the epiphyseal plate and in cases of a crushing injury and interference with the blood supply. Many other classifications have been presented (*Poland* 1898, *Bergenfeldt* 1933, *Aitken* 1936).

Damage to the epiphyseal plate can be found as a sequel of bone and joint infections (*Nové-Josserand* 1893, *Phemister* 1933) and irradiation (*Perthes* 1903, *Langenskiöld* 1953). Damage is also found in connection with long-term immobilization of a leg due to the treatment of tuberculosis or other diseases (*Gill* 1944, *Parke, Colvin & Almond* 1949, *Sissons* 1952, *Botting & Scrase* 1965).

Using autoradiography and histology *Hulth & Westerborn* (1963) were able to prove a temporary decrease in the growth rate of the epiphyseal plate. Bony connections between the epiphysis and metaphysis have also been found as a complication of Osgood-Schlatter's disease (*Stirling* 1952, *Langenskiöld* 1967 b), and an adolescent form of tibia vara (*Langenskiöld & Riska* 1964).

A corrective osteotomy has been generally recommended as a treatment of choice in injuries of the epiphyseal plate causing deformity. This procedure may occasionally have to be performed repeatedly in cases of progressive deformity. In addition to osteotomy the rest of the epiphyseal plate can be destroyed in order to prevent the progression of angulation, but this results in the loss of longitudinal growth of the bone. To equalize leg length the opposite leg may require epiphyseodesis or a shortening operation unless a lengthening operation on the shortened leg is possible (*Abbott & Gill* 1942, *Blount* 1954, *Salter & Harris* 1963, *Rang* 1969).

There are only few reports in the literature on the possiblities of preventing the progression of deformity by operatively removing the deforming bone bridge. In 1878 *Vogt*, in investigating experimental epiphyseal separations, was, however, able to prevent the growth of capillaries between the epiphysis and metaphysis by interposing a thin gold leaf or rubber film between the epiphysis and metaphysis. *Friedenberg* (1957) made considerable efforts to solve this problem by removing operatively the bony connection between the epiphysis and metaphysis in ten rabbits. He tried to prevent the recurrence of the bone bridge and progression of deformity by interposing bone wax, but his experiments were not encouraging. Bone wax has also been used to protect the experimental defects of the epiphyseal plate by other authors (*Key & Ford* 1958, *Campbell, Grisolia & Zanconato* 1959, *Serafin* 1970), but fragmentation of this material in the growth process prevented it from remaining protective during the whole growth period. The results with methyl metacrylate as the interposition material were also poor (*Friedenberg* 1957).

Nordentoft (1969) experimentally removed the bone bridge between the epiphysis and metaphysis in the proximal tibia of a dog by performing epiphyseal separation at the same time, but he did not achieve positive results by this method. His results were a little better with partial resection of the metaphysis proximal to the epiphyseal injury to prevent the retardation of growth, but he does not recommend this method for clinical use.

In addition to bone wax *Serafin* (1970) covered experimental defects of the epiphyseal plate with a free muscular transplant, and he found it the most effective in preventing bone bridge formation across the traumatized epiphyseal plate.

Regeneration after excision of the epiphyseal plate has been observed at least in experiments with younger animals (*Selye* 1934, *Nunnenmacher* 1939). Regeneration of the epiphyseal plate has also been observed after experimental roentgen-ray injuries (*Langenskiöld & Edgren* 1949) and in connection with experimental epiphyseal transplantations (*Heikel* 1960). *Nordentoft* (1969) observed that the epiphyseal cartilage regenerates and fills the drill hole traversing the epiphyseal plate. However, in experiments where a bony connection exists between the epiphysis and metaphysis no regeneration has been observed (*Ford & Key* 1956, *Friedenberg* 1957, *Campbell, Grisolia & Zanconato* 1959).

The clinical case reported by *Langenskiöld* (1967 b) is the first known example in which a bone bridge was verified by means of clinical and roentgenological evidence and found sufficient to cause deformity but disappeared after a corrective metaphyseal osteotomy. In his other patient the operative elimination of the bone bridge evidently normalized bone growth.

MATERIAL AND METHODS

I EXPERIMENTAL ANIMALS AND GENERAL OPERATIVE TECHNIQUE

The present study was performed on rabbits which were aged three or six weeks at the beginning of the experiment. A total of 178 rabbits were operated on, but 23 preliminary experiments are not included in the results. The site of operations was the distal epiphyseal plate of the femur, which was exposed through lateral parapatellar incision aseptically under local anesthesia (0.25 per cent Xylocain-Exadrin®, Astra). The right femur was used in all experiments while the left femur served as a control treated in different ways or left intact. Wounds were closed with catgut, no immobilization was used and the animals were fed and treated according to general principles. Most animals were given penicillin subcutaneously during the operation, and no wound infections appeared.

II SPECIAL TECHNIQUE

The operations were performed in two phases. The first phase consisted of a provocative operation (first operation). At this operation a piece 4 mm in diameter was removed from the lateral side of the distal epiphyseal plate of the right femur by using a round punch. The trauma extended to the cancellous bone of the metaphysis and epiphysis. The gap was filled with a bone transplant taken from the iliac bone and it usually consisted of one lamina of the bone. A piece of stainless steel wire was implanted into the metaphysis for measurements (Figs. 1 and 2).

As to the control femur, the material was divided into three groups. In the first group the left femur was operated on in the same way as the right one (bone bridge control). The animals in group two were treated by using soft tissue operation on the left leg corresponding to that of the first group to control the effects of soft tissue injury. This

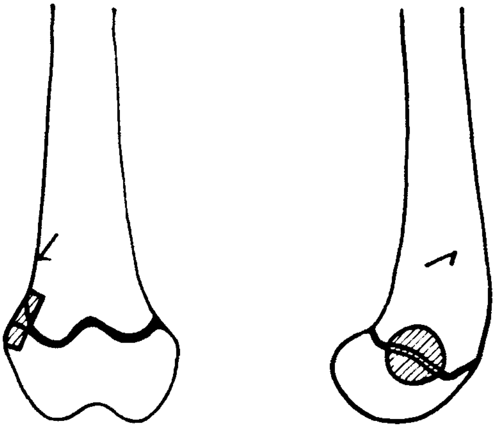

Fig. 1. The site of the provocative operation and the metal marker.

Fig. 2. Rabbit No. 105. Radiograph immediately after a bilateral provocative operation.

group is later referred to as arthrotomy control. The animals in group three received only a metal marker in the diaphysis of the left femur for measurements (normal control).

A corrective operation on the right femur (second operation) was performed two weeks later, when, as a rule, a valgus deformity was

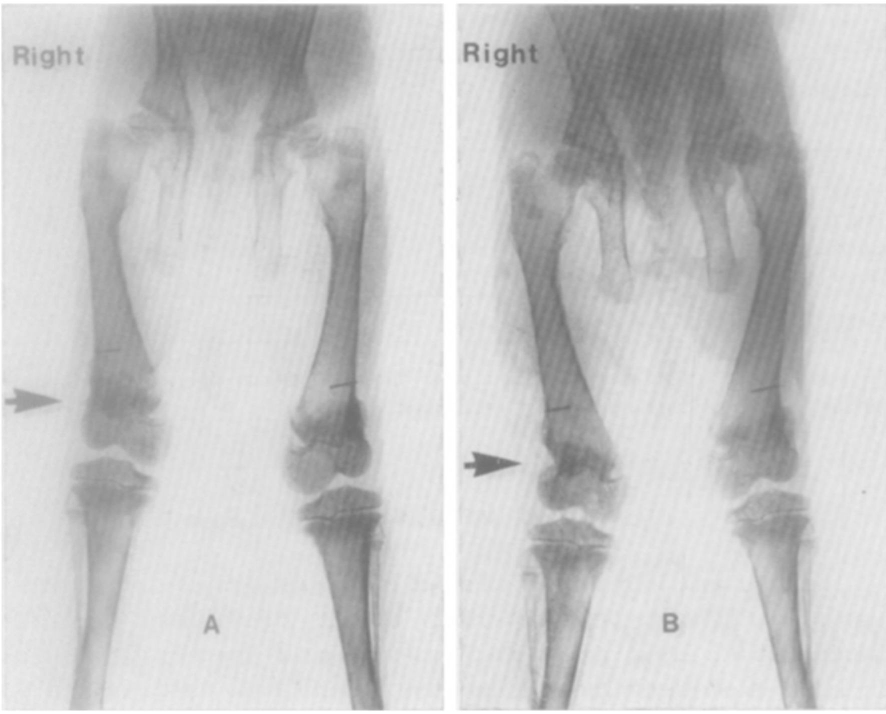

Fig. 3. Rabbit No. 26. Radiograph 14 days after a provocative operation.
A. A bone bridge and valgus deformity of both femurs.
B. Immediately after a corrective operation of the right femur.

already visible. In this operation the bone bridge between the epiphysis and metaphysis was removed using a dental drill and an operation microscope. The size of the bone bridge varied but it clearly exceeded the size of the bone transplant and consisted of about 1/4 to 1/3 of the frontal diameter of the epiphyseal plate. The semicircular defect, at the bottom of which the epiphyseal plate was visible, was filled with interposition material when this was used. Special efforts were made to assure hemostasis. A corresponding soft tissue operation was performed on the left leg in the arthrotomy control group (Fig. 3).

The animals were killed 2 to 150 days after the second operation and the femurs were dissected. Twenty-two animals were killed 1 to 15 days after the first operation in order to make observations on the early changes in the epiphyseal plate and the bone transplant.

The number of animals in the different groups is shown in Table 1.

TABLE I. *Total number of experiments with bone bridge resection.*

Interposition material (in the right leg)	Total	Control leg (left)		
		Bone bridge	Arthrotomy	Normal
None	32	15	2	15
Fat tissue	52	25	12	15
Cartilage	29	11	—	18
Bone wax	20	10	—	10
Total	133	61	14	58

In addition 22 animals were killed after the provocative operation without a corrective operation having been performed.

III INTERPOSITION MATERIALS

The interposition materials consisted of free autogenous f a t t i s s u e transplant, heterogenous deep-frozen hyaline c a r t i l a g e (cartilage from a rib of a pig) and b o n e w a x (B o n e w a x ®, E t h i c o n). In some experiments no interposition material was used. Based on earlier observations, most emphasis was placed on fat tissue and cartilage as interposition materials.

The use of a free fat tissue transplant as interposition material is based on the observation that it remains fat tissue in its new location. This phenomenon has been thoroughly discussed by *Lexer* in 1924. Earlier fat tissue was even used to fill cavities in bone (*Klopfer* 1913). In the clinical case presented by *Langenskiöld* (1967 b) fat tissue was also used as an interposition material. Concerning clinical applications, fat tissue is readily available and easy to implant.

Some observations made on the regeneration of the epiphyseal plate after an experimental x-ray injury suggest that dead cartilage is able to prevent ossification between the epiphysis and metaphysis (*Langenskiöld & Edgren* 1949). This observation has also been made in connection with experimental epiphyseal transplantations (*Heikel* 1960).

Some investigators have used bone wax in their experiments affecting the epiphyseal plate (*Friedenberg* 1957, *Campbell, Grisolia & Zanconato* 1959, *Serafin* 1970). Bone wax has been noticed to prevent ossification at a distance of 5 mm (*Howard & Kelley* 1969). This property is probably due to the histamine concentration of the bone wax (*Penttinen* 1971).

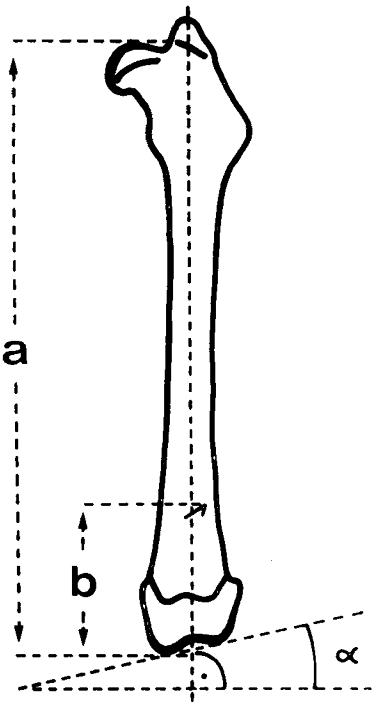

Fig. 4. Diagrammatic representation of measurements.
a — Total length.
b — The distance between the metal marker and the distal end of the bone.
α — Valgus angle of the femur.

IV RADIOLOGICAL TECHNIQUE, MEASUREMENTS

The femurs were x-ray photographed immediately after the first operation and both before and after the second operation. The animals were re-examined at intervals of 2 to 3 weeks and finally the dissected femurs were x-rayed. The radiographs were taken in the anteroposterior projection with the animal in a ventral position, and in the lateral projection, at a focus distance of 90 cm (film Ilford Ilfex for non-screen technique). The state of the epiphyseal plate, the longitudinal growth of the bone, changes in the valgus deformity, and the site of the interposition material were recorded on the radiographs.

The length of both femurs was measured on the radiographs (Fig. 4) and the total of longitudinal growth and the growth caused by the distal epiphyseal plate during the observation period was calculated by subtracting the measuring results at the time of the second operation from the final results measured on the radiographs of the dissected femurs. In addition, growth difference between the right and left femur was calculated.

Measurements of longitudinal growth were made by projecting them on the longitudinal axis of the femur in order to eliminate the error caused by rotation (*Brodin* 1955) and the lateral site of the metal marker.

The valgus angle of the femur was defined by measuring the angle between the line perpendicular to the longitudinal axis of the femur and the line drawn tangential to both femoral condyles. The longitudinal axis was drawn through the tip of the greater trochanter and the middle point of the distal epiphyseal plate in the anteroposterior projection except in some cases where the bone was badly deformed.

The accuracy of measurements on the radiographs of the living animals is inferior to that on the radiographs of the dissected femurs. In some cases measurements on the radiographs of living animals were not reliable. On the radiographs of living animals the error in longitudinal growth measurements of the femurs was apparently in the same direction because the animals were x-rayed by using the same technique in all cases.

The measurements of longitudinal growth were computed and because the material was very heterogenous owing to different observation periods, main attention was paid to the differences in each pair of bones.

V HISTOLOGICAL TECHNIQUE

The distal parts of the femurs were cut in the frontal plane in the middle of the epiphysis with a saw. They were fixed, decalcified in five per cent nitric acid or in ten per cent EDTA (ethylene diamine tetra-acetic acid), embedded in paraffin wax and cut into 7 μ thick sections at intervals of 500 μ and stained with haematoxylin van Gieson. In these sections observations were made on the state of the epiphyseal plate, the site and quality of the interposition material, the presence of bone bridges and the differences between the right and left femurs.

VI TETRACYCLINE TECHNIQUE

The deposition of tetracycline in newly-formed bone and its identification by means of fluorescence when exposed to ultraviolet light (*Milch, Rall & Tobie* 1957) has proved to be a simple and efficient technique in investigating the growth and remodelling of bone. In the present study 127 rabbits were injected with oxytetracycline (Terramycin

®, P f i z e r)* 50 mg per kg of body weight. The first dosage was injected after the first or second operation and the injection was repeated at intervals of 1—2 months in order to measure the terminal growth of bone. The split surface of the distal parts of the femurs cut in the frontal plane in the middle of the epiphysis were photographed by using the same techniques as *Puranen* (1966) and *Videman* (1970).

On these photographs the distal epiphyseal growth after the last injection of the tetracycline was recorded and compared with that of the control femur. Besides, asymmetric growth and bone bridges and their remodelling were controlled. By means of tetracycline labelling the moment when some bone bridges were formed could also be determined.

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RESULTS

I THE EFFECT OF PARTIAL PREMATURE EPIPHYSEAL CLOSURE ON THE GROWTH OF A TUBULAR BONE AND ITS EPIPHYSEAL PLATE

The material consists of bone bridge control femurs of 61 rabbits. In addition, 22 rabbits killed after the first operation without a second operation having been performed are included in the material.

A Radiological findings

A growth disturbance appeared in the distal part of the femur resulting in a progressive valgus deformity (Fig. 5). The deformity usually increased in correlation with time and reached its maximum

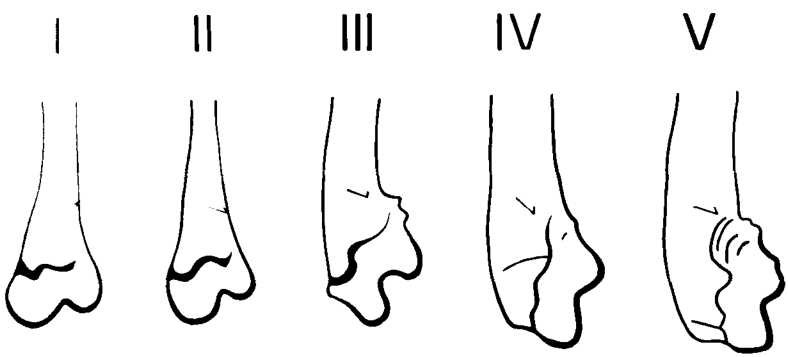

Fig. 5. Diagrammatic representation of a typical growth disturbance of the bone bridge control.

I — Bone bridge 14 days after the provocative operation. Rabbit No. 150.
II — Metaphysis 20 days after the provocative operation. Rabbit No. 157.
III — Deformity 41 days from the beginning. Rabbit No. 152.
IV — 98 days from the beginning. Rabbit No. 37.
V — 149 days from the beginning. Rabbit No. 135.

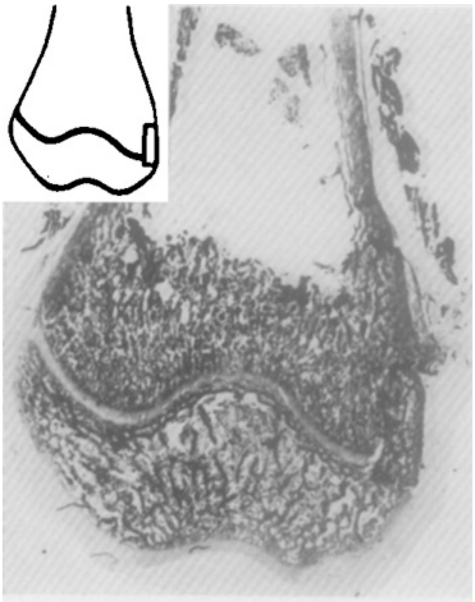

Fig. 6. Rabbit No. 174. Histological picture of the epiphysis four days after a provocative operation. The bone transplant is still visible but adhering to its bed. (x7)

at the end of growth (Figs. 11, 19, 25, 30) although in a few cases the progression caused by the primary injury was interrupted and after that the growth continued rather normally. The size of deformity varied widely in individual animals and in general a growth disturbance developed more quickly in animals operated on at the age of three weeks. In these animals the trauma caused by the provocative operation was also relatively large.

The bone bridge between the epiphysis and metaphysis could be identified in the radiograph but it was difficult to estimate its size. After the trauma the epiphyseal plate usually became thinner on the side of the bone bridge. This asymmetry of the epiphyseal plate was more marked in younger animals (Fig. 3). At the end of growth the epiphyseal plate disappeared and the progress of the deformity stopped.

Lateral dislocation of the patella, osteoporosis and sclerotic changes at the site of the injury could be observed as secondary findings. Osteoarthritis of the knee was seen in advanced cases. The epiphysis of the injured bone became larger than normal.

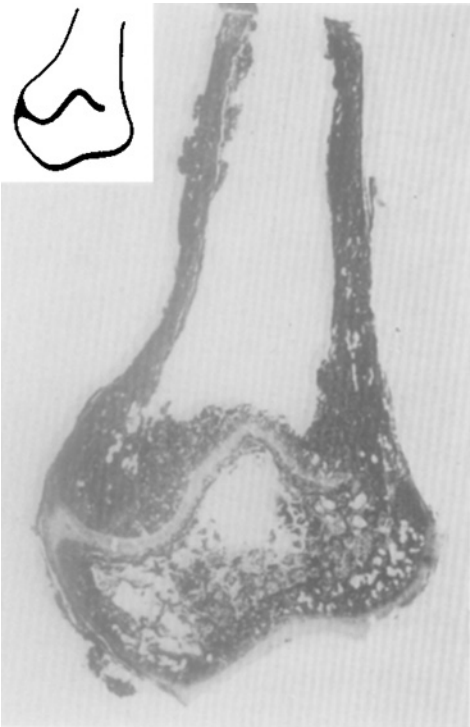

Fig. 7. Rabbit No. 93. Histological picture 14 days after a provocative operation. A solid bony connection between the epiphysis and metaphysis observed. Growth asymmetry and thinning of the epiphyseal plate starting from the side of the trauma. (x7)

B Histological findings

After partial epiphyseodesis the bone transplant remained viable and grew into its ground within 3—4 days (Fig. 6). It merged into the surrounding bone as a result of quick remodelling. Simultaneously the bone bridge grew thicker replacing a part of the epiphyseal plate. Starting from the injury the growth activity of the epiphyseal plate diminished, and the plate became thinner resulting in asymmetric growth (Fig. 7). Later on the changes became more prominent and resulted in a severe deformation and premature ossification of the epiphyseal plate. In advanced stages cartilage islets and fibrotic scar tissue were often noticed corresponding to the site of the epiphyseal plate. At the same time an appositional bulge of bone arose between the epiphysis and metaphysis on the side of the injury. On the opposite side part of the epiphyseal plate retained its growth potential for a considerably longer time (Fig. 8). Qualitatively, late changes in this group resemble those found in the group treated without any interposition material.

Fig. 8. Rabbit No. 104. Histological picture 66 days after a provocative operation. Gross deformity, cartilaginous islets and scar tissue replacing the epiphyseal plate, the medial part of which is left and causes progressive deformity. (x7)

In some cases remodelling causing elongation of thin bone bridges was observable, and in some cases, a remnant projecting to the metaphysis of the injured epiphyseal plate was formed by the growth process. This remnant was also found in other groups.

Osteoporosis and secondary arthrotic changes were normal findings in advanced cases.

C Tetracycline findings

By means of tetracycline labelling it was demonstrated that partial epiphyseodesis resulted in retardation of longitudinal growth and formation of a rigid bone bridge on the injured side of the epiphysis. In the initial stage this caused asymmetric longitudinal growth (Fig. 34). Later on it was observed that the progressing deformity was compensated partly by the latitudinal growth process in the direction of the injury in the metaphysis. In spite of that, the original bone bridge might remain as a lock at the edge of the epiphyseal plate. In the final stage, retardation and premature cessation of growth was observed. In some cases remodelling in the metaphysis caused by elongation of thinner bone bridges was found.

II GROWTH OF A BONE AFTER ELIMINATION OF PARTIAL PREMATURE EPIPHYSEAL CLOSURE WITH NO INTERPOSITION MATERIAL

The material consisted of 32 femurs.

A Radiological findings

After the second operation the progression of valgus deformity stopped for 2—3 weeks, after which a new progression of deformity took place (Fig. 9). This phenomenon was more common in the present group

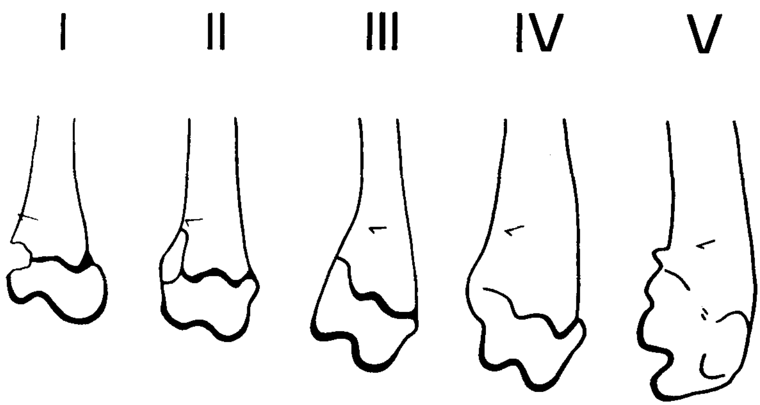

Fig. 9. Diagrammatic representation of typical growth after a corrective operation without any interposition material.

I — Immediately after the corrective operation. Defect in bone bordering on the epiphyseal plate. Rabbit No. 178.
II — 13 days later. Defect remodelled and left in the metaphysis. Rabbit No. 176.
III — 69 days after a corrective operation. Reformed bone bridge had increased in size, causing deformity. Rabbit No. 155.
IV — 86 days after a corrective operation. Bone bridge persisting and firm, epiphyseal plate disappearing, starting from the side of the trauma. Rabbit No. 86.
V — 114 days after a corrective operation. Deformity at its maximum and growth finished. Rabbit No. 100.

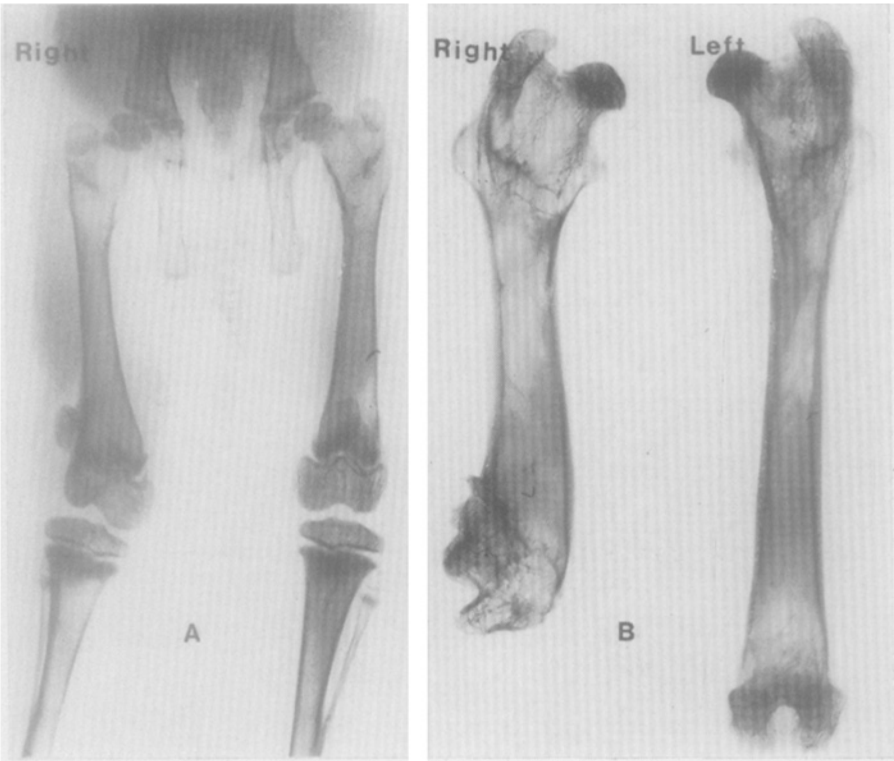

Fig. 10. Rabbit No. 100. Epiphyseal plate injury treated by removing the bone bridge without adding any interposition material. Left femur as a normal control.

A. Condition immediately before the corrective operation.
B. Condition 114 days later. Progression of valgus deformity from 34°—77°. The right femur 17 mm shorter and distal growth 21.5 mm less than in the control femur.

than in the groups with some interposition material, but in some cases the deformity remained unchanged or was corrected (Fig. 44). Compared with the normal control femur in typical cases the deformity was severe (Fig. 10) but usually remained smaller than that of the bone bridge control femur (Fig. 11).

Immediately after removal of the bone bridge a defect could be found in the bone. Sometimes a wedgelike figure characterizing the recurrence of the bone bridge was observable in the metaphysis. On the other hand, a figure characterizing new cortical bone formation was observed only seldom at the site of the defect in the metaphysis. In some cases

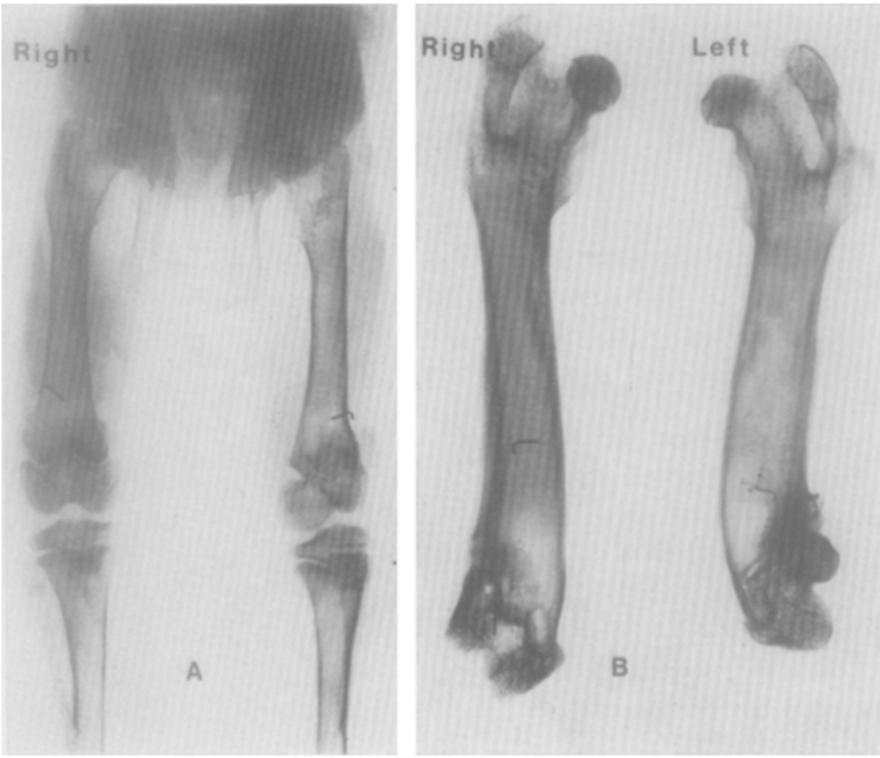

Fig. 11. Rabbit No. 153. Epiphyseal plate injury treated by removing the bone bridge without adding any interposition material. Left femur as a bone bridge control.

A. Condition immediately after the corrective operation.

B. Final result 100 days later. Valgus deformity 46° in the right femur, 90° in the left. Right femur 10 mm longer than the left one and distal growth 12.5 mm more in the right femur. Note: Valgus deformity has developed in spite of minimal primary deformity.

a steplike deformity was found in the epiphyseal plate on the injured side.

Secondarily, osteoarthritis of the knee, osteoporosis of the femur and sclerotic changes in the bone bridge developed at later stages. Lateral dislocation of the patella was a common finding in the animals with a severe deformity.

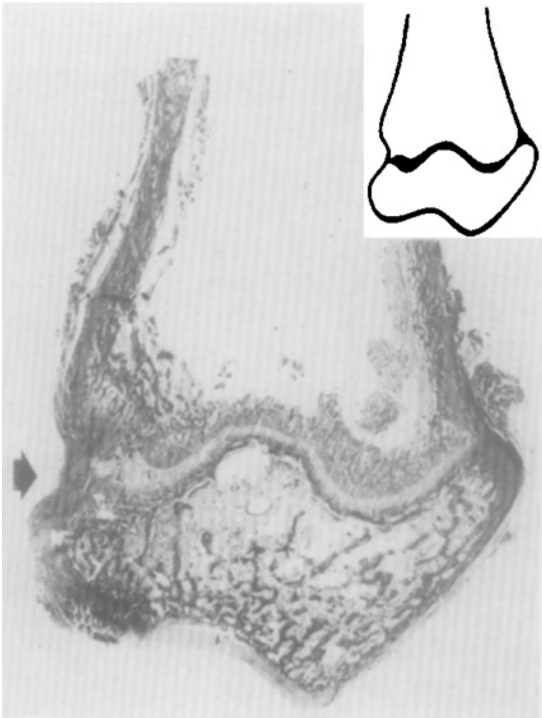

Fig. 12. Rabbit No. 176. Epiphysis 13 days after the corrective operation without any interposition material. The epiphyseal plate shows growth activity. The arrow indicates the defect filled with scar tissue after removal of the bone bridge. No signs of bone bridge recurrence.

B Histological findings

Immediately after removal of the bone bridge a defect was found in the bone extending to the epiphyseal plate. At first it was filled by a blood clot that organized in about 2 weeks (Fig. 12). Loose cartilage cells were found in the cavity in one case. After this the edge of the epiphyseal plate was built up, and a ribbonlike cartilage remnant often appeared towards the metaphysis. Simultaneously bone trabeculae grew into the vascularized defect, especially from the epiphysis. When they reached the metaphysis a loose connection was formed between the epiphysis and metaphysis (Fig. 13).

In the course of the observation period the bone bridge thus formed became more solid and firm (Fig. 14) and resulted in a new progression of deformity and premature ossification of the epiphyseal plate. The changes resemble those found in connection with bone bridge controls (Fig. 15). Appositional bone formation was found on the operated side,

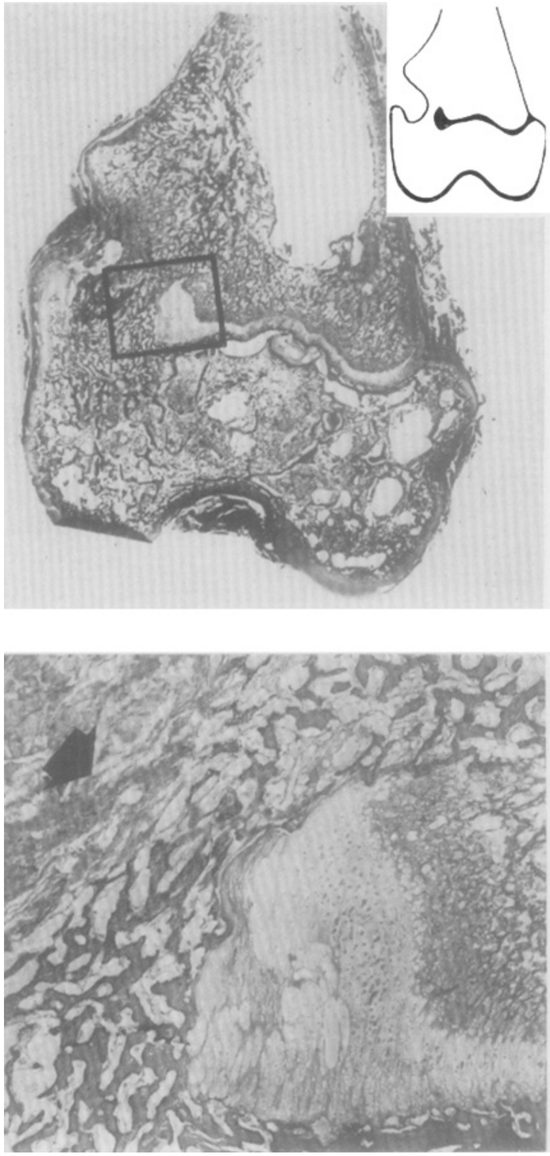

Fig. 13. Rabbit No. 98. Histological picture 17 days after the corrective operation without any interposition material. The epiphyseal plate shows growth activity, but there are thin bone trabeculae joining the epiphysis and metaphysis, as shown by the arrow. (x7, x40)

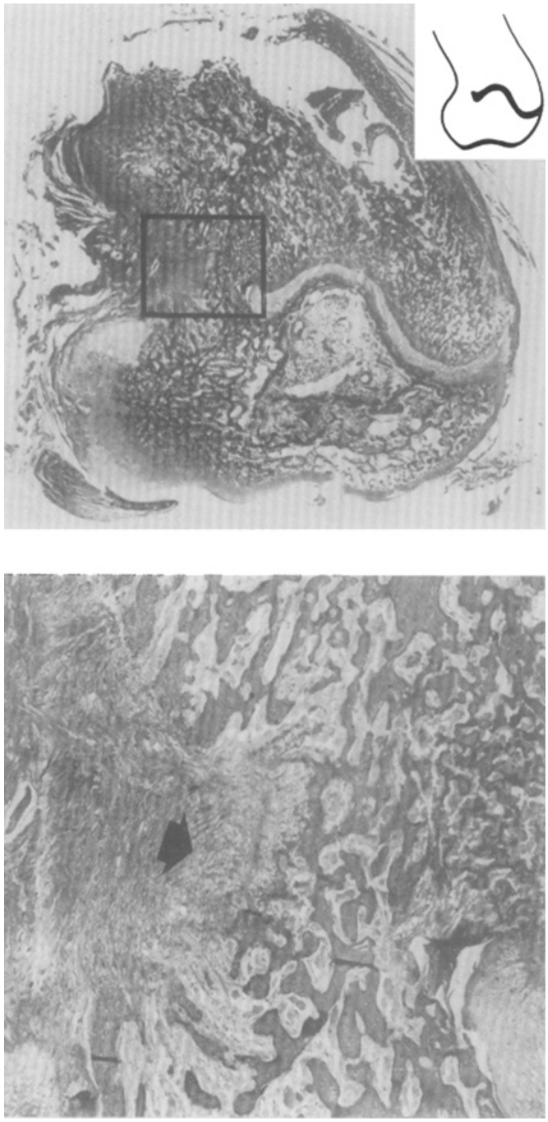

Fig. 14. Rabbit No. 150. Histological picture 20 days after the corrective operation without any interposition material. The epiphyseal plate shows growth activity, but the bone bridge has reappeared. (x7, x40)

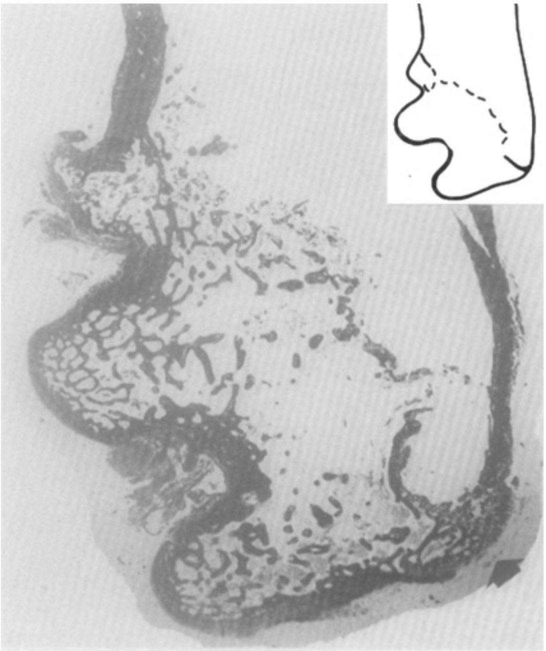

Fig. 15. Rabbit No. 153. Histological picture 100 days after the corrective operation without any interposition material. The bone bridge is reformed and has caused a severe deformity. A small remnant of the epiphyseal plate still visible, as shown by the arrow. (x7) See Fig. 8.

and the intact side of the epiphyseal plate was able to maintain its growth potential, increasing deformity for a considerable time.

In the cases where no new progression of deformity was found it appeared that the epiphyseal plate maintained its growth potential. In a thin bone bridge remodelling indicating elongation was found in the metaphysis (Fig. 16). This was in correlation with the tetracycline findings. Four cases showed no recurrence of a bone bridge, but in these even the deformity provoked by the first operation was slight. Compared with the control femur it appeared that the epiphyseal plate disappeared earlier than in the normal control but in representative cases later than in the bone bridge control.

C Tetracycline findings

Immediately after removal of the bone bridge growth was at first released and tended to correct the deformity by means of normal longitudinal growth and lateral growth in the direction of the injury.

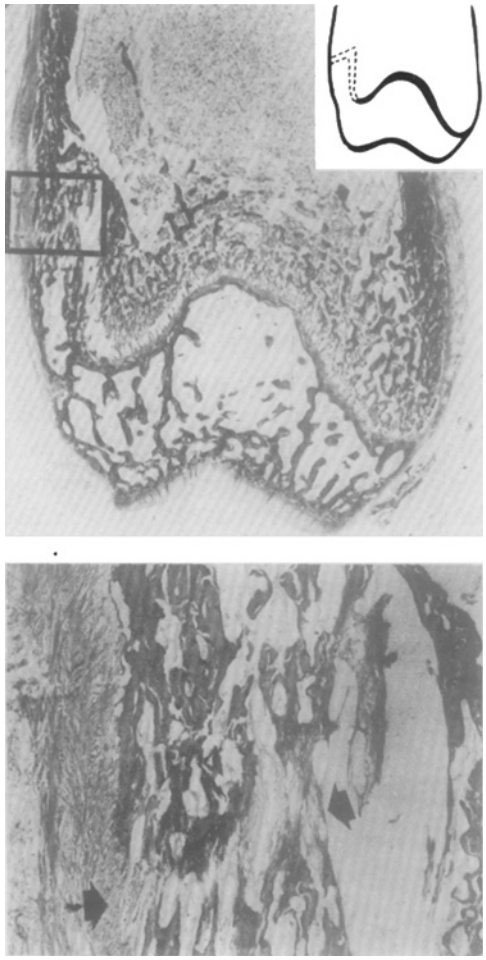

Fig. 16. Rabbit No. 75. Histological picture 66 days after the corrective operation without any interposition material. The bone bridge is reformed, but no growth asymmetry is observed, because remodelling of the bone bridge causes elongation in the metaphysis, as indicated by the arrows. (x7, x40) See Fig. 36.

Later on a bony connection reappeared between the epiphysis and metaphysis leading to new deformity and asymmetric growth (Fig. 35). Elongation of the bone bridge in the metaphysis was observed in cases where no new progression of deformity developed after removal of the bone bridge. This remodelling corresponded to the histological finding and progressed in accordance with normal growth (Fig. 36). Compared with the normal control femur growth stopped earlier and was slower and asymmetric. Compared with the bone bridge control longitudinal growth was quicker and as a rule less asymmetric, corresponding to the measurements.

III GROWTH OF A BONE AFTER ELIMINATION OF PARTIAL PREMATURE EPIPHYSEAL CLOSURE WITH FAT TISSUE AS AN INTERPOSITION MATERIAL

The material consisted of 52 femurs. When dissecting the bones fat tissue was usually found in the metaphyseal area, and in many cases the transplant had grown larger during the observation period.

A Radiological findings

During the first two weeks following the removal of the bone bridge the valgus deformity did not decrease and sometimes even slightly increased. Simultaneously a considerable progression took place in the deformity of the bone bridge control. The correction of deformity began after 3—4 weeks and continued, even causing overcorrection in a few cases (Figs. 17, 18, 19). In the third postoperative month a new progression of deformity was found in six cases.

The defect of bone filled with a fat tissue transplant was usually clearly visible immediately after the operation and was in contact with

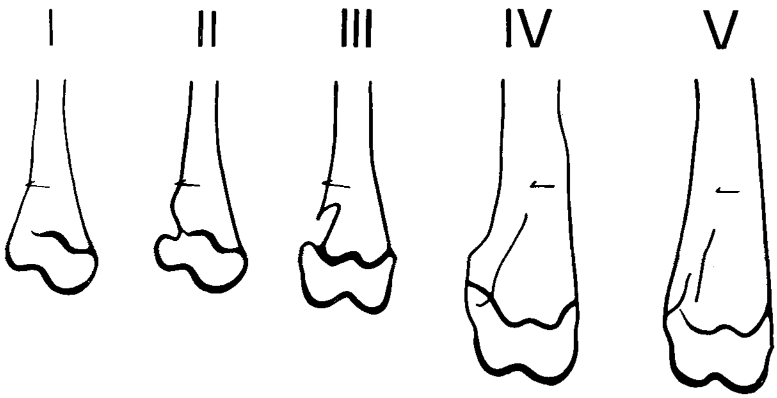

Fig. 17. Diagrammatic representation of typical growth of the metaphysis after the corrective operation with fat tissue as an interposition material.

I — Immediately before the corrective operation. Rabbit No. 26.
II — Two days after the corrective operation. Rabbit No. 26.
III — 24 days after the corrective operation. Growth symmetric, no bone bridge. Rabbit No. 160.
IV — 84 days after the corrective operation. Valgus deformity had disappeared and growth was symmetric in spite of a small bone bridge recurrence. Rabbit No. 37.
V — Final result 135 days after the corrective operation. Symmetric longitudinal growth nearly completed. Rabbit No. 38.

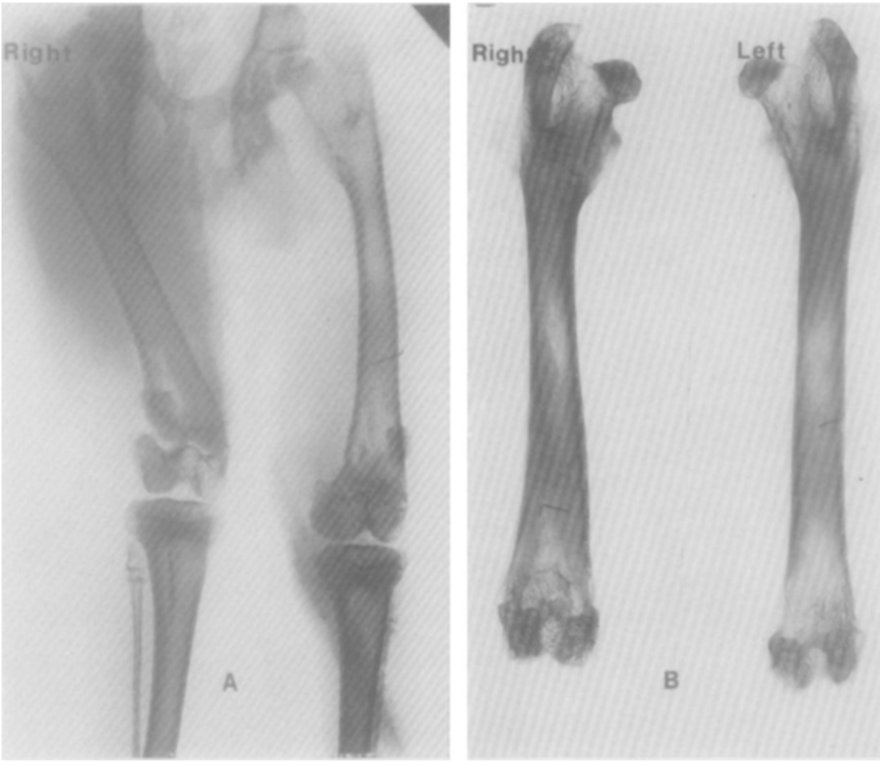

Fig. 18. Rabbit No. 137. Epiphyseal plate injury treated by removing the bone bridge and adding a fat tissue transplant. The left femur as a normal control.

A. Condition 14 days after the corrective operation. Valgus deformity still visible, no bone bridge observed.

B. Final result 150 days after the corrective operation. Valgus deformity corrected, shape of the bone normal. Right femur 4 mm shorter, loss of distal growth 7 mm compared with the normal control, which indicates slight growth stimulation in the proximal end of the bone.

the epiphyseal plate (Fig. 3). At the same time a new cortical bone layer was formed on the operated side at the edge of the epiphyseal plate, and it migrated in a lateral direction during the growth process (Figs. 18, 19). This phenomenon was more conspicuous in cases where the primary deformity was not very severe. On the operated side a slight steplike deformity to the metaphysis appeared in the epiphyseal plate in almost half the cases.

Secondarily, some deformity in the lateral condyle of the femur was found but the degenerative changes in the bone and joint were

Fig. 19. Rabbit No. 38. Epiphyseal plate injury treated by removing the bone bridge and adding a fat tissue transplant. The left femur as a bone bridge control.

A. Condition immediately after the corrective operation.

B. Final result 135 days after the corrective operation. A relatively large primary valgus deformity corrected. Simultaneous valgus progression in bone bridge control from 19°—77°. Shortening of 11 mm on the left.

not so striking as in the bone bridge control. The epiphysis usually grew larger than normal. In the course of time the epiphyseal plate, clearly visible postoperatively, became thinner and folded and thus its interpretation became less accurate.

B Histological findings

At first, two days after the second operation a defect was observed in the bone filled by a fat tissue transplant. This was in close contact with the epiphyseal plate and seemed to be viable but was not adhered to the surrounding bone. Compared with the bone bridge control the

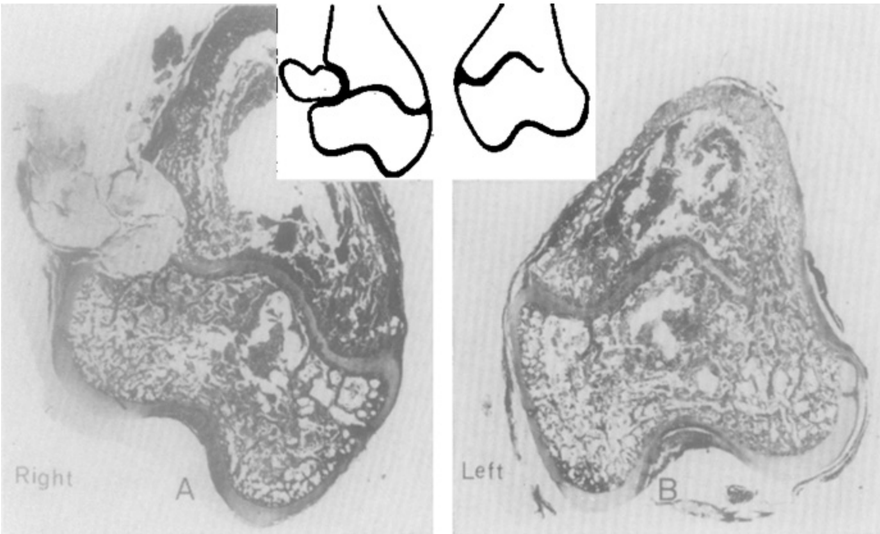

Fig. 20. Rabbit No. 26.
A. Histological picture two days after the corrective operation with fat tissue as interposition material. The epiphyseal plate borders on the fat tissue transplant, which seems to be viable.
B. Bone bridge control of the same rabbit. (x7)

epiphyseal plate seemed to be more active on the operated side (Fig. 20). Towards the end of the first postoperative week, when longitudinal growth continued, the bone defect was left behind in the metaphysis. The transplant was partly necrotized and attached to the wall of the bone defect. Between the transplant and the bone a narrow strip of organizing blood clot could be observed. In the second week these changes became more accentuated, but presumably some of the fat cells remained viable all the time. The ossification groove was remodelled and scar tissue was found between the transplant and the bone (Fig. 21).

In the course of later growth the fat tissue transplant was seen to react in two ways. In some cases the transplant was attached to the epiphysis and followed the epiphyseal plate in connection with the longitudinal growth. Accordingly it formed an impression bordering on the epiphyseal plate and the ossification groove (Fig. 22). More fibrosis than normal was found in fat tissue newly formed at the latest in the second month.

In other cases the fat tissue transplant adhered to the metaphysis and was gradually left behind in the diaphysis when growth continued.

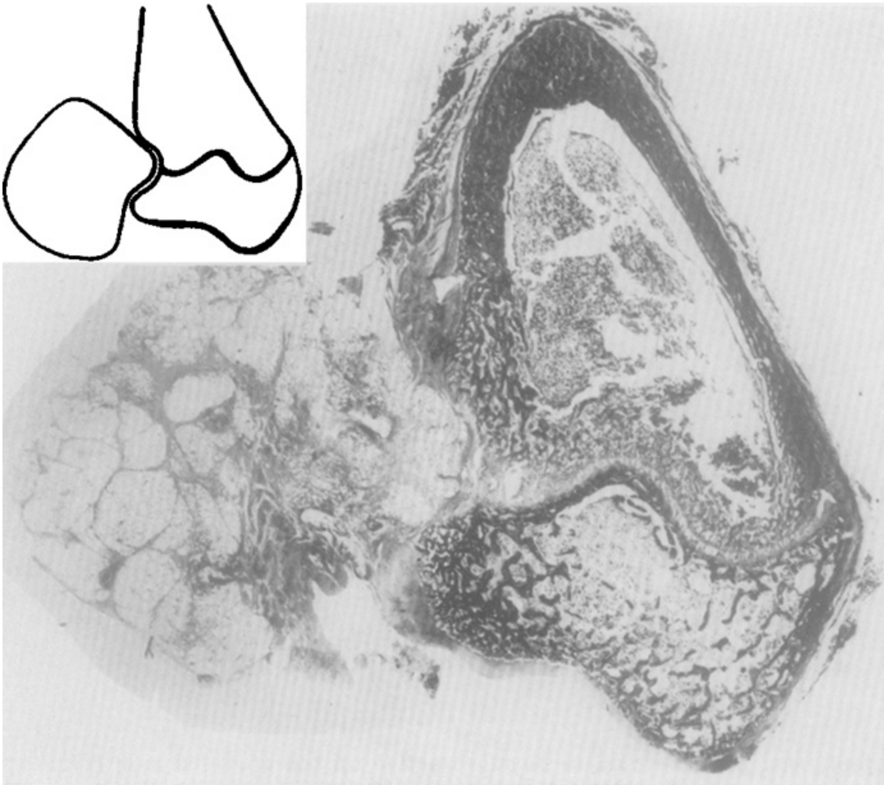

Fig. 21. Rabbit No. 161. Histological picture 12 days after the corrective operation with fat tissue as an interposition material. The big transplant borders on the edge of the epiphyseal plate and is adherent to its surroundings. Most of the fat tissue necrotized. (x7)

Simultaneously the diameter of the epiphyseal plate was normalized by increased growth in diameter. Accordingly, the fat tissue transplant in the diaphysis formed a figure typically projecting in the distal and lateral direction. This figure was also characteristic when other interposition materials were used (Fig. 28).

In experiments with a fat tissue transplant a thin bone bridge recurrence was found in some sections after the second postoperative month, but it did not usually cause deformity. Increased growth in width could not always restore the normal diameter of the epiphyseal plate, especially in cases with severe injury. In these cases a steplike deformity was often found in the epiphyseal plate, too.

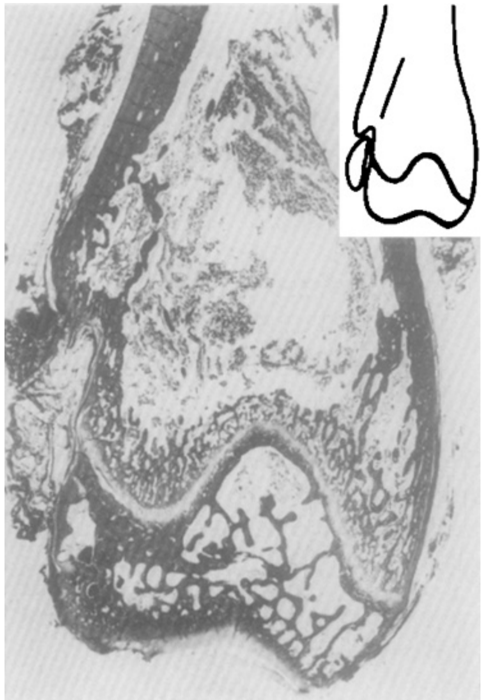

Fig. 22. Rabbit No. 37. Histological picture of an epiphyseal injury treated by resection of bone bridge and implantation of fat tissue 84 days after the corrective operation. The transplant has remained at the level of the epiphyseal plate in connection with growth. The epiphyseal plate is active and has a normal configuration. The fat tissue is living but shows some fibrotic changes. (x7)

At the end of the growth period the ossification of the epiphyseal plate began from the injured side. Thus a small terminal valgus progression was possible.

Compared with the control femur it appeared that the epiphyseal plate disappeared a little earlier than in the normal control, but considerably later than in the bone bridge control.

C Tetracycline findings

In the initial stage the fat tissue transplant gave a blue fluorescence, in the later stages it was not always visualized. During the first week no correction of deformity was demonstrated. Later on the deformity was corrected by means of longitudinal and lateral growth, and these two processes were indistinguishable during the rapid initial growth period.

Comparison with the normal control showed that growth ceased a little earlier and was slower at the end of the growth period. On the other hand, comparison with the bone bridge control showed that growth was considerably quicker and went on for longer.

At the end of the growth period the growth ceased starting from the injured side, so that a small valgus progression was still observed (Fig. 37). In thin bone bridge recurrences an elongation was observed demonstrated by lack of fluorescence.

IV GROWTH OF A BONE AFTER ELIMINATION OF PARTIAL PREMATURE EPIPHYSEAL CLOSURE WITH A CARTILAGE TRANSPLANT AS AN INTERPOSITION MATERIAL

The material consisted of 29 femurs. When dissecting the bones, the cartilage transplant was loose in its bed if the observation time was short, but later on it was attached to the surrounding tissue and was not always visible.

A Radiological findings

In this group the correction of valgus deformity started after about two weeks and was observed in all but one case (Fig. 23). At the same

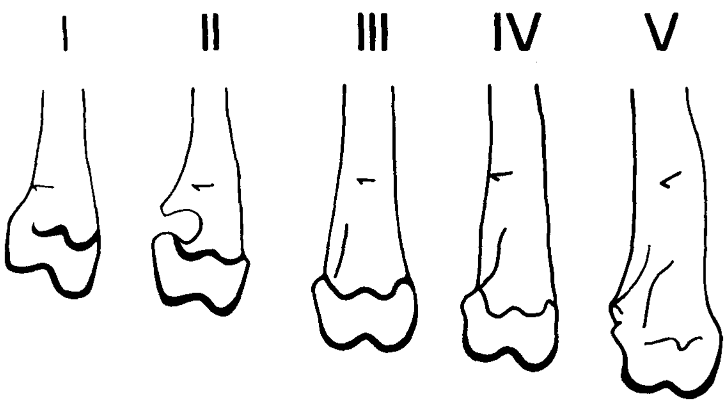

Fig. 23. Diagrammatic representation of typical growth of the metaphysis after a corrective operation with cartilage as an interposition material.
I — Immediately before the corrective operation. Rabbit No. 127.
II — 15 days after the corrective operation. The defect of bone is clearly visible. Rabbit No. 121.
III — 52 days after the corrective operation. Rabbit No. 119.
IV — 84 days after the corrective operation. Rabbit No. 127.
V — 122 days after the corrective operation, at the end of the growth period. Rabbit No. 107.

Fig. 24. Rabbit No. 127. Epiphyseal plate injury treated with a cartilage transplant. The left femur as a normal control.

A. Condition immediately before the corrective operation.
B. Final result 84 days after the corrective operation. Valgus deformity corrected, no shortening. A loss of 2 mm in the distal growth observed.

time the deformity of the bone bridge control made considerable progress. The mark caused by the cartilage transplant was often seen on radiographs, and was sometimes left in the metaphysis or diaphysis as growth continued (Fig. 24). The bone surrounding the transplant underwent sclerotic changes, and in the later stage the transplant also became calcified (Fig. 25).

In the initial stage the epiphyseal plate was in contact with the clear-cut bone defect and the epiphyseal plate formed a new cortical bone layer which migrated in a lateral direction as growth proceeded. This phenomenon was observable in about two thirds of all cases.

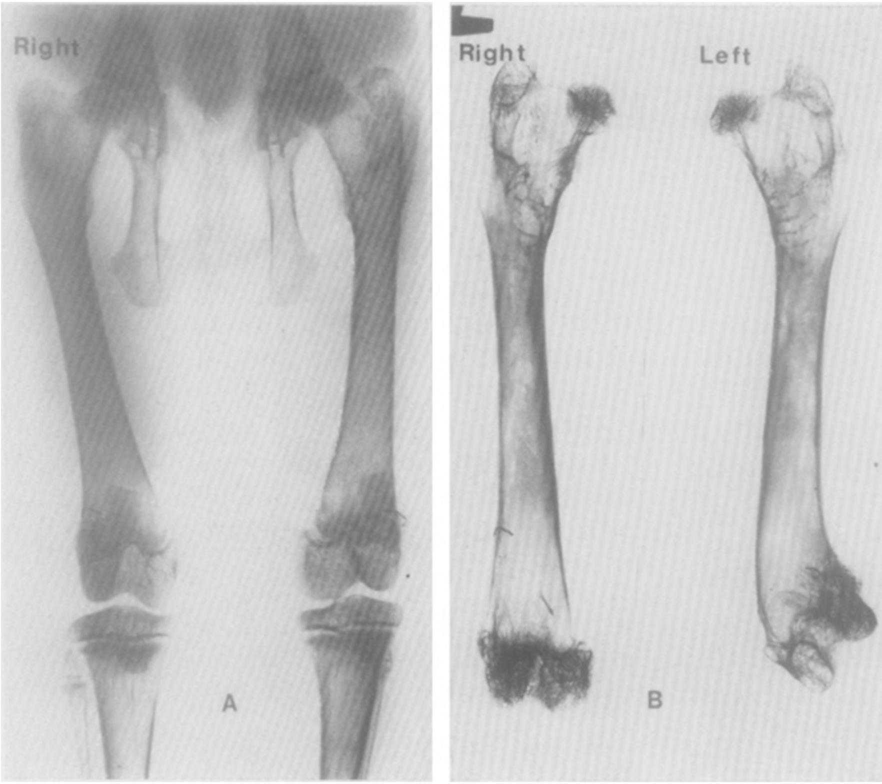

Fig. 25. Rabbit No. 112. Radiographs of the epiphyseal plate injury treated with a cartilage transplant. The left femur as a bone bridge control.

A. Condition immediately before the corrective operation. Valgus deformity observed in both femurs.

B. Final result 90 days after the corrective operation. The valgus of the right femur normalized but the left femur shows a progression to 53 degrees. A shortening of 4.5 mm observed on the left.

The end result closely resembled a normal bone (Fig. 24) and the deformation of the bone bridge control was as usual striking (Fig. 25).

As a rule, secondary changes were slight. The epiphysis grew a little larger than normal and the lateral condyle of the femur was slighty deformed (Figs. 23, 25).

B Histological findings

During the first two weeks it was found that the epiphyseal plate was in close contact with the defect but the cartilaginous transplant

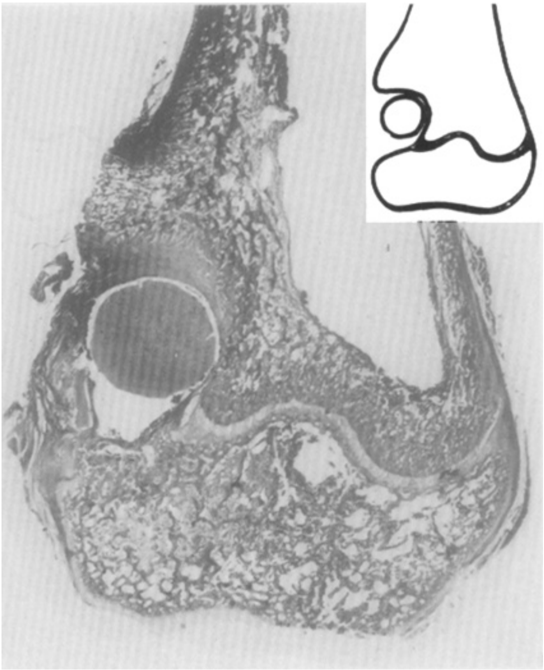

Fig. 26. Rabbit No. 121. Epiphyseal plate injury treated with a cartilage transplant 15 days after the corrective operation. The ossification groove is reformed and the edge of the epiphyseal plate is growing in the distal and lateral direction. (x7)

had disappeared, probably owing to the preparation, because it was still loose in its bed. However, the transplant was very effective in preventing the invasion of the bone bridge at the stage when the ossification groove was reformed (Fig. 26).

As growth proceeded, the transplant reacted like the fat tissue transplant. In some cases it adhered to the epiphysis and followed the epiphyseal plate in connection with the longitudinal growth and sometimes formed an impression bordering on the epiphyseal plate (Fig. 27).

In other cases the transplant adhered to the metaphysis and was gradually left behind in the diaphysis as growth continued. The diameter of the epiphyseal plate was normalized and the transplant formed a figure characterizing the increased growth in diameter (Fig. 28).

The initially big transplant degenerated and shrank and was sometimes later calcified. At the same time it became encapsulated (Figs. 26, 27, 28).

Small bone bridge recurrences were found in some sections, but these did not cause growth disturbances. The epiphyseal plate preserved its growth potential for a long time on the operated side, too, and growth

Fig. 27. Rabbit No. 112. Epiphyseal plate injury treated with a cartilage transplant 90 days after the corrective operation. Distal growth 16 mm, the transplant has followed the epiphyseal plate during the growth period, no bone bridge recurrence. (x7)

terminated only a little earlier than in the normal control, in contrast to the bone bridge control, where premature cessation of growth and a bad deformity appeared.

C Tetracycline findings

The cartilage transplant displayed a blue autofluorescence in the beginning, but in the later stage it was sometimes calcified and gave a yellow fluorescence.

Deformity was corrected by means of simultaneous asymmetric longitudinal and lateral growth. Later on the growth was predominantly longitudinal. Thus the results resemble those obtained with the fat tissue transplant (Fig. 38). Also compared with the growth of the control femur similar changes were found. The growth of the bone bridge control ceased earlier but the growth of the normal control continued for a somewhat longer time. The ossification of the epiphyseal plate began on the injured side and caused a small terminal valgus progression.

Fig. 28. Rabbit No. 127. Epiphyseal plate injury treated with a cartilage transplant 84 days after the corrective operation. The transplant left behind in the diaphysis has become degenerated, but normalization of the epiphyseal plate is evident. (x7)

No solid bone bridges labelled by tetracycline could be demonstrated between the epiphysis and metaphysis during the growth period in this series (Fig. 39).

V GROWTH OF A BONE AFTER ELIMINATION OF PARTIAL PREMATURE EPIPHYSEAL CLOSURE WITH BONE WAX AS AN INTERPOSITION MATERIAL

The material consisted of 20 femurs. Bone wax surrounded by scar tissue was found in the bone preparations, especially in cases with short observation period.

A Radiological findings

In the beginning the valgus deformity progressed slightly in certain cases after removal of the bone bridge, but later on correction of the valgus deformity was observed. Thus the results correspond to those

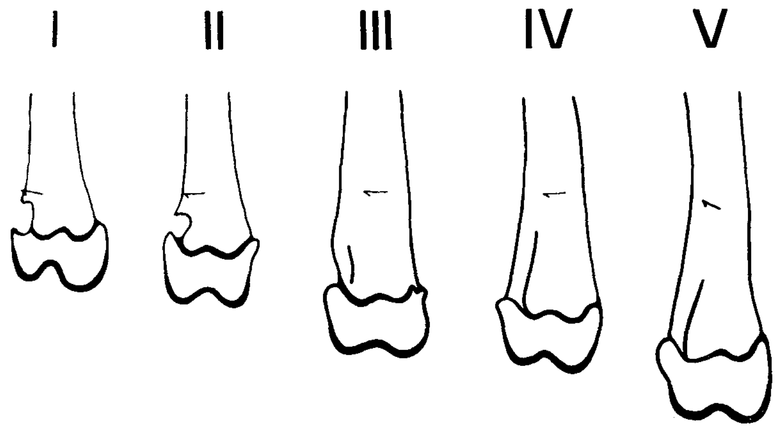

Fig. 29. Diagrammatic representation of typical growth of the metaphysis after a corrective operation with bone wax as an interposition material.

I — Immediately after the corrective operation. Rabbit No. 164.
II — 19 days after the corrective operation. Rabbit No. 164.
III — 67 days after the corrective operation. Rabbit No. 165.
IV — 83 days after the corrective operation. Rabbit No. 169.
V — 108 days after the corrective operation. Rabbit No. 148.

obtained with other interposition materials (Fig. 29). A good end result was achieved especially in cases where the deformity provoked by the primary injury was slight. A slight increase in valgus deformity appeared in some cases, but in every case the end result showed a lesser deformity than that of the bone bridge control (Fig. 30). Compared with the normal bone the correction was good in most cases (Fig. 31).

The defect caused by removal of the bone bridge and filled with bone wax was easily detectable on radiographs because of its clear-cut contours. Sometimes its elongation in the metaphysis as a result of growth was clearly demonstrated (Fig. 31). The figure formed by the cortical bone layer, indicating lateral growth of the epiphyseal plate, was also clearly observable in cases where the observation time was long enough. On the operated side a steplike deformity was often encountered in the epiphyseal plate.

Secondary degenerative changes were insignificant, the epiphysis grew somewhat larger.

B Histological findings

The trace formed by bone wax was observed in every case. It was formed by cavities surrounded by scar tissue fibres bordering on

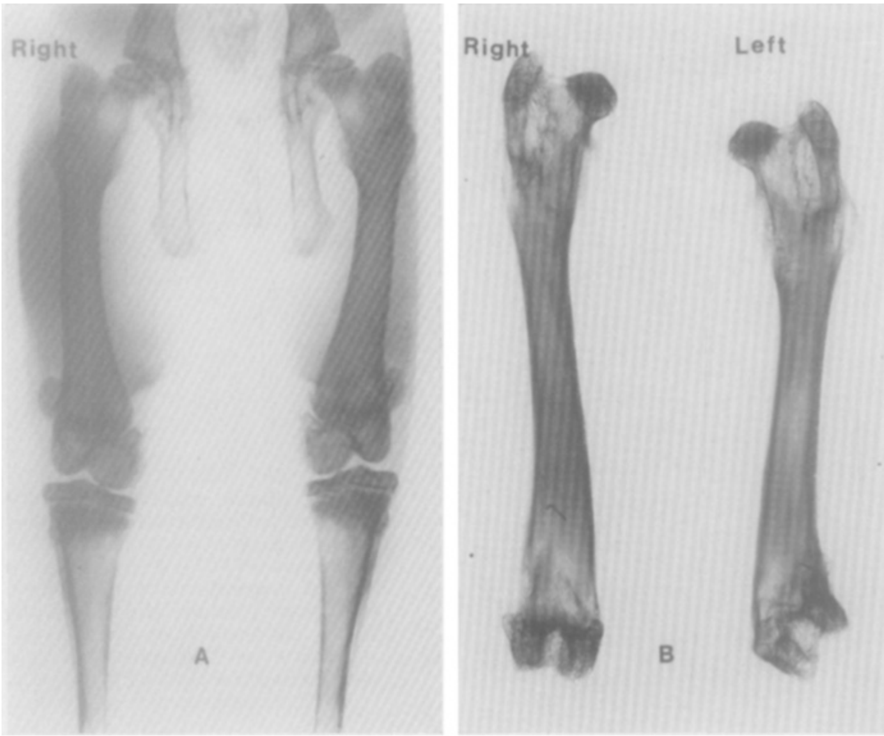

Fig. 30. Rabbit No. 169. Radiographs of the epiphyseal plate injury treated with bone wax. The left femur as a bone bridge control.

A. Condition immediately before the corrective operation.
B. Final result 83 days after the corrective operation. Valgus of the right femur corrected, the left femur shows a remarkable progression of valgus deformity and a shortening of 7 mm.

the epiphyseal plate. In the beginning, when the ossification groove was reformed, it was able to prevent reformation of the bone bridge (Fig. 32). Later on growth caused fragmentation of the bone wax, which increased the risk of bone bridge recurrences, but in this material this phenomenon was seldom present. Bone wax did sometimes follow the epiphyseal plate as growth proceeded and its controlling effect on the growth in diameter of the epiphyseal plate was clearly demonstrated (Fig. 33). Even in this series the ossification of the epiphyseal plate started on the operated side, somewhat earlier than in the normal control but considerably later than in the bone bridge control.

Fig. 31. Rabbit No. 168. Epiphyseal plate injury treated with bone wax 90 days after the corrective operation. The left femur as a normal control. The line from the diaphysis to the epiphysis shows the growth of the epiphyseal plate and migration of bone wax during the observation period.

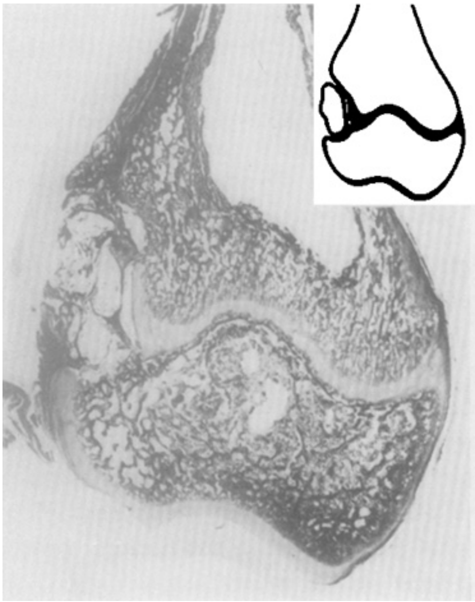

Fig. 32. Rabbit No. 142. Histological picture of the epiphyseal plate injury treated with bone wax 8 days after the corrective operation. The ossification groove shows signs of reforming and the epiphyseal plate is recovering. A ribbonlike remnant of cartilage to the metaphysis observed. (x7)

Fig. 33. Rabbit No. 168. Epiphyseal plate injury treated with bone wax 90 days after the corrective operation. The bone wax shows fragmentation, but has partly followed in growth. The primary defect in the epiphyseal plate is corrected by lateral growth. (x7) See Fig. 31.

Fig. 34. Rabbit No. 151. Photograph showing a bone bridge between the epiphysis and metaphysis labelled with tetracycline. Longitudinal growth and the epiphyseal plate are asymmetric. The provocative operation was performed 11 days earlier and the tetracycline labelling was carried out 5 days after the provocative operation.

Fig. 35. Rabbit No. 155. Photograph showing a femur treated by removing the bone bridge without adding any interposition material. The corrective operation was carried out 69 days earlier and the tetracycline was given ten days before the end of the experiment. Rigid bone bridge recurrence and asymmetric growth in the metaphysis are observed.

Fig. 36. Rabbit No. 175. Photograph showing narrow elongating bone bridge recurrence in a femur treated by removing the bone bridge without adding any interposition material 66 days earlier. The tetracycline was administered ten days before the end of the experiment. The finding correlates with histology. See Fig. 16.

Fig. 37. Rabbit No. 41. Photograph showing an injury to the epiphyseal plate treated with fat tissue 112 days earlier. The transplant has followed the epiphyseal plate. Slight longitudinal growth is demonstrated by tetracycline administered 19 days before the end of the experiment. Growth is coming to an end starting from the injured side.

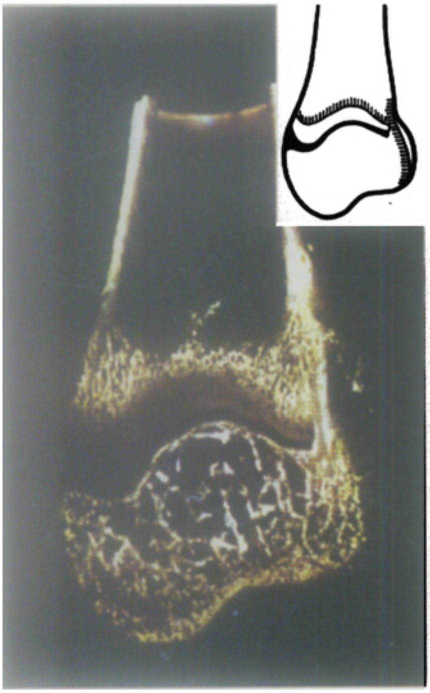

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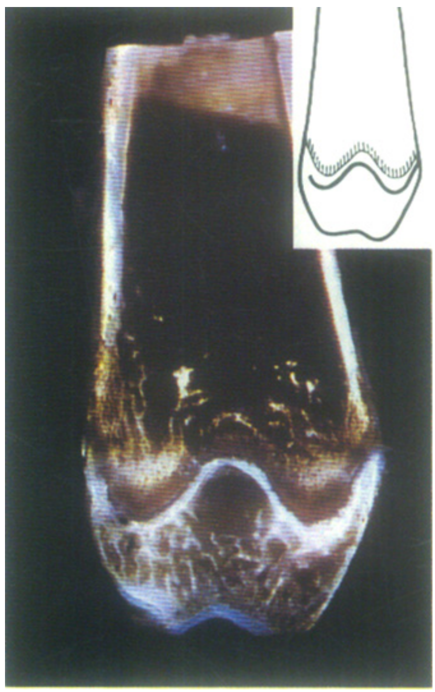
Fig. 38. Rabbit No. 121. Photograph showing a femur treated with cartilage 15 days earlier. The tetracycline was administered 28 days before the end of the experiment. Abundant longitudinal growth and growth in the direction of the injury are observed. These two processes correct the deformity.

Fig. 39. Rabbit No. 127. Photograph showing a femur treated with cartilage 84 days earlier. The tetracycline was administered ten days before the end of the experiment. Longitudinal growth is symmetric, the transplant is disappearing and a distinct lateral growth has taken place in the epiphyseal plate.

Fig. 40. Rabbit No. 169. Photograph showing a femur treated with bone wax 83 days earlier. The tetracycline administered 27 days before the end of the experiment. Longitudinal growth is symmetric and the bone wax follows the epiphyseal plate, giving a blue fluorescence.



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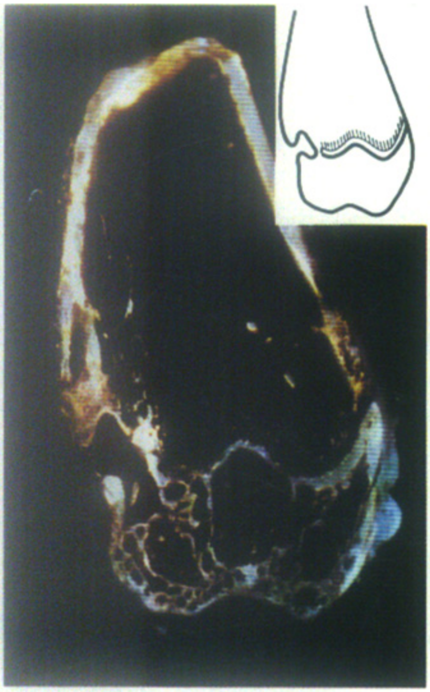
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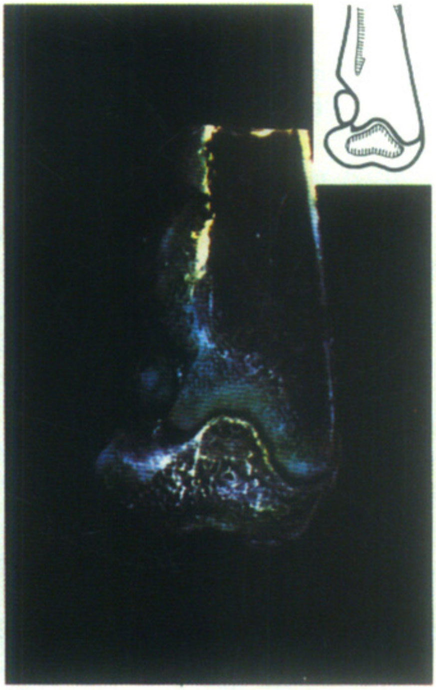
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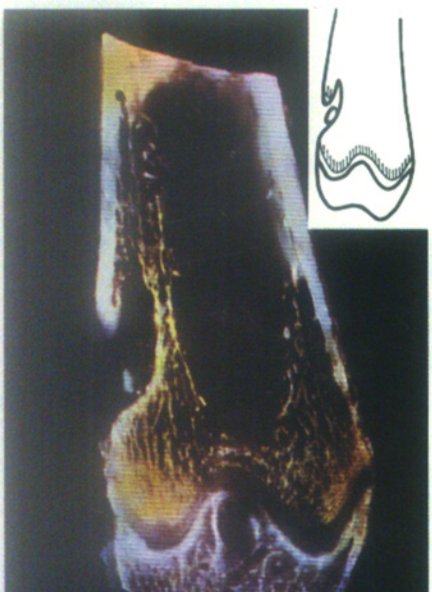
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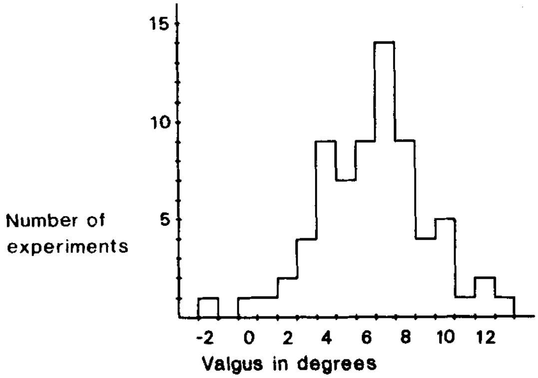
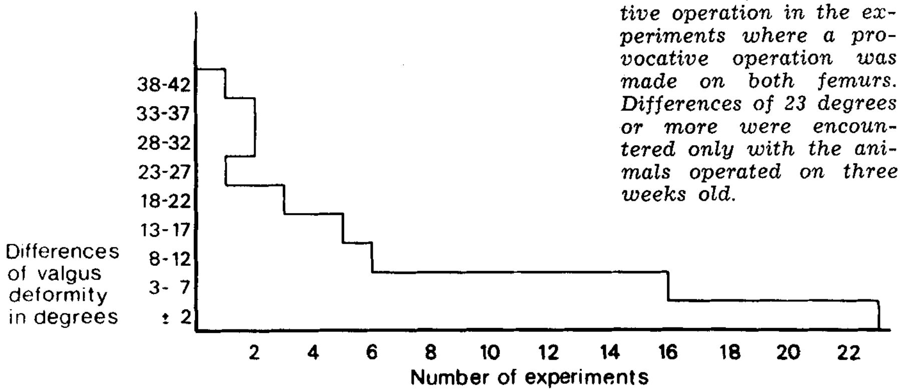


Fig. 41. Distribution of the valgus angle of a normal rabbit femur.

Fig. 42. Differences in valgus deformity between pairs of femurs at the time of the corrective operation in the experiments where a provocative operation was made on both femurs. Differences of 23 degrees or more were encountered only with the animals operated on three weeks old.



C Tetracycline findings

Bone wax displayed a blue autofluorescence and its position was easily demonstrated at all stages of the growth period (Fig. 40).

Growth became normalized after the second operation, at first by means of the longitudinal and lateral growth process, but later normal symmetric longitudinal growth was achieved. The femur treated with bone wax exhibited a stronger growth potential than the bone bridge control, and only a minimal growth difference in comparison with the normal control was noted.

Elongation of small bone bridge recurrences was confirmed by tetracycline labelling. As a result of longitudinal growth sliding between the bone and the bone wax sometimes took place. Rigid bony connections between the epiphysis and metaphysis only appeared as a sign of maturity.

VI FINDINGS ON ARTHROTOMY CONTROL

14 rabbits were operated on using a sham-operation which was repeated in connection with the second operation. As a result of this soft tissue injury intra-articular adhesions in the knee were observed, but no effect on bone growth was demonstrated. In one case a medial dislocation of the patella appeared as a sequel to the soft tissue injury. This resulted in the varus angulation of the femur, which was compensated by the valgus deformity in the proximal end of the tibia.

VII MEASUREMENTS

A Measurements on control femurs

In order to assess the distribution caused by measurement errors and normal variations and in order to determine the normal valgus angle of the femur, the valgus angle of the normal control femur preparation was measured. No attention was paid to the age of the animals. The distribution of the valgus angle (Fig. 41) shows that the normal valgus angle is 6.5 $\pm$ 3 degrees. The accuracy of a single measurement was estimated to be $\pm$ 2 degrees.

In order to assess the accuracy of the provocative operation the valgus deformity at the time of the second operation was measured and com-

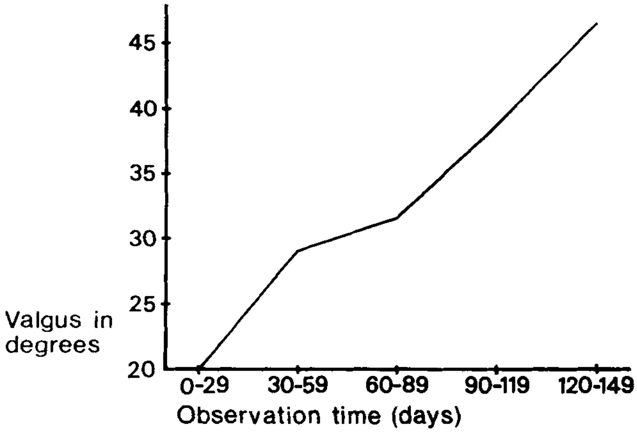


Fig. 43. Progression of the valgus deformity in the bone bridge control in correlation with time.

pared with the bone bridge control. It was noted that a symmetric deformity usually developed in spite of great invidual variations (Fig. 42). It was particularly predominant in animals operated on at the age of six weeks. This group also presented uniformity of all other measurements. This tendency towards symmetric growth was even regarded as a criterion in assessing the results of the treatment.

The effect of the size of the primary deformity caused by the provocative operation on the final results was studied by dividing the bone bridge control material into two groups according to the size of the final valgus deformity. It was observed that the group with a final valgus deformity of less than 60 degrees also at the time of the second operation, showed a valgus deformity of about 10 degrees less than the group in which the final deformity exceeded 60 degrees.

The increase in the valgus deformity of the bone bridge control correlated with time, as shown in Fig. 43. The numbers of animals in the age groups of three and six weeks were then assumed to be equal.

B Valgus deformity after corrective operation

The changes in valgus deformity following the second operation are shown in Fig. 44. A considerable increase in valgus deformity of the bone bridge control is observed and only four cases exhibit correction of the deformity. Of the femurs treated by different methods the cases in which the observation period is two weeks or less are not included in the figure. The final result with cartilage was as good as or better

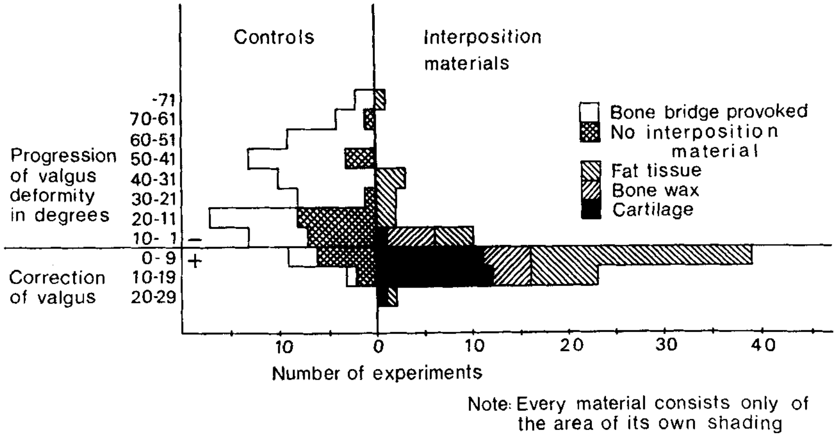


Fig. 44. Changes in valgus deformity after the corrective operation and simultaneous changes in valgus deformity of bone bridge controls.

than the deformity at the time of the second operation in all but one case. On the other hand the group treated without any interposition material showed an increase in valgus deformity more often than the series with interposition materials. However, this group presented two cases in which a correction of the deformity of more than ten degrees was obtained. Femurs treated with bone wax do not present failures of more than ten degrees, but this group is the smallest. The group treated with fat tissue transplant presents a failure of more than ten degrees in eight cases, but in most cases correction was observed.

As shown before, the valgus deformity tended to grow symmetrically in pairs of femurs injured in the same way (Fig. 42). On the other hand, because different methods aimed at a final result symmetric with the normal femur differences in valgus deformity between the right and left femur of every rabbit were compared in groups treated by different methods (Fig. 45).

The result was considered positive if the final result was symmetric with the normal control or asymmetric with the bone bridge control. The differences in valgus deformity were divided into four groups. The figure shows that with cartilage full symmetry compared with the normal control was obtained in 76 per cent of the cases. On the other hand, the result was asymmetric with the bone bridge control in 91 per cent of the cases. A similar result was obtained with a fat tissue transplant, but the results were more scattered. The femurs treated

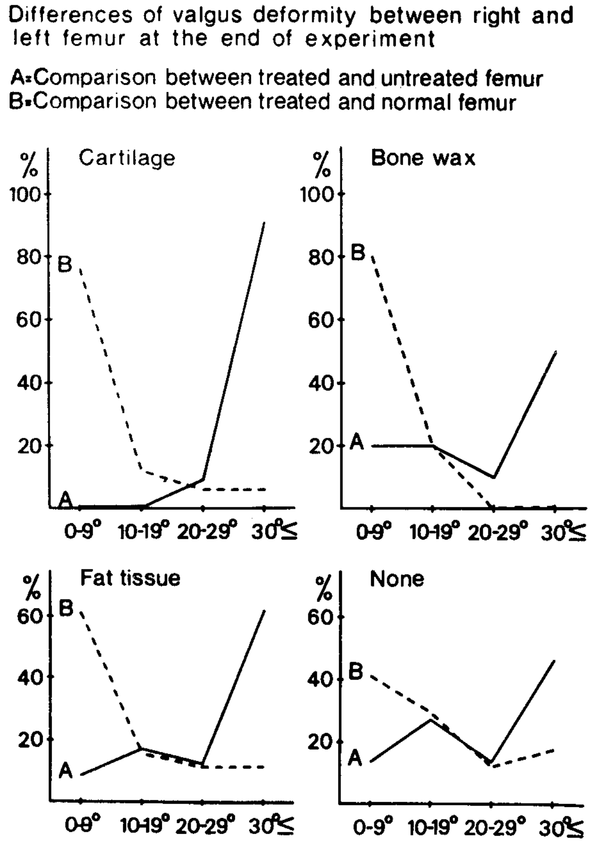
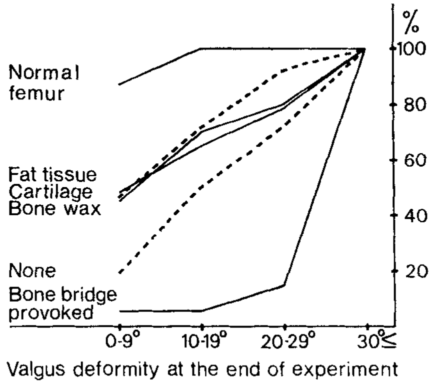


Fig. 45. Comparison of symmetry in the valgus of pairs of femurs treated with different interposition materials at the end of the experiment.

with bone wax show a symmetric end result (80 per cent) compared with the normal control, but in comparison with the bone bridge control they showed a larger distribution. When no interposition material was used the end result was symmetric in only 41 per cent of the cases, compared with the normal control. When compared with the bone bridge control, an asymmetry of 30 degrees or more was encountered in only 46 per cent of the cases. These figures show a considerable tendency towards asymmetry contrasted with the groups treated with interposition materials.

The final valgus deformity in different groups was represented by cumulative distribution graphs (Fig. 46). Quantitatively, the valgus angle was divided into four groups. It appeared that the difference in valgus deformity between the normal control and the bone bridge

Fig. 46. Size of the valgus deformity in different groups at the end of the experiment presented by using cumulative distribution graphs. The valgus angle was divided into four groups. The difference between the intact normal control and the bone bridge control was evident and the groups treated by using interposition materials were superior to the group treated without any interposition material, see text.



control was especially prominent, and the different methods of treatment lay between these graphs. In the group corresponding to the normal femur (0—9 degrees) the percentual portions of groups treated with interposition materials were almost equal, whereas the portion of the group without any interposition material was smaller. In other groups the femurs treated with cartilage proved somewhat better than the others, whereas the bones treated with fat tissue or bone wax were equal in this respect.

C Longitudinal growth after corrective operation

In measuring longitudinal growth attention was mainly paid to differences in length and growth between the right and the left femur of a rabbit, because measurements of average length could not be considered reliable because of the heterogeneous age distribution of the animals.

Differences in length between the right and left femur are shown in Fig. 47. With the exception of two cases, the femur treated became as long as or longer than the bone bridge control. On the other hand, compared with the normal femur no excessive growth stimulation was noted. In most cases equal length was obtained with the normal control, but in some cases the bone remained shorter. As a whole there were, however, fewer treated femurs that were shorter than the normal control (black columns) than there were treated femurs exceeding the length of the bone bridge control (white columns). Consequently, the end result as a whole approached the normal bone. No notable differences were found between different methods of treatment.

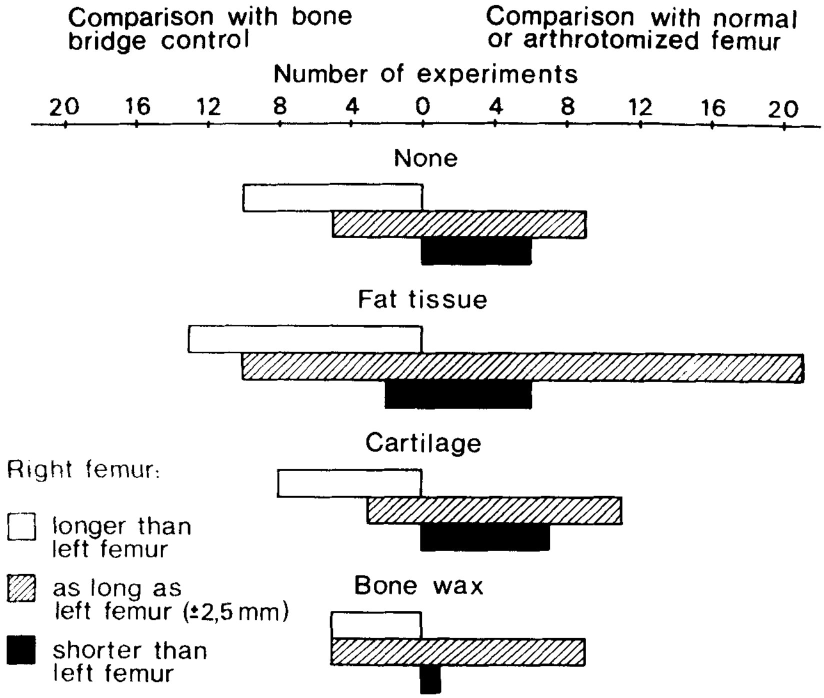


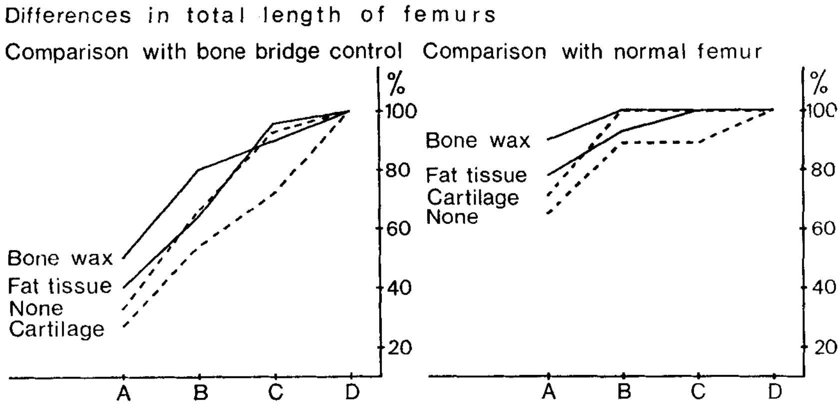
Fig. 47. Differences in length between the pairs of femurs at the end of the experiment in the groups treated with different interposition materials.

To compare quantitative differences in length the pairs of femurs were divided into four groups according to the differences in length as follows:

A   2.5 mm
B = 2.6— 7.5 mm
C = 7.6—12.5 mm
D = 12.6 mm or more

and represented by cumulative distribution graphs.

The differences in length between the femur operated on and the bone bridge control are shown in Fig. 48. Here a big difference in length represents a positive result, a small difference a negative result. The best result was achieved using cartilage as the interposition material. The group where fat tissue was used and the group with no interposition material showed similar results. Bone wax gave the poorest final result, resembling the bone bridge control most.



Differences in length:

A : ≤ 2.5 mm
B : 2.6 – 7.5 mm
C : 7.6 – 12.5 mm
D : 12.6 mm or more

Fig. 48. Differences in length between the pairs of femurs at the end of the experiment presented by using cumulative distribution graphs. Comparisons between the femurs treated with different interposition materials and the bone bridge controls on the left. Comparisons between the femurs treated with different interposition materials and the normal control on the right. In general the length of femurs after treatment was relatively nearer to the normal femur than to the bone bridge control, see text.

A similar comparison between the treated femur and the normal control (Fig. 48) showed that the final result most resembled the normal femur in groups treated with bone wax or cartilage. In this comparison a positive result is denoted by a small, a negative result by a big difference in length. The biggest loss of growth was found in the group without any interposition material, and the cases treated with a fat tissue transplant fell between the outermost graphs.

The graphs in Fig. 48 show that with different methods of treatment a result was achieved in which the length of the femur was relatively nearer to the normal control than to the bone bridge control. By calculating the means of percentage frequencies from the graphs crosswise in every group, it was noted that the best total result was obtained in the group treated with cartilage. In about half the cases a good result was also obtained with bone wax. The result gained with fat tissue was similar to that gained with cartilage, but not quite as good. The worst result was obtained in the group without any interposition material.

The measurements of distal growth were in direct correlation with the measurements of the total length of the femurs, and this was true in all groups treated by different methods. Measurements of longitudinal growth in several separate cases do, however, indicate that injury to the distal epiphyseal plate can stimulate growth produced by the proximal epiphyseal plate, and thus the loss of growth is partly compensated.

D Comments

The quantitative results reported here are suggestive. In estimating the results, uneven age distribution, invidual variations and materials of unequal size must be considered.

Usually the end result was better if the first operation was performed at the age of six weeks, when the injury was also relatively smaller. The results showed that apparently no correction in valgus deformity occurred during the first two weeks after the second operation, but meanwhile the bone bridge control became grossly deformed.

DISCUSSION AND CONCLUSIONS

Problems connected with fractures in children are closely related to bone growth. Though most epiphyseal fractures and traumatic epiphyseal separations usually heal well, epiphyseal injury leading to growth disturbances is a complicated clinical problem. If the epiphyseal plate of a bone is entirely destroyed as a sequel of a severe contusion or ischaemic necrosis, the current opinion is that there is no means of restoring longitudinal growth. In clinical practice these injuries e.g. to the lower limb, must be treated by arresting growth in the longer limb, by lengthening of growth stimulating operations and by means of orthopaedic devices in order to obtain as good as possible a result. Fortunately these injuries are rare — according to *Rogers* (1970) about one per cent of injuries involving the epiphyseal plate — and besides some of them might be treated by the operative method described in this study.

A bony connection between the epiphysis and metaphysis conflicts with the growth potential of the epiphyseal plate. If the growth-retarding effect of the bone bridge surpasses the growth potential of the epiphyseal plate, the result is degeneration and ossification of the primarily non-injured part of the epiphyseal plate. This process cannot be prevented by the repeated osteotomies normally used in treating progressive angular deformities. The loss of longitudinal growth is even greater if the partial epiphyseal closure is completed, and consequently the progression of angulation and longitudinal growth terminate.

The experimental observation that insignificant injuries crossing the epiphyseal plate do not cause a bad deformity (*Ollier* 1867, *Haas* 1919, *Kolesnikov* 1967), is presumably also valid in man. However, a bone bridge able to cause a detectable deformity tends to increase in size and destroy the epiphyseal plate. The case reported by *Langenskiöld* (1967 b) is the first exception to this rule in the literature.

Deforming injuries to the epiphyseal plate frequently occur in the region of the knee, where a special problem is caused by disturbances in longitudinal growth and progressive angular deformities, while repeated osteotomies impose additional strain on the patient.

In the present experimental study observations were made on an epiphyseal injury imitating a clinical model. The trauma was standardized and made big enough to cause a progressive growth disturbance but, on the other hand, precautions were taken not to hurt the epiphyseal plate irreversibly, thus assuring chances of successful treatment.

The treatment consisted of an operation by which the bone bridge was removed under an operation microscope. It is, however, known that the bony connection between the epiphysis and metaphysis is preceded by an invasion of capillaries in this area *(Trueta & Amato* 1960). Accordingly, the removal of the bone bridge was not considered sufficient, so interposition materials must be used to prevent the progression of bone without disturbing normal growth.

This fact has also been referred to by *Friedenberg* (1957), *Nordentoft* (1969) and *Serafin* (1970).

Serafin used bone wax or a free muscular transplant to protect the defect in the epiphyseal plate. He demonstrated that least growth disturbance was caused using a muscular transplant, and that results with bone wax were even preferred to those without any interposition material. In the present study some preliminary experiments were also performed using a muscular transplant. In the experiments carried out by *Serafin* no temporary bony arrestment was provoked in the epiphyseal plate. *Nordentoft* (1969) did not manage to normalize growth in the proximal tibia of a dog after the removal of the bone bridge. According to him, too extensive a secondary injury was caused by the operation. In the experiments carried out by *Friedenberg* (1957), the trauma was presumably larger and the deformity was allowed to develop for longer than in the present study, which was why no positive results were obtained.

The observations made on the present material show that the distal epiphyseal plate of a rabbit femur is a very vulnerable and highly differentiated organ. Injuries directed at this plate often cause angulation and disturbances in longitudinal growth. The opposite epiphyseal plate of a long bone may, however, partly compensate for the loss in length. The results do, however, show that a progressing bone bridge means a much greater trauma in the epiphyseal plate than the additional procedure caused by the operative elimination of the bone bridge. In the present study this is most clearly observed in valgus deformity. If untreated, the deformity increased in more than 90 per cent of the cases and healed spontaneously only in exceptional cases (Figs. 43, 44, 46). The cases where only the bone bridge was removed show that this procedure was able to interrupt the progression of deformity for a time. Some cases with a small primary injury developed no new progression.

In these cases a weak bone bridge was elongated in the metaphysis. This phenomenon was described by *Johnson & Southwick* (1960), but in the present study it was also verified by using tetracycline labelling (Figs. 16, 36). In typical cases the bone bridge reappeared after about three weeks and led up to a new progression of deformity. Because the deformity of the bone bridge control progressed without an interval, the end result of this treatment was, however, better than that of the bone bridge control (Fig. 11). Reoperation at the beginning of a new progression would possibly have given better results in this group. The bone bridge prevented normal growth in diameter of the epiphyseal plate and sometimes preserved its structure unchanged for a long time in the course of remodelling.

The importance of interposition materials was clearly demonstrated and was considered to be due to their ability to prevent the progress of capillaries and thus bone bridge formation. The thin bone bridges, frequently encountered histologically, were apparently due to technical faults during operation and were unable to cause progression of deformity, but undoubtedly every bone bridge means an additional growth disturbance risk.

Valgus deformity did not decrease during the first two postoperative weeks after the resection of the bone bridge and even increased in some cases. Probably the damage caused by compression in the epiphyseal plate makes a gradual recovery, and the ossification groove is concomitantly reformed.

Some differences were observed between the interposition materials. The significance of the interposition materials is apparently most important immediately after the removal of a bone bridge, because otherwise the postoperative haematoma makes it possible for a new bone bridge to be formed.

The advantage of a fat tissue transplant was that under experimental and even clinical conditions it is readily available and easy to implant. However, because fat tissue is reorganized after being partially necrotized (*Lexer* 1924) — a phenomenon also encountered in this study — the rapidly growing bone may displace the necrotized fat tissue. The postoperative haematoma may also provoke a bony bridge by intruding between the transplant and the bone. Some of the failures in treatment presented in Fig. 44 may be explained on the basis of these disadvantages of fat tissue.

The best end results, with regard to both the correction and final results of the valgus angle and the results of longitudinal growth, were achieved with a heterogenous cartilage transplant (Figs. 44, 46, 47). Increased metabolism, caused by reaction against foreign tissue, possibly had a stimulating effect on growth in this group. No harmful effects were observed due to the rigidity of the cartilage transplant, and the results obtained were surprisingly good from a technical point of view.

Bone wax assured a good haemostasis in the operative field, and its ability to prevent ossification (*Howard & Kelley* 1969) may be an advantage in this group. In the course of the growth process its protective effect decreases due to fragmentation which is, however, retarded by scar tissue enveloping and infiltrating the bone wax.

In the present study the trauma was directed at the peripheral part of the epiphyseal plate.

For this reason the changes in valgus deformity were of primary importance in assessing the results. Differences in the length of the bones were obviously interfered with by the compensatory effect of the opposite epiphyseal plate of the bone, and presumably by the growth-stimulating effect of the operative injury.

In the course of growth the interposition materials were observed as behaving in two ways. In some cases the transplant became attached to the metaphysis and as growth continued it was gradually left behind in the diaphysis (Figs. 28, 39). At the same time the diameter of the epiphyseal plate was normalized and a new cortical bone layer following the edge of the epiphyseal plate was formed. The figure greatly resembles bone growth in connection with Ollier's disease (*Langenskiöld* 1947, 1967 a). In the other cases the transplant adhered to the epiphysis and followed the epiphyseal plate in accordance with longitudinal growth (Figs. 22, 27). Combinations of these two forms were also found in which the interposition material followed the epiphyseal plate in the initial stages. These cases show that the interposition material is able to prevent the normal growth in diameter of the epiphyseal plate (Fig. 33). The bone bridge apparently has the same effect.

Certain observations support the view that the growth in width of the epiphyseal plate occurs interstitially. For instance, the figure corresponding to that in Ollier's disease (Figs. 28, 33, 39) is apparently due to this kind of growth. A remnant of the epiphyseal plate projecting to the metaphysis (Fig. 32) can be explained naturally as a result of interstitial growth of the epiphyseal plate. This problem might perhaps be further solved by using radioisotopes, but the problem was beyond the scope of this study.

A steplike deformity was often observed in the injured side of the epiphyseal plate. This phenomenon has also been observed under some other pathological conditions (*Langenskiöld* 1955, *Langenskiöld & Riska* 1964). The present study could not give an unambiguous explanation to the phenomenon, but it is presumably caused at least by a cartilage remnant of the epiphyseal plate and the elongation of the bone bridge in the metaphysis (Fig. 16).

The growth asymmetry caused by the bone bridges was demonstrated by means of tetracycline labelling (Fig. 34). On the other hand the deformity was compensated by the latitudinal growth process in the direction of the injury. The deformity is also partly corrected in the same way after treatment (Fig. 38). It is obvious that periosteal activity also plays some role.

At the terminal stage growth came to an end starting from the injured side and caused a small progression of deformity.

The present study was performed on rabbits, so the results cannot be adapted as such to human clinical use. The great vulnerability found in the epiphyseal plate of the rabbit femur is, however, in accordance with clinical observations. The great difference between the treated and the untreated femur in the present study, in which the trauma imitated a clinical model, suggests that if the epiphyseal plate of a human being reacts in the same way operative treatment must be considered. This does, however, presuppose that the bone bridge is easily accessible, so that the epiphyseal plate is not the object of an additional trauma by the operation, and that the bone bridge is able to cause deformity. The use of an interposition material is recommended in eliminating the bone bridge. A fat tissue transplant is easily available but the experimental results with cartilage were even better, and the haemostatic effect of bone wax may be of importance.

It is worth noting that the progression of deformity indicates that the epiphyseal plate has preserved some of its growth potential.

Conclusions

1) Injuries to the epiphyseal plate of a rabbit femur leading to a bony connection between the epiphysis and metaphysis seriously disturb the growth of bone.

2) If the deforming bone bridge is removed without injuring the epiphyseal plate the progression of deformity can be interrupted.

3) By using suitable interposition materials in connection with resection of a bone bridge the recurrence of it can be prevented and the deformity corrected by growth.

4) The results support the view proposed by *Langenskiöld* (1967 b) that in selected patients the operative elimination of the bone bridge together with the use of some interposition material must be considered.

SUMMARY

The purpose of the present study was to investigate experimentally injuries to a growing tubular bone in which a bony connection is formed between the epiphysis and metaphysis but the rest of the epiphyseal plate preserves its growth potential. This problem was already clinically and experimentally recognized in the last century, but in clinical cases the treatment has not been directed at the growth retarding bone bridge. In experimental investigations the removal of the bone bridge has not given satisfactory results.

The experimental animals consisted of 178 rabbits aged three or six weeks at the beginning of the experiment. The distal epiphyseal plate of the right femur was partially injured by a provocative operation (Fig. 1) after which, when growth disturbance appeared, a corrective operation was performed by removing the bone bridge between the epiphysis and metaphysis. A free fat tissue transplant, heterogenous cartilage and bone wax were used to prevent the recurrence of the bone bridge. Some cases were treated without any interposition material. The left femur served as a normal or bone bridge control. In the latter only a provocative operation was performed. The observation time varied from 2 to 150 days and the results were evaluated by means of radiological and histological techniques and by using tetracycline labelling. Because the peripheral part of the epiphyseal plate was injured, attention was mainly paid to changes in the valgus deformity, but the differences in length between the right and left femur were also considered.

The provocative operation caused a progressive valgus deformity in the distal femur in 95 per cent of the cases (Fig. 46). When a corrective operation was performed without any interposition material the progression of the deformity was interrupted, and in some cases relatively unaltered growth was restored. Usually, however, a new progression of valgus deformity resulted but the deformity did not reach the size

of the bone bridge control (Fig. 11). Histologically a recurrence of the bone bridge was observed in the third postoperative week (Fig. 13). In cases where no new progression was observed a remodelling and elongation of the bone bridge was demonstrated. This remodelling and the asymmetric growth caused by bigger bone bridges were also revealed by tetracycline labelling.

The benefit of the interposition materials was clearly demonstrated because in these groups correction of the valgus was obtained more often than in the cases without any interposition material (Fig. 44). This held good with regard to the differences in length and the resulting valgus. Histologically it was seen that in some cases the interposition material adhered to the metaphysis and was left behind in the diaphysis when growth continued. Simultaneously the defect in the epiphyseal plate was repaired (Fig. 28). In the other cases the interposition material adhered to the epiphysis and followed the epiphyseal plate in connection with the longitudinal growth, causing a defect in the epiphyseal plate (Fig. 27). In both groups the deformity could be corrected.

Tetracycline labelling revealed that the growth asymmetry caused by the bone bridge was partly compensated by the growth in the direction of the trauma (Figs. 34, 38). This lateral growth and the longitudinal growth together led to correction of the valgus deformity as a result of treatment.

The best end results with regard to the valgus deformity and longitudinal growth were achieved with a cartilage transplant (Fig. 24), but the differences between interposition materials were small. The implantation of cartilage required most technical skill, whereas the use of fat tissue and bone wax was easy. In addition to the successful cases achieved with fat tissue (Fig. 18) a temporary necrosis of the fat tissue and the postoperative haematoma were sometimes harmful, as was fragmentation of bone wax, which sometimes led to a recurrence of the bone bridge, though it also gave rather satisfactory end results.

The following conclusions can be drawn from this study:

1) Injuries to the epiphyseal plate of a rabbit femur leading to a bony connection between the epiphysis and metaphysis seriously disturb the growth of the bone.
2) If the deforming bone bridge is removed without injuring the epiphyseal plate the progression of deformity can be interrupted.

3) By using suitable interposition materials the recurrence of the bone bridge can be prevented and the deformity may be corrected by growth.

4) The results support the view that even in selected patients the operative elimination of the bone bridge together with the use of some interposition material should be considered.

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