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AN EXPERIMENTAL STUDY OF THE RATE OF FRACTURE HEALING

AS ASSESSED FROM THE TENSILE STRENGTH AND Sr^{85}-ACTIVITY OF THE CALLUS WITH SPECIAL REFERENCE TO THE EFFECT OF INTRAMEDULLARY NAILING

BY

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CONTENS

INTRODUCTION

The physical properties of intact cortical bone are well known, but less attention has been given to the characteristics of callus. Apart from a few experiments (McKeown et al. 1932, Häbler & Reiss 1936, Copp & Greenberg 1945) by mechanical methods to determine the strength of callus during fracture healing, the callus has been judged radiographically and histologically in experimental animals. As shown by Häbler & Reiss (1936) and Eskelund & Plum (1950), however, these methods do not give reliable data on the strength of the callus.

Several investigators (Berg & Kugelmass 1931, Key 1934, Key & Odell 1955) have tried to stimulate the formation of callus in various ways but without success. In contrast, ever since his earliest publications Küntscher has claimed, on the basis of clinical and experimental observations that medullary nailing stimulates the formation of callus (Küntscher 1958).

Although opinions founded on clinical experience differ regarding the effect of nailing, most authors feel that nailing neither stimulates nor inhibits callus formation (Maatz 1943, Rieder & Schuman 1943, Lauritzen 1949, Böhler 1948, Street 1951, Fontaine et al. 1954), only few believing the use of an intramedullary nail to stimulate callus formation (Soeur 1946, Granjon & Soeur 1955).

This lack of unanimity on the effect of intramedullary nailing on callus formation is probably due in some measure to the difficulty in collecting representative data, *i.e.* sufficiently large clinical series of uniform, comparable fractures. In addition, no clinical method is available for judging the degree of healing with certainty. Roentgenography will give information on the amount of callus but, it yields no reliable information on the stage of healing.

In contrast to clinical experience, studies in experimental animals of bones fractured as uniformly as possible suggest that nailing may stimulate the formation of callus (Fitts Jr. et al. 1949, Galuzzi & Gianelli 1953, Trueta & Cavadias 1955). But in these investigations the callus was judged histologically and radiographically, and neither of these methods permits exact estimation of the strength of the callus.

To secure reliable information on experimental fracture healing we require a method for making comparable fractures and, secondly, a method permitting assessment of the formation and quality of the callus. In clinical investigations, callus is judged by its strength. This criterion for judging the quality of the callus would therefore appear rational also in experimental investigations.

The present investigation is concerned with measurement of the strength of the callus in nailed and unnailed fractures of the radius of the rabbit. Determinations were made of the absolute tensile strength (in kg.) of the callus in different stages of healing. The specific tensile strength of the callus (kg./mm.^{2}) was calculated after measurement of the transverse area of the callus. In order to secure additional data on the biological activity of the callus, most of the experimental animals recieved an injection of Sr^{85} after which the ash weight and the radioactivity of the fracture area and the end-parts of radius were determined.

CHAPTER I

PREVIOUS DETERMINATIONS OF THE STRENGTH OF CALLUS IN EXPERIMENTAL FRACTURES

Since the skeleton serves as an organ of support, it is but natural that attempts were made to judge the physical properties of the bone by methods used in the testing of materials in industry. The first attempts to judge the strength of human bone were published by WERTHEIM in 1847. Since then numerous experiments have been carried out to measure the strength and elasticity of bone and to elucidate the mechanism of different types of fractures.

It is now known that bone is almost as strong as cast iron, but only one third as heavy and much more elastic. In addition it retains its elasticity, *i.e.* it follows Hooke's law (the elongation of a loaded elastic body is proportional to the load) until the stress is three fourths of that necessary to break the bone, and even then the deviation from the straight line is only slight (BELL 1959). According to MAJ & TOAJARI (1937) and EVANS (1958), the strength of a bone varies with the number of collagen fibres in the transverse area and the course of the fibres in relation to the axis of the bone. The greater the number of fibres and the more parallel they are to the axis of the bone, the stronger the bone will be. EVANS (1958) also stated that the strength of a bone appears to depend on the number of osteons per unit of transverse area. In experiments determining the tensile strength of the bone he found that few and large osteons gave greater strength than numerous small ones for the same transverse area.

To what extent the organic and inorganic substances, respectively, are responsible for the physical properties of the bone is not known. However, the strength of bone seems to vary with its mineral content (BELL, CHAMBERS & DAWSON 1947, WIER, BELL & CHAMBERS 1949, VOSE & KUBALA 1959) and intoxication with beta-proprionitrile, which inhibits the formation of the groundsubstance, but appears to have no effect on the collagen fibrils (PONSETI & SHEPARD 1954) is found to reduce the strength of bone to about one fourth of normal (BELL, OLIVE DUNBAR, GILLESPIE, IBALL & JEAN OLIVER 1957).

Little, however, is known concerning the mechanical properties of the callus during the course of healing of a fracture. MCKEOWN, LINDSAY, HARVEY & HOWES (1932) published a study of fractures of the fibula in

rats fed on a standard diet and made determinations of the breaking strength of the callus with an apparatus described by LINDSAY & HOWES (1931).

This apparatus consists of a balance with a scale on which are mounted, at a constant distance, two supporting points to which the fibula is applied. The bone is loaded by a lever, which is constructed in such a way that the former is loaded at two points a constant distance from the fracture line. The load is applied by allowing water to flow at a constant rate into a container connected to the arm of the balance. As soon as the bone breaks, the inflow of water is stopped. The strength is given in the number of grams necessary to break the callus.

MCKEOWN et al. found the strength of the callus to increase rapidly from day 6 to day 15 following fracture, by which time it approached the strength of intact bone. From day 15 to day 24 the strength decreased considerably, but then rose gradually, to reach normal value after about 45 days.

In parallel histological examinations of the callus DOWNS Jr. et al. (1932) found that the initial increase in the strength occurred at the time of calcification of the primary callus and that the strength reached a maximum at the same time as the amount of callus was largest. The subsequent fall coincided with the restoration of the marrow-cavity, while the final rise coincided with advancing organization of the fracture callus.

MCKEOWN et al. found a similar variation in the strength of the intact left fibula of experimental animals and suggested that this might be due to a generalized effect on the skeleton during fracture healing. However, a considerable variation was found in the strength of the fibula of the control animals, which continuously lost weight during the period covered by the investigation. The experimental animals also showed a wide fluctuation in bodyweight, particularly during the last third of the experimental period. It can thus not be excluded that the experimental conditions, *i.e.* the diet, might have influenced the results. It is well known that vitamin C and vitamin D deficiency impair callus formation. HERTZ (1936) found abnormal calcification and poor formation of collagen fibres in the callus in C-avitaminosis. HERTZ (1936) and URIST & MCLEAN (1941) found calcification of the callus to be delayed in D-avitaminosis and COPP & GREENBERG (1945) demonstrated decreased strength of the callus in animals with vitamin D deficiency.

COPP & GREENBERG (1945) also studied the breaking strength of fracture callus in the fibula of the rat. Determination of the strength was made in a slightly modified Lindsay-Howes apparatus, and registered in the same way as in the experiments of MCKEOWN et al.

COPP & GREENBERG found that the breaking strength had recovered

normal values within 30 days. The curve for the breaking strength in their experiments showed a steady ascent. COPP & GREENBERG's results thus strengthen the impression of the unreliability of the results reported by MCKEOWN et al.

In the experiments referred to above no attempts were made to study the elasticity of the callus. Such experiments have been made by HÄBLER & REISS (1936). They studied the breaking and torsion strength of experimental fractures of the radius, ulna and tibia of dogs. The fractures were loaded to the elastic limit with simultaneous measurement of the strain. The load noted at the elastic limit was taken as a measure of the strength of the callus. In addition the callus was ashed and the Ca-content determined. The experiments were performed on fractures 50 to 90 days old, and the healing was also judged radiographically and clinically. The strength of the fractures was 70—50 per cent less than that of the intact bone.

As for intact bone, the curve for the deflection of callus in the experiments was linear up to the elastic limit, but the ascent was more gentle, particularly for fractures with poor healing.

Since the diagrams given are not stress-strain diagrams (kg./mm.^{2}-deflection), it is not possible to draw any conclusions about the quality of the callus in the experimental bone compared with that of the intact control bone because of differences in the transverse area of the two bones.

HÄBLER & REISS found no correlation between the amount of Ca and the physical properties of callus and concluded that the strength of the callus is dependent not only on the mineral content but also on the bond between organic and inorganic material.

Summary

The physical properties of intact cortical bone are well known. The strength of bone appears to vary with the number of collagen fibrils in the transverse area of the bone and with the direction of the fibils in relation of the axis of the bone. The number of osteons in the transverse area of the bone is said to be of importance.

The strength of bone increases with its mineral content, but the function of the organic substance and its effect on the strength of bone are not known.

The physical properties of callus and the changes the former undergo during repair of a fracture are not properly understood. In investigations on record the strength of callus has been estimated under almost identical experimental conditions, but the results obtained are not unequivocal.

CHAPTER II

PREVIOUS EXPERIMENTS WITH INTRAMEDULLARY NAILING OF FRACTURES

KÜNTSCHER published his first paper on the results of intramedullary nailing of diaphyseal fractures in 1940. In all previous experiments (LAMBOTTE 1910, HEY GROVES 1914, MÜLLER-MERNACH 1933, RUSH & RUSH 1939, LAMBRINUDI 1940) short nails had been used, which provided poor fixation. In diaphyseal fractures, the method could only be applied after surgical exposure of the fracture, and removal of the nail required osteotomy. KÜNTSCHER, however, introduced a long and strong nail which could provide effective fixation, permit early mobilization and could be easily removed.

The first results of experimental intramedullary nailing of diaphyseal fractures were published in 1920 by HEY GROVES, who also used short nails.

Before applying his method clinically KÜNTSCHER (1940) studied the use of nails of varying shape for fixation of femoral fractures in dogs. In later experiments (1941, 1955, 1957) he tried to find support for his mechanical theory of the formation of callus in fractures fixed by nailing.

Later experiments fall into two groups. The first group consists of experimental nailing of the femur or the tibia of guinea-pigs, rats or dogs without control fractures (FONTAINE et al. 1950, HASCHE-KLÜNDER 1952) or with control fractures of the opposite leg fixed with plaster (RAISCH 1943—44, GRIESSMANN & REICH 1944, SILANI & AMANTE 1949). These experiments provide a possibility of histologically judging the effect of the nail on the bone and on the formation of callus, but, owing to insufficient fixation of the control bones, they cannot be accepted as a reliable basis for comparing the rate of healing of experimental and control fractures.

The other group of experiments is that carried out on the lower foreleg, for example on the ulna of dogs (FITTS Jr. et al. 1949) or on the radius of rabbits (GALUZZI & GIANELLI 1953, TRUETA & CAVADIAS 1955). In these animals pronation-supination of the foreleg is not possible. The ulna or the radius can therefore be fractured without dislocation even in the absence of additional fixation. The most conclusive work on nailing appears to be that published by TRUETA & CAVADIAS (1955). In their experiments with transverse osteotomy of the radius of the rabbit they studied the effect of the nail on the bone and callus by arteriography and judged callus formation radiographically and histologically.

These authors found that in fractures fixed by an intramedullary nail the callus formed somewhat earlier and was somewhat smaller in amount than on the control side (TRUETA & CAVADIAS, FITTS Jr. et al., GALUZZI & GIANELLI). FITTS Jr. et al. state that radiographically the fractures fixed by the nail healed quicker than those on the control side. TRUETA & CAVADIAS confirmed this conclusion in their experiments, but at the same time stressed that the difference was very small.

The experiments referred to above allow of no valid conclusions on the effect of nailing on fracture healing, because the number of animals used in the experiments was too small and because radiographical estimation of callus is unreliable.

CHAPTER III

PREVIOUS EXPERIMENTAL INVESTIGATIONS OF HEALING OF FRACTURES WITH RADIOACTIVE ISOTOPES

Most isotope studies of fracture healing have been performed on rats with fracture of the shaft of the femur, tibia or the fibula and without fixation of the fracture. (COPP & GREENBERG 1945, BOHR & SØRENSEN 1950, KARCHER 1952, BAUER 1954 c, BAUER & CARLSSON 1955, BOHR 1955, MACDONALD, LORICK & PETRIELLO 1957). MACDONALD (1958) studied mineral metabolism in unfixed fractures of the rabbit. A few experiments have been performed on fractures of the rat femur fixed with a medullary nail (CARTIER, DE BERNARD & LAGRANGE 1956) or on rats with a sawcut in the tibia (MARSHAK & BYRON 1945). Studies in fracture healing in man with the aid of isotopes have been performed by WENDERBERG (1961).

In experiments referred to above isotopes of calcium, phosphorus or strontium were used. The activity determinations were performed either by external counting over the fracture or by direct measurement of the ash.

After injection the isotopes accumulate in excess amounts in the fracture region. The excess uptake varies with the age of the fracture. Thus is femoral fractures in rats maximal activity was observed 8—15 days after fracture, when it was 2—8 times higher than in the opposite leg (BAUER 1954 c, BOHR 1955). In tibial fractures in rabbits the activity maximum was reached somewhat later namely 10—25 days after the fracture (MACDONALD, 1958).

The increased uptake in the fracture region subsequently diminishes, but even in 50 week old fractures the activity has been found to be higher than normal (BOHR 1955).

The increased activity in the callus is accompanied by an increased activity in other parts of the fractured leg. (BAUER 1954c, BOHR 1955). In animals with femoral fractures it was most pronounced in the epiphysis of the fractured femur, less in the epiphysis of the tibia, and least in the diaphysis of the tibia (BOHR 1955),

The rise in activity is accompanied by an increase in the ash weight of the fracture region (BAUER 1954c, BOHR 1955). The ash weight reaches its maximum on the 16—20th day, thus somewhat later than the radioactivity. BAUER (1954c) found a rise of about 50 % in the ash weight of

the fracture region and BOHR (1955), about 30 %. Later the ash weight decreased successively with reorganisation of the callus, but in 50 week old fractures the ash weight was still increased (BOHR 1955).

In bone parts adjacent to the fracture the ash weight falls initially indicating a higher rate of bone resorption than bone formation. The resorption is earliest and strongest in the epiphysis of the fractured leg. The decrease in ash weight is considerable. According to BAUER (1954c), it is 30 % in the epiphysis of the fractured femur. The surrounding bone recovers its normal mineral content but slowly. Thus BAUER & CARLSSON (1955) found a decrease in the ash weight of the ends of the fractured femur even in 60 day old fractures.

BOHR (1955) tried to relate the degree of fracture healing to the ash weight and activity of the callus. Fracture healing was judged by the degree of mobility of the fracture. BOHR found that the increase in activity was the same whether healing was good or poor, but that fractures with a high ash weight of the callus showed good healing and a good recovery of the ash weight of the epiphysis. In poorly healing fractures there was a continuous decrease in the ash weight of the epihysis.

Observations made by CARLSSON (1952) and BAUER (1954a) have shown that only a small percentage of the calcium content of the bone is exchangeable, while the bulk of the calcium is irreversibly incorporated and can be released only by resorption. It has been possible to determine these calcium fractions quantitativly (BAUER, CARLSSON & LINDQVIST 1955a).

After parenteral injection of Ca^{45} the serum acitivity decreases owing to the intermixture of isotopes with exchangeable Ca-fractions of the skeleton, to excretion and to deposition of Ca^{45} in the skeleton by accretion. The bone-seeking isotopes accumulate mainly in those parts of the skeleton where growth is most rapid (CARLSSON 1951, BAUER 1954b), and it is also in those parts of the skeleton that the isotopes are resorbed first (LEBLOND, WILKINSON, BELANGER & ROBICHON 1950, BAUER 1954d).

The acitivity recovered from the skeleton is an expression of the rate of accretion, provided the measurement is made at a time when the effect of the exchange reaction and the resorption can be precluded. As judged be plasma activity curves in rats and rabbits (BAUER 1954c, BAUER, CARLSSON & LINDQUIST 1955b, MACDONALD 1958), the amount of activity in the exchangeable calcium fraction may be considered low a few days after injection of the isotope. At the same time also the resorption is low (BAUER, CARLSSON & LINDQUIST 1955b, MACDONALD 1958).

BAUER (1954c) showed that the increased mineral content of the callus of 8 day old fractures of the femur of the rat is incorporated by accre-

tion and not reached by resorption until after 4—5 days. It is therefore possible to correlate the radioactivity measured in the callus with the amount of bone salt formed.

Summary

Experiments with bone-seeking isotopes have shown that the major part of the Ca-content of the skeleton is incorporated by an irreversible process (accretion) and can only be released by resorption. A few per cent of the Ca is reversibly bound and available for exchange with calcium in the body fluids.

Isotope experiments with fractures have shown that fracture healing is a generalized process and that the increased deposition of bone salts in the callus is accompanied by an increased resorption and an increased accretion of bone salt in the surrounding bone. Also the bone salt deposited in the callus is bound by an irreversible process, so that the amount of radioactivity measured in the callus is related to the amount of new-formed bone salt.

CHAPTER IV

MATERIAL

The material consisted of adult albino rabbits of one and the same breed. The animals were about 6 month old and weighed between 2.2 and 3.0 kg. Animals of both sexes were used. The ratio between males and females was 6 : 1, no pregnancy was observed. The animals were fed on corn, turnips and hay and, in summer, also on greens. During the winter months vitamin D was added to the diet. The different groups consisted of animals operated upon during different seasons of the year.

One animal died soon after the operation owing to the anaesthesia and a relatively small number of animals died under anaesthesia before the operation. These animals are not included in the material accounted for in the tables.

No deaths from infection of the wound occurred, but 2 animals were killed because of infection with abscess formation. During the experimental period 21 animals died from intercurrent diseases, mostly enteritis. In none of these animals were any signs of infection of the region of the wound detectable. The mortality was about 8 per cent. In addition 2 animals were rejected because of fracture of the ulna on the control side during the experimental period and 3 because the radius fractured during preparation.

A small number of animals in which the radius split during nailing were excluded. In addition, 10 animals operated upon and used for preliminary experiments are not included.

The material proper consisted of 244 operated animals in which the strength of the callus was measured. In 180 of these animals determinations were made of the ash weight and of the radioactivity of the experimental bones after injection of Sr^{85}.

The experimental animals were divided into 10 groups, one of 28 animals and nine of 24 animals each.

The ages of the fractures in these groups were 10, 20, 30, 40, 50, 60, 70, 80, 100 and 120 days, respectively.

The experimental animals were weighed before operation and immediately they had been killed. The control animals were weighed just before they were killed. The length of the radius was measured in all animals.

The mean values found for the various determinations are given in Tables 1 and 2 a and 2 b in the appendix.

OPERATIVE METHOD AND TECHNIQUE

The method of operation used was, with but small modifications, that described by TRUETA & CAVADIAS (1955). Transverse osteotomy of the radius was done on both sides. The radius on one side was nailed while the other was used as a control bone.

The following determinations were made.

1) Absolute strength of callus in kg. measured in traction apparatus after preparation of the radius. In order to calculate the specific strength, which is given in kg./mm.^{2}, determinations were made of:
2) the transverse area of the callus at the site of osteotomy by photography and weighing. Determinations were also made of:
3) the ash weight of the radius, after dividing it in 3 parts A, B and C (Fig 5 pg. 26).
4) the ratio between the ash weight in the B-parts and the transverese area of the callus was calculated and taken as an expression of the mineral density of the callus.[1]
5) the radioactivity of the ash.

Anatomical remarks. (Fig. 1). The shape of the radius of the rabbit resembles that of the human radius, but it is relatively stronger, and the proximal part shows a slight dorsal curve. The head is not disk-shaped as in human beings but is more irregular and has a saddle-shaped articular

Fig. 1
Normal radius and ulna of the rabbit. Inset: cross section at level of osteotomy.

[1]) Here the term mineral density is an expression of the average mineral content per unit of volume of callus without regard to porosity and thus not the true degree of mineralization.

surface. The radius and the ulna lie close to one another and are connected by a very narrow and firm interosseous membrane. Owing to these anatomical relationships pronation and supination movements between the bones is not possible. This implies that on osteotomy of the radius the ulna serves as a splint and prevents dislocation. The marrow cavity of the radius is hour-glass shaped and narrowest a short distance above the middle of the bone.

The nail is made of stainless steel wire of 1.2—1.6 mm. in diameter and 6 cm. long. To be sure that the nail passes through the narrowest part of the cavity the nail is pointed.

In 15 animals, *i.e.* in about 6 per cent of the experiments, the nail showed signs of corrosion. This was always located at the tip of the nail only. The corrosion is probably ascribable to the surface of the nail having been damaged by the grinding and not always having been properly polished afterwards (BECHTOL, FERGUSON & LAING 1959).

The effect of corrosion was seen in the cortex as a dark-coloured spot. The corrosion may have a toxic effect on the bone tissue, as shown by JØRGENSEN (1941) and MAATZ (1948) and may cause cortical necrosis with peri- and endosteal bone-formation and subsequent reorganization. Such changes might possibly affect the ash weight and thereby also the radioactivity in the C-parts (see Fig. 5) of the nailed bone. Examination of the ash weight of C-parts with corrosion of the nail, however, showed that the weight varied mainly with the length of the C-part. It may therefore be assumed that the corrosion was not of such an extent as to affect the results.

OPERATIVE TECHNIQUE

The animals were anaesthetized with Nembutal injected intraperitoneally and placed on a special operating table in a way allowing of fixation of both forelegs, so that the radius on either side could be operated upon without moving the animal.

The hair on the radial side of the foreleg was cut off with electric clippers and the skin was washed with alcohol and covered with Nobecutan and sterile gauze, which was fixed to the skin by the Nobecutan.

The incision was placed in the lower half of the radial side of the foreleg. There the radius is subcutaneous and covered only by the extensor tendons. Small, specially designed osteotomy hooks for protection of the ulna, muscles and tendons were inserted between the two forelegs. Osteotomy of both radii was done with a fine circular saw mounted on a dental engine.

On the right side a fine burr hole was made in the lower end of the radius and a nail of suitable thickness was inserted. The left radius was used as a control leg. The wounds were sutured with thin stainless steel wire and

covered with Nobecutan. The operation caused hardly any loss of blood and the animals tolerated the operation well. In the course of a few days they were moving about unhindered in their cages.

In order to check that the nail had passed through the site of oesteotomy and a sufficient distance into the upper fragment of the radius, all of the nails used were originally of the same length. The length of the radius varies only slightly and it is therefore easy to judge how far the nail has entered the marrow cavity and thereby to decide whether the nail has passed through the narrowest portion of the cavity before resistance is offered. If resistance was offered to the insertion of the nail earlier than expected, the nail was extracted and replaced by a thinner one. The projecting part of the nail — about 1 cm. — was cut off flush with the bone. Only in a few animals was it necessary to replace the nail by a thinner one.

In order to decrease the effect of any infection on the results of the experiment special attention was given to sterility. Nobecutan contains a bacteriostatic agent, and the incision was placed through the sterile gauze, which was fastened to the skin by the Nobecutan, so that all contact between the skin and the operative region was avoided.

Care was taken to place the osteotomy at about 3 cm. proximal to the lower end of the radius. Expecially in the early stage of this work the level of the osteotomy varied somewhat. The variation was of roughly the same order in all of the groups (Table 1 appendix).

Preparation of radius

The animals were killed by injection of Nembutal and air intravenously. Both forelegs were amputated, the musculature including the periosteum was removed, and the nail was extracted. The length of the nail and its transverse area were noted (Table 1 appendix). It was difficult to separate the radius from the ulna, particularly in animals in which fracture healing was advanced because the callus had grown to a varying extent over on the ulna which was thus partly embedded in callus. The ulna was sawn through above and below the osteotomy and the proximal and distal parts of the ulna were removed by dividing the interosseous membrane. The remaining part of the ulna was carefully removed with fine bone forceps. In eight experimental bones the preparation caused fissures in the callus. These bones were excluded from the determinations of tensile strength. As the determination of the strength etc. was too timeconsuming to be performed on freshly removed bones, the isolated radius was stored in 5 per cent formalin solution until examined.

The formalin treatment, to which all the experimental bones as well as

the bones used for determination of the normal values were exposed, affects the organic components of the bones. Formalin has a tendency to decrease the tensile strength of the bone, but it is not known by how much (cited EVANS 1957). On the other hand, the strength in compression tests is said to decrease by 13 per cent (CALIBRISI & SMITH 1951). Since all of the bones in the present investigation were treated uniformly any effect of the formalin on the tensile strength have influenced the results in a uniform manner.

Apparatus and technique for testing tensile strength

The apparatus[1)] used for testing the tensile strength of the bone is illustrated in Fig. 2. It is constructed of T-iron, 3.5 cm. × 3.5 cm. × 0.5 cm. and consists of a lever (A) with a fulerum (C) at the tip of a standard (B). The lever (A) can be connected with a spring balance by means of 5 holes in the lever (A). The spring balance is connected with an extension (D), which is passing freely through the footplate (E). The spring of the balance can be loaded by turning the screw (F). The indicator of the spring balance is connected with a writing device, which traces changes in load on squared paper. (I) is a weight for balancing the lever (A). The holders in which the bone is fixed are attached to the lever at (G) and to the foot-plate at (H). The apparatus has a maximum capacity of 125 kg. and was adjusted before use. The adjustment was done in the following way. For every hole in

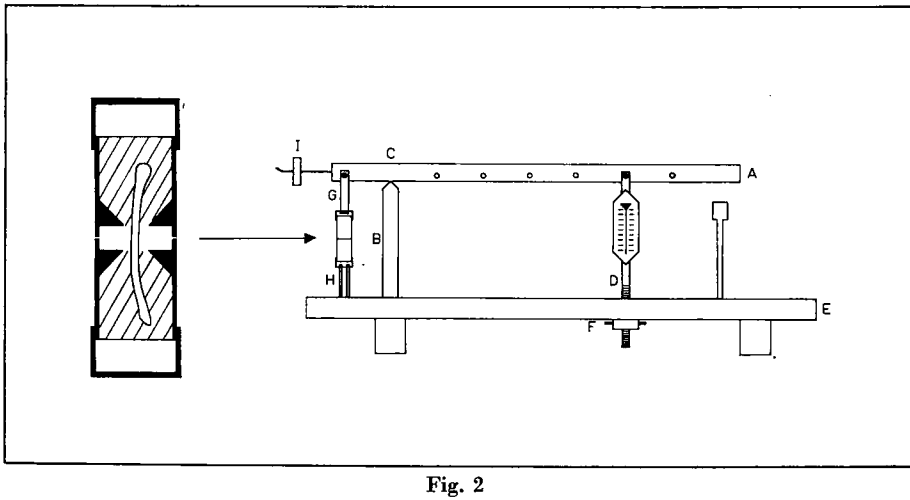

Fig. 2

Diagram of traction apparatus (see text). To left enlargement of cross section of holders with bone inserted.

[1)] The traction apparatus was designed by Engineer Åke Isberg, Department of Physics, University of Lund

the lever (A) the spring balance was loaded by applying increasing loads on the lever at (G) For every load the elongation of the spring was registered by the writer connected with the spring. With these recordings a spring-load-elongation diagram could be plotted for each hole in the lever. From these diagrams it was possible to read the observed load necessary to break the callus since the elongation of the spring was always recorded on squared paper. During the experimental period the apparatus was repeatedly checked and no change in the elasticity of the spring was demonstrable.

In the experiments two spring balances were used. One small one permitting a maximal load of 12 kg. and a larger one permitting a maximum load of 25 kg. The smaller balance was used for the first hole in the lever for determination of the absolute tensile strength of callus in the experimental bones in the first group of animals, since in that group the callus

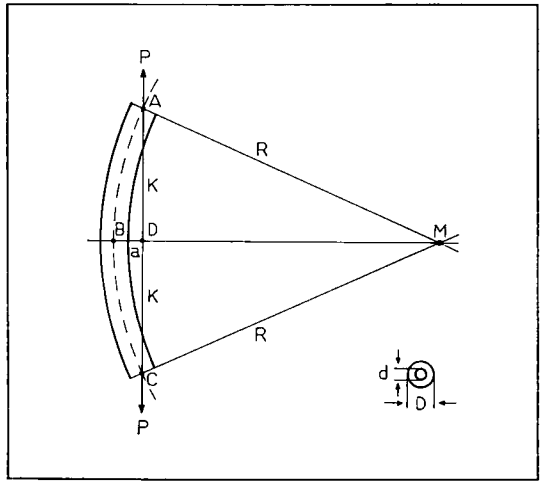

Fig. 3.

Calculation

Application of the two traction forces (P) to the slightly curved homogenous tube causes both traction and breaking in the tube, which finally breaks at (B) on increasing magnitude of the forces. If the eccentricity (BD) = (a) is small in relation to the radius of the curvature of the tube (R) it is possible approximately to determine (a) from the formula $K^2 = 2\,Ra$. The force resulting in the breakdown of a tube can be calculated from the following formula:

$$\text{Ultimate marginal stress} = \frac{P}{\frac{\pi}{4}(D^2-d^2)} + \frac{P \cdot a}{\frac{\pi}{32} \cdot \frac{D^4-d^4}{D}}$$

of which the first part represents the pure traction and the second the breaking force.

I thank Chief-engineer Kr. Trentemöller, Copenhagen, for Fig. 3 and Fig. 8 and pertinent calculations.

was not strong enough to tolerate a force necessary to produce any appreciable expansion of the larger spring.

In the present traction tests the callus was affected not only by traction but owing to the curvature of the radius, also by a breaking force. However, with knowledge of the transverse area of the callus as well as the radius of the curvature of the bone at the site where the forces are applied, it is possible to calculate the magnitude of the breaking force. This was calculated for the 60 day group of experimental bones with the use of the mean values found for the transverse area of the callus. The transverse area was assumed to be circular and the curvature of the radius in the osteotomy area was estimated to have a radius of 100 cm. The free space between the holders is 1 cm. The distance between the two points where the forces (P) act, *i. e.* 2 K (Fig. 3) is assumed to be 2 cm. Using the formula (Fig. 3) below it was found that the sum of the forces acting upon the callus at the breaking moment was about 10 per cent larger than that measured in the traction apparatus.

On suspension of the holders on the traction apparatus care was taken that they were properly positioned in order to avoid an asymmetric pull. An asymmetric pull would increase the breaking force in the bone and decrease the tensile strength. The traction apparatus was balanced before application of the bone to be tested so that any traction caused by the lever and the spring balance is eliminated. The rate at which the force is applied is of importance for the tensile strength. In the traction apparatus the force acting upon the bone was produced by means of a screw arrangement which made it possible to apply the force at the same rate in all of the tests.

The holders (Fig. 2) were made of brass 2 mm. thick. They consisted of two symmetrical parts, each of which had the shape of a rectangular tube. The holders were provided with a metal hanger for connection to the traction apparatus. The free opening, opposite the hanger is diminished by a metal wedge on either side to prevent the bone from being pulled out of the holder when loaded. The holders were designed in such a way that when they were fitted together there was a free space between them, so that the part of the bone to be loaded was free.

In the beginning plaster was used as a fixative for the bones. A disadvantage of plaster, however, is that it is impossible to remove the bone fragments undamaged after the absolute tensile strength has been determined. In later experiments, *i.e.* in all traction experiments in which determinations were also made of the ash weight and of the Sr^{85} activity of the bones, Wood's metal, which is an alloy of cadmium, vismuth, lead and tin, and which has a melting point of + 67°C, was used as a fixative.

Before the bone was placed in the holders a piece of rubber sponge was

threaded over the bone. The shape and size of the rubber sponge were adjusted to the free space between the holders and filled it when the two parts were brought together. During the fixation process the holders were fixed firmly against one another in a frame. The rubber sponge holded the bone in position in the holders and at the same time prevented the molten metal from running down into the free space between the holders. As soon as the molten metal, which was poured into the holders from a small crucible, had set, the holders together with the bone were placed in water and cooled and was then ready for application in the traction apparatus. As soon as the tensile strength had been determined, the bone fragments were readily removed from the holders by carefully heating the latter.

In the melting process, the metal was carefully heated in a crucible. If the process was regulated in such a way that there was always a little unmelted metal in the crucible, the metal would never be heated above its melting point. In 20 experiments in which the bones were of the same size as the experimental bones the average temperature at the time of insertion (one temperature recorded for each right and left bone) measured thermoelectrically was 41.9°C. The temperature to which the bone was exposed on insertion was so near the physiological temperature of the rabbit, which is 39°C, that any effect of the temperature on the physical properties of both organic and inorganic substances of the bone may be neglected.

On insertion of the radius in the holders care was taken that the curvature of the bone was always in the same plane and that the bone was inserted vertically in the holders, so that the bending force in the bone, when loaded, did not vary from one experiment to another.

On loading of the bone in the traction apparatus the radius fractured at the site of osteotomy. In the most recent fracture groups (10—20—30 days) the site of the fracture still showed the smooth bone surface at the site of osteotomy surrounded by a more irregular endosteal and periosteal callus. As healing progressed the fracture surface become more irregular but the fractures retained their character of a transverse fracture throughout the experimental period.

Only in 4 cases did the radius fracture outside of the osteotomy region. These fractures occurred in three bones in the 100-day group and in one in the 120-day group. In all 4 cases it was the nailed bone that fractured in this way. The transverse areas of these bones were determined at the site of osteotomy while the values for tensile strength were excluded from the material.

Measurement of cross sectional area of callus and marrow

For determination of the area of the callus and marrow a transverse

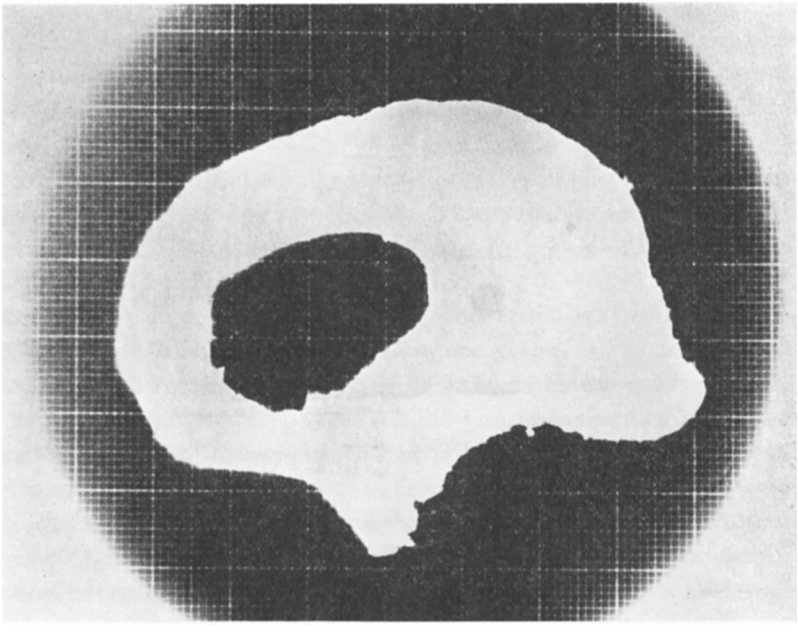

Fig. 4
Enlargement of bone-callus section on photosensitive paper.

callus-bone section about 2 mm. thick was cut off from one of the fracture-ends. Residual periosteum and marrow tissue were removed with the aid of a needle. A microscope was provided with a loupe objective, and the ocular replaced by an accessory with room for a photographic cassette. By means of this apparatus a reproduction of the transverse area of the callus-bone section could be obtained on photographic paper.

After development, fixation and drying of the photo-sensitive paper the part covered by the bone and the marrow respectively were cut out, and the areas determined by weighing.

Here *the cross sectional area of the callus* is to be understood as the area of the total cross section of the radius at the site of oestotomy minus the marrow cavity and other cavities (see page 29) and — in nailed bones — the nail cavity.

The cross sectional area of the marrow is to be understood as the total cross sectional area of the marrow cavity inclusive other cavities (see page 29) and — in nailed bones — also the nail cavity.

The microscope was adjusted for tenfold enlargement (Fig. 4). In the experiments it was not possible to make double determinations of the transverse area, because the callus was usually stripped on one side or the

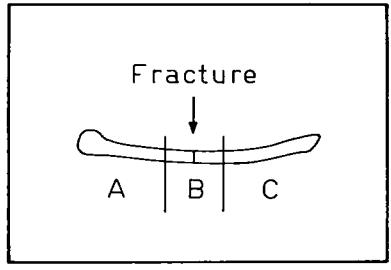

Fig. 5

other during the traction experiment, so that only one part of the fragments was suitable for determination of the transverse area.

The transverse area of the callus and of the marrow could be determined in this way with satisfactory accuracy. In experiments with a total of 20 determinations of the same section of the bone the mean error of the mean was found to be about 0.5 per cent. The specific tensile strength was then calculated by dividing the absolute tensile strength by the transverse area.

Measurement of ash weight and radioactivity after injection of Sr^{85}

In the isotope experiments each animals received a dose of 5 uc of Sr^{85} dissolved in 1 ml. of physiological saline. The dose was given intravenously 4 days before the animals were killed.

After the tensile strength and the areas had been measured the radius was divided into three parts, A, B and C (Fig. 5). The pieces of bone were then ashed in an electric oven at a temperature of 800—850°C and the ash of each of the 3 pieces was weighed on an analytical balance with an accuracy of 0.5 mg. The ash was then dissolved in concentrated nitric acid which was afterwards made up to 50 ml. with distilled water. The activity in the entire solution was determined. In a few instances in the beginning of the investigation only 4 ml. of the solution was used for assessing the radioactivity.

The activity was measured in a scintillation counter or a scintillation well counter for the 4 ml. aliquot. 10,000 counts were recorded for each specimen. The background was recorded for 3,000 counts. The counting rate of the samples varied between the groups from 2 to 20 counts per second. The background varied from 0.8 to 1.3 counts per second mostly because of variation in discriminator- and HV-settings of the equipment. The standard deviation of the values were less than 5 per cent of the net counts of the samples. The activity is expressed in per cent of the doses given $\times 10^2$.

Determination of normal values

The 32 animals used for determinations of normal values of the bone and marrow area, tensile strength, ash weight and radioactivity were of the same breed as the experimental animals and of the same weight (Table 2 a and 2 b, appendix).

Normal values for bone and marrow areas were based on measurements in 16 animals of transverse sections of the radius made about 3 cm. proximal to its lower end. These values are given as the means of 32 determinations (16 right and 16 left) (Table 2 b appendix).

The normal values for the absolute and specific tensile strength were determined on other 16 animals. They are given as the means of 32 determinations (16 right and 16 left) (Table 2 a appendix).

The normal values for the ash weight and radioactivity were based on all of the 32 control animals and the normal values are given as means of 64 determinations (32 right and 32 left) (Table 2 b appendix).

On estimation of the normal absolute tensile strength of the radius, the intact bone was fixed in the holders in the same way as the experimental bones. That part of the radius corresponding to the site of the osteotomy in the experimental bones was placed in the free space between the holders. The purpose of the test was to fracture the intact radius at the site where the osteotomy was made in the experimental bones. But it was found that as a rule the intact radius did not fracture at the intended site but a short distance above or below the free space in the part fixed by the metal. This can be explained by the strong forces to which the intact radius was exposed were acting nearer the ends of the bone with the result that owing to the stronger curvature, particularly in the proximal part of the bone, the bending forces arising during the test were greater than in the experimental bones.

The values found for the total and specific tensile strength of the bones must therefore be accepted with caution. The specific tensile strength of the rabbit radius in the experiments described was found to be 11.6 kg./mm.^{2}, and was thus much the same than those reported in the literature, where an average value of about 10 kg./mm.^{2} has been given for a variety of long bones of different animals (Evans 1957).

Statistical methods

The mean, standard deviation, and standard error of the mean were calculated according to conventional formulae. The t-test was used in comparing the means. The significance is denoted by P, which signifies the probability of a difference at least as large as that observed arising by chance. The difference was said to be highly significant when $P < 0.001$,

significant when $0.001 < P < 0.01$ and probably significant when $0.01 < P < 0.05$. These levels of significance are given in the text as ***, **, and *, respectively.

The difference between the results in the nailed and unnailed bones was judged on the basis of the calculated ratio between nailed and unnailed bones. The significance was judged by comparison with the ratio between the normal values found for the right and left radius.

An analysis was made of the mutual relationship of the absolute tensile strength on one hand, and the ash weight, activity and mineral density of the callus on the other hand.[1]

In order to ascertain whether any difference existed regarding the above mentioned data, each of the various groups of animals was studied separately. For this purpose the data were first studied by a qualitative method. Each experimental group was divided into two subgroups according to the strength of the callus, plus variants and minus variants, in relation to the median values. In the same way the animals were classified according to the other data into plus and minus variants. The number of experimental animals that were plus variants for both tensile strength and ash weight, for example, will indicate whether any demonstrable covariation exists.

If the number of experimental animals is N, the number of animals with plus variation regarding tensile strength is n_1, the number of animals with plus variation regarding ash weight, for example, is n_2, and the number of animals with plus variation for both properties n_{12}, and if both properties are independent of one another, the expected value of n_{12} is $= n_1 \cdot n_2/N$. The limits of error can be deduced from the mean error of the difference between the observed and expected value, which is $\frac{1}{4}\sqrt{N}$, since n_1 and n_2, owing to the method of division of the groups, is, practically speaking, $^1/_2 N$. Comparison of the differences between the observed and calculated values for n_{12} with the mean error will show whether any demonstrable covariation exists.

Those data which appeared to show a covariation, as judged by the preliminary qualitative analysis, were then studied quantitatively with calculation of the correlation coefficient, and the magnitude of the latter was compared with its mean error, which is of the order $1/\sqrt{N}$.

[1] The statistical analysis was performed by Prof. C.-E. QUENSEL of the Institute of Statistics, University of Lund.

CHAPTER VI

RESULTS

At operation the fixation of the fragments of the bones submitted to osteotomy was distinctly better in those bones in which an intramedullary nail had been used. While a certain amount of mobility was noted at the site of osteotomy in the unnailed bones the nailed bones were rigid. On preparation the unnailed bones showed no signs of dislocation of the osteotomy and pseudoarthrosis was not seen in any of the experimental bones.

Findings around the end of the nail

The end of the nail, which projected 1—2 mm. beyond the cortex at the site on insertion, was found to be surrounded by connective tissue on the 10th day and after about 4—6 weeks it was more or less enclosed in callus.

The periosteal and endosteal callus

The periosteal callus on the control side was found to be more or less egg-shaped, while on the nailed side it was spindle-shaped (Fig. 6). This difference gradually disappeared and from the 50-day group on it was no longer demonstrable. On the nailed side the periosteal callus tended to extend somewhat longer proximally and distally to the osteotomy. There was a difference also in the extent of the endosteal callus between the nailed bone and the control bone. In the control bones endosteal callus formed only near the osteotomy, 1—2 mm. proximally and distally to the latter. In the nailed bones, and then particularly radially, endosteal callus extended more or less continuously along the nail.

The callus in the 10-day group was fibrous and elastic, but already from the 20-day group on it was firm and hard.

Resorption cavities in callus

During the course of healing gross cavities of different shape, size, and number were seen in the callus. The cavities were scattered so widely in the cross section of the callus that it was often not possible to distinguish endosteal from periosteal cavities with the naked eye. The cavities showed up distinctly in the photographs of the cross section of the callus on which they could be counted. The occurrence of these cavities within the different

Fig. 6
Illustration of 20 day old unnailed (r) and nailed (l) fractures and of normal bones (below).

age of fracture in days	No. of animals	nailed: No. of bones with cavities	unnailed: No. of bones with cavities
10	24	0	7 (0)
20	28	0	0
30	24	1 (0)	4 (0)
40	24	3 (0)	17 (0)
50	24	2 (0)	23 (3)
60	24	7 (3)	24 (0)
70	24	7 (3)	24 (10)
80	24	10 (3)	24 (4)
100	24	15 (5)	24 (3)
120	24	15 (6)	24 (4)

Figures in brackets indicate number of bones with more than one cavity.

Table 1

groups of the material is given in Table 1, which shows that cavity formation was more pronounced in the control bones.

From the 60-day group cavities were found in all control bones. In the beginning the cavities were solitary but then appeared in varying number. Later the cavities tended to become solitary again, *i.e.* the marrow cavity was re-formed (See photo of cross section of bone in appendix). In the nailed bones, where there was a nail cavity, which cannot be regarded as a cavity proper the cavities tended to develop later than on the control side and the number of cavities was smaller (See Table 1). In the 60-day group it was, however, possible to observe that the nail cavities began to grow in size and to assume a more irregular outline and in some of the bones the nail cavity was surrounded by one or more small cavities. At the end of the experimental period and in contradistinction to the control side, the nailed bone showed not a solitary marrow cavity but usually a nail cavity or rests of such a cavity surrounded by one or more other cavities (See photo in appendix).

Defects in radius and ulna (See Fig. 7)

In the later experimental groups (70-, 80-, 100- and 120-day groups) it was found in some of the bones that the marrow cavities of the radius and of the ulna had fused at the site of osteotomy. Thus a bone defect occurred in the cortex of both bones. While it was otherwise possible on preparation to distinguish the cortex of the ulna from the callus of the radius, in the defects the cortex of the two bones merged. The defects were irregular and about 1×2 mm. in size. They consisted either of a smooth edged hole or more frequently a cortex defect filled with loose spongiosa. The defects were seen in both nailed and control bones with largely equal frequency. They were first observed in some bones in the 70-day group, but afterwards occurred in about one half of three fourths of the bones in the 100- and 120-day goups (See Table 2).

The defects complicates the determination of the cross sectional areas of the callus and the marrow, because when attempts were made to saw off a slice of bone including the defect in the bone the bone split. The slice of bone used for measurement of the cross sectional area therefore included a small part of the contiguous intact bone so that the defects do not show up on photographs of the cross sectional area of bone. The cross sectional area of the marrow was therefore in reality somewhat larger than that indicated by the measurements, while the area of the bone was smaller. Therefore the specific tensile strength measured will be too small in relation to that of normal bone. The error thereby introduced will, however, be small (7—8 %) compared with the total decrease in absolute ten-

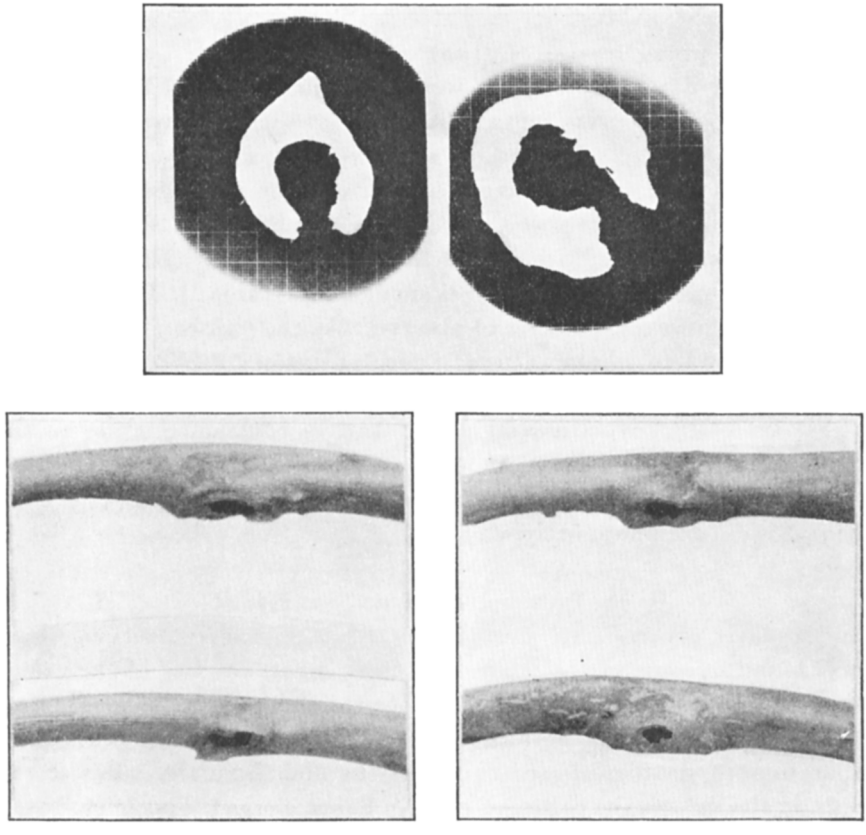

Fig. 7
Bones with defect. Above: cross section.

age of fracture in days	No. of animals	nailed	unnailed
		No. of bones with cortical defects	No. of bones with cortical defects
70	24	2	2
80	24	1	4
100	24	12	18
120	24	16	18

Table 2

sile strength owing to the defect. The influence of the defect on the tensile strength can be approximately calculated (See Fig. 8). If the size of the defect is taken as 1 mm. $\times$ 2 mm. on the average and if the mean values of the transverse area of the marrow and the bone in the 100-day group

of experimental animals be used, the tensile strength, calculated according to the formulae below, will be about 40 % less than it would have been if the radius had been without defect.

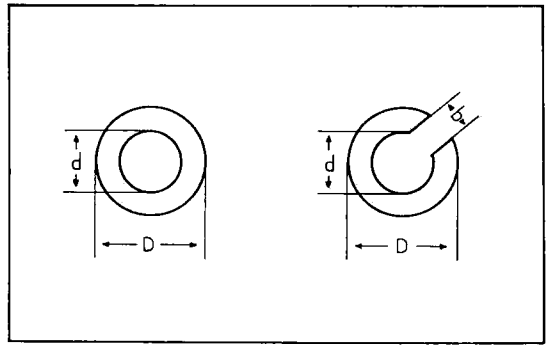

Fig. 8

Fig. 8. In a straight homogenous tube exposed to pull of P the following tension will arise.

$$\sigma = \frac{P}{\frac{\pi}{4}(D^2 - d^2)}$$

In a corresponding tube with a hole with a diameter (b) is subjected to the same pull (P) the tension in the edge of the hole will be

$$\sigma = \frac{P}{\frac{\pi}{4}(D^2 - d^2) - b\left(\frac{D-d}{2}\right)} + \frac{P \cdot e}{W}$$

the first member representing the tension and the second the bending force. In the above formula (e) is the eccentricity and can be calculated from the formula

$$e = \frac{\frac{\pi}{4}(D^2 - d^2) \cdot \frac{D}{2} - b\left(\frac{D-d}{2}\right) \cdot \left(\frac{D-d}{4}\right)}{\frac{\pi}{4}(D^2 - d^2) - b\left(\frac{D-d}{2}\right)} - \frac{D}{2}$$

and the resistance (W) can be calculated from the formula

$$W = \frac{1}{\frac{D}{2} + e}\left[\frac{\pi}{64}(D^4 - d^4) + \frac{\pi}{4}(D^2 - d^2) \cdot e^2 - \frac{1}{12} b \left(\frac{D-d}{2}\right)^3 - b \frac{D-d}{2}\left(\frac{D-d}{4} + \frac{d}{2} + e\right)^2\right]$$

The tension will be (1) for the cross section without any defect

$$\sigma = \frac{P}{F}$$

for a transverse area of (F), and (2) for a cross section with a defect

$$\sigma = \frac{P}{F_1} + \frac{M}{W}$$

where (F_1) is the transverse area minus the area of the defect and $M = P \cdot e$.

Estimation of tensile strength

The absolute tensile strength (Fig. 9 and Table) of both experimental bones increased from the 10th day. The increase was almost linear during the first two thirds of the experimental period. From about the 40th day the absolute strength on the control side showed a tendency to lie above that on the nailed side, and about the 60th day the absolute strength of the control bones was higher than that of the nailed bones(***).

In the further course no difference was found in the absolute tensile strength, though the strength of the control bone continued to show a tendency to be higher than on the nailed side. After the 80th day the increase in strength was less rapid.

The absolute strength on the 10th day was about 4 % of normal, on the 30th day it rose to 20 % and on the 80th day it was about 50 % of normal. The absolute strength on the 60th day was about 30 % higher on the control side than on the nailed side.

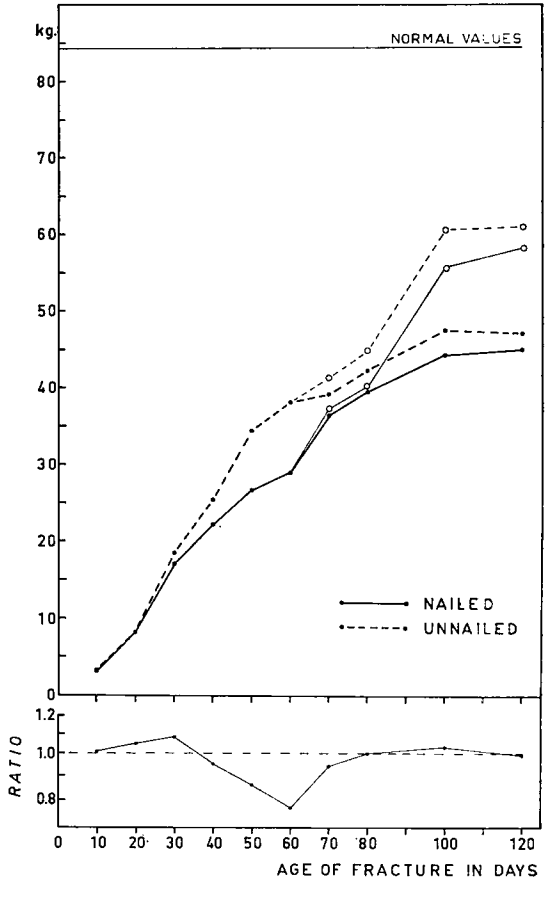

Fig. 9

Variation in absolute tensile strength with age of fracture.

Thin lines indicate values corrected for defects in bones.

Below: Curve for ratio between nailed and unnailed bones. in log. scale.

The data forming the basis of the curves are given in tabular form below.

age of fracture in days	absolute tensile strength in kg.								ratio absolute tensile strength nailed/unnailed			
	nailed				unnailed							
	No. of animals	mean	s. d.	error of mean	No. of animals	mean	s. d.	error of mean	No. of animals	mean	s. d.	error of mean
10	22	3.1	1.0	0.21	24	3.2	1.0	0.20	22	1.01	0.40	0.083
20	27	8.1	3.3	0.63	27	8.1	3.4	0.65	26	1.06	0.43	0.084
30	24	17.1	5.6	1.14	24	18.5	7.4	1.53	24	1.08	0.64	0.130
40	24	22.1	8.0	1.63	24	25.4	8.7	1.77	24	0.95	0.42	0.085
50	24	26.7	7.7	1.57	24	34.4	11.2	2.28	24	0.86	0.39	0.080
60	24	29.0	11.2	2.28	24	38.2	12.8	2.61	24	0.77	0.23	0.047
70	23	36.5	12.0	2.49	24	39.3	8.1	1.64	23	0.94	0.29	0.061
80	22	39.6	10.9	2.31	24	42.4	10.1	2.07	22	1.00	0.42	0.090
100	21	45.8	13.3	2.89	24	47.8	14.9	3.05	21	1.03	0.42	0.092
120	23	46.4	14.2	2.95	23	47.3	12.6	2.63	22	0.99	0.29	0.061
mean normal values 31 bones		84.2	13.3	2.35						1.02	0.15	0.037

The specific tensile strength (See Fig. 10 and Table) of both experimental bones increased from the 10th day. Like the absolute strength, the specific tensile strength increased almost linearly during the first two thirds of the experimental period. About the 20th day the specific strength was greater on the nailed side(***). From then on no difference was found in the strength on the two sides until about the 60th day, when the specific strength on the control side was greater(**). The increase in strength was then less rapid and no subsequent difference was found between the specific strength on the two sides.

The specific strength on the 10th day was about 1 % of normal, on the 30th day it was about 6 %, and on the 80th day about 20 % of normal.

On the 20th day the specific strength on the nailed side was more than 50 % greater than on the control side, while on the 60th day it was about 40 % greater on the control side than on the nailed side.

Estimation of cross sectional of area of callus and marrow

The cross sectional area of the callus (Fig 11, and Table) increased from the beginning of the experimental period in both the nailed bones and the control bones. The increase on either side reached a maximum on about the 20th day, after which the cross sectional area decreased on both sides. On the 10th day there was no significant difference between the area on either side, but on the 20th and 30th days the area on the

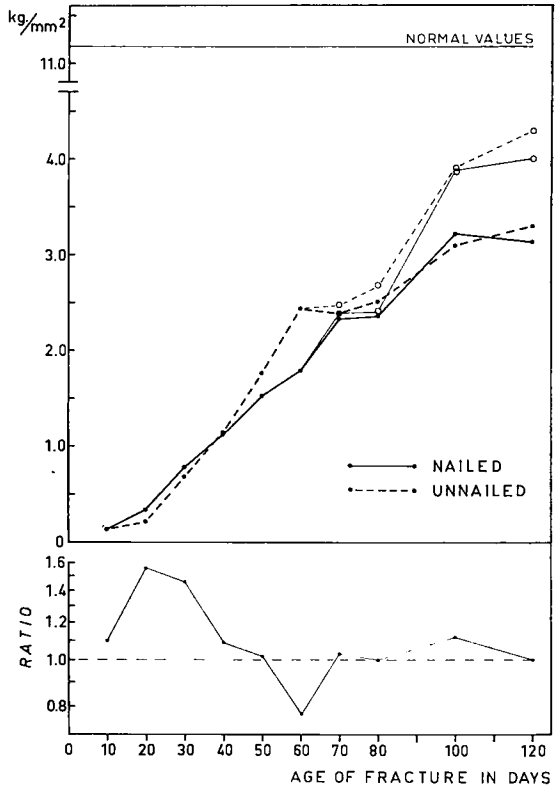

Fig. 10

Variation in the specific tensile strength with age of fracture.

Thin lines indicate values corrected for defects in bone.

Below: Curve for ratio between nailed and unnailed bones given in log. scale.

N. B. Scale broken between 4.0 and 11.0 kg./mm².

The data forming the basis of the curves are given in tabular form below.

age of fracture in days	specific tensile strength in kg./mm.²								ratio specific tensile strength nailed/unnailed			
	nailed				unnailed							
	No. of animals	mean	s. d.	error of mean	No. of animals	mean	s. d.	error of mean	No. of animals	mean	s. d.	error of mean
10	22	0.14	0.06	0.012	24	0.13	0.05	0.010	22	1.11	0.38	0.081
20	27	0.34	0.15	0.029	27	0.22	0.09	0.017	26	1.56	0.21	0.040
30	24	0.78	0.33	0.069	24	0.68	0.33	0.068	24	1.46	1.09	0.222
40	24	1.13	0.49	0.099	24	1.14	0.50	0.102	24	1.09	0.48	0.098
50	24	1.52	0.47	0.096	24	1.77	0.70	0.142	24	1.02	0.59	0.120
60	24	1.78	0.65	0.132	24	2.44	0.86	0.176	24	0.77	0.27	0.055
70	23	2.33	0.60	0.124	24	2.39	0.65	0.132	23	1.03	0.35	0.072
80	22	2.36	0.51	0.109	24	2.51	0.59	0.121	22	1.00	0.33	0.069
100	21	3.22	1.05	0.230	24	3.10	1.36	0.270	21	1.12	0.53	0.114
120	23	3.13	0.91	0.189	23	3.29	0.97	0.203	22	1.00	0.38	0.081
mean normal values 31 bones		11.16	15.1	0.272						0.99	0.18	0.046

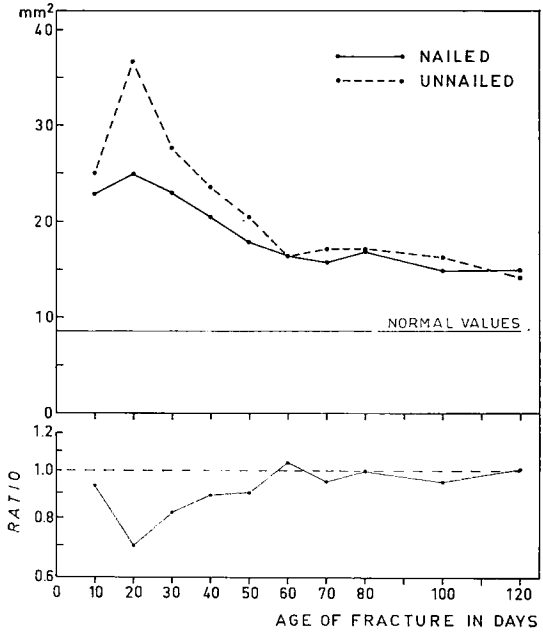

Fig. 11

Variation in cross sectional area of callus with age of fracture. Below: Curve for ratio between nailed and unnailed bones given in log. scale.

The data forming the basis of the curves are given in tabular form below.

age of fracture in days	cross section of callus in mm.²								ratio cross section of callus nailed/unnailed			
	nailed				unnailed							
	No. of animals	mean	s. d.	error of mean	No. of animals	mean	s. d.	error of men	No. of animals	mean	s. d.	error of mean
10	24	22.8	6.3	1.28	24	25.0	5.6	1.15	24	0.93	0.22	0.045
20	28	24.9	6.8	1.29	28	36.7	8.7	1.64	28	0.70	0.22	0.041
30	24	23.0	4.6	0.93	24	28.7	5.2	1.06	24	0.82	0.18	0.037
40	24	20.5	5.3	1.08	24	23.6	5.0	1.02	24	0.89	0.24	0.049
50	24	17.9	2.8	0.58	24	20.5	4.4	0.89	24	0.90	0.20	0.041
60	24	16.4	3.5	0.72	24	16.4	5.1	1.03	24	1.04	0.22	0.044
70	24	15.8	3.1	0.62	24	17.2	4.2	0.85	24	0.95	0.22	0.045
80	24	16.9	3.4	0.69	24	17.1	3.1	0.64	24	1.00	0.21	0.043
100	21	14.9	3.8	0.81	24	16.3	4.0	0.81	21	0.95	0.14	0.030
120	23	15.0	3.2	0.67	24	15.2	3.4	0.69	23	1.01	0.16	0.033
mean normal values 32 bones		8.6	1.2	0.21						0.99	0.08	0.020

control side was about 50 % and 25 %, respectively, larger than on the nailed side(***). From about the40th day and during the rest of the experimental period there was no significant difference in the area on the two sides.

The transverse area of the radius at the site of osteotomy increased considerably because of the callus formation. When the callus reached its maximum the cross sectional area of the nailed bone was almost 3 times normal and that on the control side about 4 times normal. The reduction in the area as a consequence of re-organization of the callus was remarkable. Thus between the 20th and 60th days the area diminished on the nailed side by about 35 % and on the control side by about 55 %. During the last half of the experimental period the cross sectional area decreased only slightly and to the same extent on both sides. At the end of the experimental period the cross sectional area on both sides was about twice as large as that of a normal radius.

The cross sectional area of marrow (Fig. 12 and Table) on the control side was markedly reduced already on the 10th day because of the formation of endosteal callus and on the 20th day it was 0, *i.e.* the marrow in all of the unnailed bones was filled with endosteal callus. On the 30th day the marrow showed signs of restoration and on the 60th day the transverse area of the marrow was of normal size. The area of the marrow increased until the 70th day and was then larger than normal(***) and retained this size during the rest of the experimental period. On the 120th day the marrow cavity consisted of a solitary cavity in nearly all of the bones in the control group (see photograph in appendix) and the area of the marrow was then increased by 50 % in relation to that of normal marrow.

Also on the nailed side the marrow cavity was reduced in size by the formation of endosteal callus. (See photograph in appendix). Since the nail filled part of the marrow cavity the amount of endosteal callus was not so large as on the control side. While the area of the marrow on the control side from the 30th day grew rapidly, the area of the marrow on the nailed side remained unchanged until the 60th day, reached normal values on the 70th day, and showed a tendency to lie above normal after the 80th day.

Measurements of ash weight and radio activity

The ash weight of the B-parts (See Fig. 13 and Table) on the 10th day was increased on the nailed side and on the control side(**). The ash weight then rose on both sides to reach a maximum on the 30th day. It then decreased on both sides, first rapidly and then slowly, during the rest of the experimental period. On the 10th day there was no difference in ash

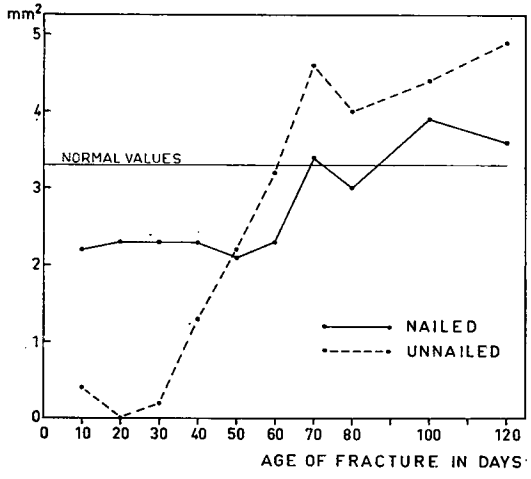

Fig. 12
Variation in cross sectional area of marrow with age of fracture. The data forming the basis of the curve are given in tabular form below.

age of fracture in days	cross section of marrow in mm²							
	nailed				unnailed			
	No. of animals	mean	s. d.	error of mean	No. of animals	mean	s. d.	error of mean
10	24	2.2	1.0	0.20	24	0.4	0.9	0.18
20	28	2.3	1.1	0.21	28	0	0	0
30	24	2.3	0.9	0.17	24	0.2	0.6	0.13
40	24	2.3	0.8	0.17	24	1.3	1.1	0.23
50	24	2.1	0.8	0.16	24	2.2	1.1	0.22
60	24	2.3	1.2	0.24	24	3.2	1.5	0.30
70	24	3.4	1.9	0.38	24	4.6	1.6	0.33
80	24	3.0	1.5	0.30	24	4.0	1.0	0.19
100	21	3.9	1.3	0.28	24	4.4	1.3	0.26
120	23	3.6	1.7	0.35	24	4.9	1.4	0.28
mean normal values 32 bones		3.3	0.9	0.16				

weight between the two sides. On the 20th through 40th days the ash weight on the control side was found to be larger than on the nailed side** The increase in relation to the nailed side varied from about 15 % to 10 %. Afterwards no difference was found in ash weight between the two sides until the 120th day, when the ash weight of the nailed side was greater(**).

The increase in ash weight of the B-parts in relation to normal values was considerable. When the ash weight of the experimental B-parts was maximal, the increase on the nailed side was about 65 %, while that on the

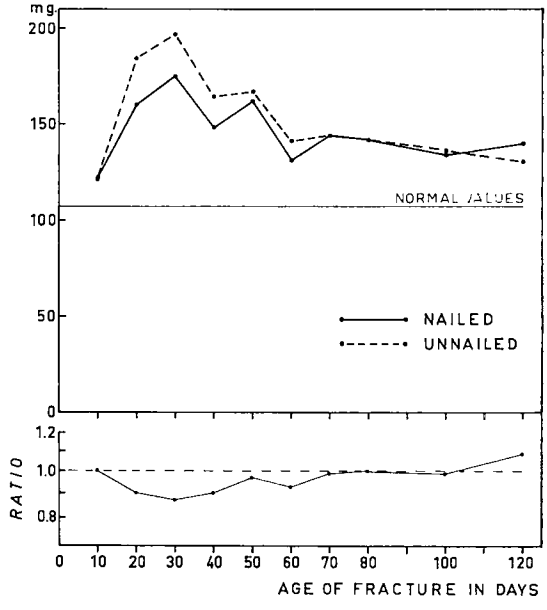

Fig. 13

Variation in the ash weight of the B-parts with age of fracture.

Below: Curve for ratio between nailed and unnailed bones given in log. scale.

The data forming the basis of the curves are given in tabular form below.

age of fracture in days	No. of animals	wt. of bone ash in mg.						ratio Wt.of bone ash nailed/unnailed		
		nailed			unnailed					
		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean
10	17	122	34	8.2	121	26	6.4	1.00	0.13	0.032
20	16	160	20	5.0	184	37	9.2	0.90	0.20	0.051
30	15	175	30	7.9	197	35	8.9	0.87	0.15	0.039
40	16	148	32	7.9	164	31	7.7	0.90	0.13	0.031
50	16	162	36	8.9	167	32	8.0	0.97	0.12	0.031
60	18	131	31	7.4	141	36	8.5	0.93	0.13	0.029
70	17	144	30	7.3	144	24	5.8	0.99	0.10	0.024
80	17	142	22	5.0	143	17	4.2	1.00	0.17	0.042
100	24	134	25	5.0	136	21	4.2	0.99	0.13	0.027
120	24	140	29	6.0	130	21	4.3	1.09	0.18	0.037
mean normal values 64 B-parts		107	14	1.8				0.98	0.07	0.012

control side was about 85 %. The ash weight of the B-parts remained increased during the entire experimental period. The increase in the ash weight at the end of the experimental period was about 25 %.

The radioactivity of the B-parts (See Fig. 14 and Table) of both experimental bones were higher than normal already on the 10th day(***). The activity then rose on both sides to reach a peak on about the 20th day. Afterwards the activity decreased, first rapidly and then slowly, and even at the end of the experimental period it was larger than normal on both sides.

On the 10th day the activity was higher on the nailed side(*). The difference was about 12 %. On the 20th day the activity was 35 % higher on the control side than on the nailed side(***). Between the 30th and 70th days no difference in activity was found between the two sides. After the 70th day the activity on the nailed side tended to be higher than on the control side, and on the 80th day and 120th day it was higher(*). The activity on the 80th day and 120th day was about 15 % and 8 %, respectively, higher than on the control side.

The increase in activity compared with normal values was considerable. When the activity was maximal it was 5.8 times normal on the nailed side and 8.3 times normal on the control side. At the end of the experimental period the activity on both sides was still some 1.7 times normal.

The ash weight of the A-parts (See Fig. 15 and Table) on the control side was lower than normal on the 10th day(***), and then increased to reach normal on the 20th day. The ash weight stayed about normal until it rose about the 70th day and remained higher than normal(**) through the end of the experimental period. The initial loss in ash weight measured on the 10th day was about 15 %. On the 80th day the ash weight was about 10 % higher than normal.

The ash weight of the nailed bones was normal on the 10th day. It then rose and on the 30th day it was higher than normal(**). The ash weight fluctuated between the 30th day and the 70th days: about the 50th day it was increased(*), while about the 40th and 60th days it lay within the normal range. From the 70th day and throughout the rest of the experimental period it remained higher than normal(**). The increase in weight on the 30th day was about 12 % and on the 80th day about 20 %, and on the 120th day about 13 % above normal.

The ash weight of the A-parts of the nailed bones was higher than on the control side throughout the experimental period exept on the 40th day The increase in ash weight in relation to the control side was about 15 % on the 10th day and then varied during the rest of the experimental period, and on the 120th day it was about 6 %.

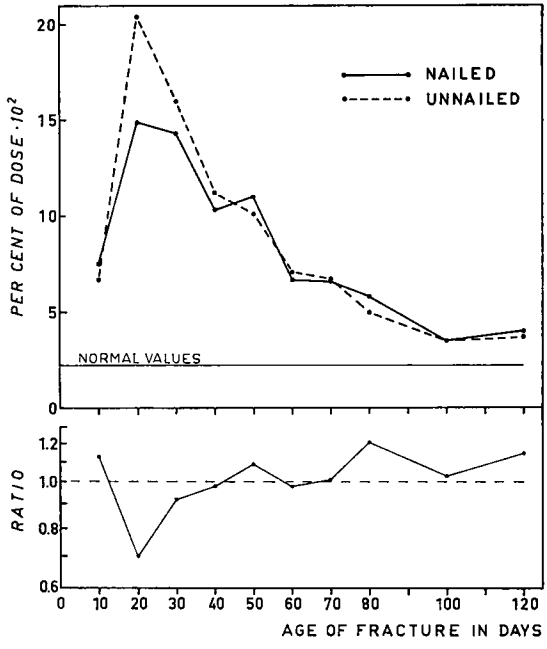

Fig. 14

Variation in the activity of the B-parts with age of fracture.

Below: Curve for ratio between nailed and unnailed bones given in log. scale.

The data forming the basis of the curves are given in tabular form below.

age of fracture in days	No. of animals	Sr^{85} activity in % of dose × 10^2						ratio Sr^{85} activtiy nailed/unnailed		
		nailed			unnailed					
		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean
10	17	7.5	2.6	0.63	6.7	1.9	0.47	1.13	0.27	0.066
20	16	14.9	8.6	2.16	20.4	9.9	2.47	0.70	0.14	0.036
30	15	14.3	6.8	1.75	16.0	6.8	1.76	0.92	0.27	0.070
40	16	10.3	3.4	0.86	11.2	3.3	0.82	0.98	0.21	0.053
50	16	11.0	6.3	1.57	10.1	4.5	1.11	1.09	0.29	0.072
60	18	6.7	2.4	0.57	7.1	3.1	0.73	0.98	0.24	0.057
70	17	6.6	2.5	0.60	6.7	2.8	0.67	1.01	0.24	0.058
80	17	5.8	2.6	0.63	5.0	2.1	0.50	1.21	0.48	0.117
100	24	3.5	1.5	0.31	3.5	1.4	0.29	1.03	0.22	0.045
120	24	4.0	1.6	0.33	3.7	1.8	0.38	1.15	0.20	0.041
mean normal values 64 B-parts		2.2	0.8	0.10				1,00	0.10	0.017

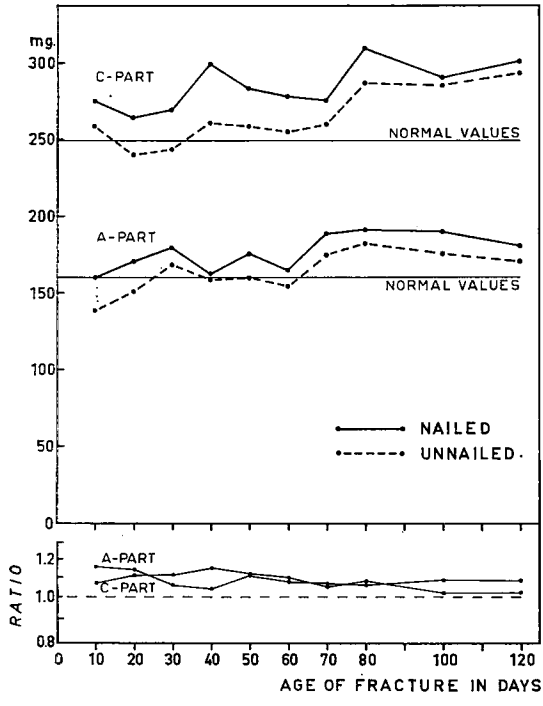

Fig. 15

Variation in ash weight of the A- and C-parts with age of fracture.

Below: Curve for ratio between nailed and unnailed bones given in log. scale.

The data forming the basis of curves are given in tabular form below.

age of fracture in days	No. of animals	wt. of bone ash in mg.						ratio wt. of bone ash nailed/unnailed			
		nailed			unnailed						
		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean	
10	17	160	26	6.3	138	19	4.7	1.16	0.09	0.022	A-parts
20	16	171	22	5.6	151	14	3.6	1.14	0.14	0.037	
30	15	179	26	6.7	168	28	7.3	1.07	0.14	0.037	
40	16	163	24	5.9	158	20	5.0	1.04	0.17	0.042	
50	16	176	37	9.2	160	36	8.9	1.11	0.15	0.038	
60	18	164	27	6.3	154	32	7.6	1.08	0.14	0.034	
70	17	188	30	7.3	175	23	5.5	1.07	0.10	0.024	
80	17	192	43	10.3	183	37	8.9	1.06	0.16	0.038	
100	24	190	42	8.7	177	38	7.7	1.09	0.19	0.039	
120	24	181	42	8.5	170	42	8.6	1.08	0.16	0.033	
mean normal values 64 A-parts		160	21	2.8				0.99	0.03	0.006	

10	17	275	46	11.2	258	49	11.8	1.07	0.06	0.015	
20	16	264	28	6.9	240	30	7.6	1.11	0.11	0.027	
30	15	269	52	13.3	244	49	12.7	1.11	0.11	0.027	
40	16	300	52	13.0	262	45	11.2	1.15	0.14	0.035	
50	16	283	43	10.6	258	36	9.0	1.11	0.16	0.040	
60	18	278	61	14.3	255	52	12.2	1.10	0.12	0.028	
70	17	276	51	12.4	260	32	7.8	1.06	0.11	0.026	
80	17	310	31	7.5	287	28	6.8	1.08	0.09	0.022	
100	24	291	51	10.5	285	52	10.5	1.03	0.12	0.025	
120	24	301	41	8.4	293	28	5.8	1.03	0.13	0.026	
mean normal values 64 C-parts		248	46	5.6				1.00	0.07	0.012	

C - parts

The radioactivity of the A-parts (See Fig. 16 and Table) on the control side rose from normal values on the 10th day to higher than normal on the 40th day(*). The activity then dropped to lower than normal on the 100th and 120th days(**).

The activity of the A-parts on the nailed side was higher than normal from the beginning of the experimental period(**) and dropped through normal on the 60th day to lower than normal on the 100th and 120th days(**).

The increase in activity on the control side in relation to the normal was about 25 % on the 30th day. On the nailed side the increase was about 45 % on the 10th day and 65 % on the 30th day. The activity at the end of the experiment was about 60—65 % of normal on both sides.

The activity in the A-parts on the nailed side was higher than on the control side throughout the experimental period(***). On the 10th day the activity on the nailed side was about 60 %, on the 30th day about 30 %, and at the end of the experiment about 10 % higher than on the control side.

The ash weight of the C-parts (See Fig. 15 and Table) on the control side did not vary from normal from the 10th day to the 70th day. On the 80th day it had increased and stayed higher than normal during the rest of the experimental period(***).

The ash weight of the C-parts on the nailed side on the 10th day was higher than normal(*). The ash weight then fell, and on the 20th and 30th days it lay within the range of normal range of variation. Between the 30th and 40th days the ash weight increased again and during the rest of the experimental period it was higher than normal(**).

On the control side the ash weight on the 80th day was about 15 % above normal and remained so throughout the rest of the experimental

period. On the nailed side the ash weight on the 10th day was about 10 %, on the 40th day about 20 %, and on the 80th day about 25 % above normal. This increase persisted largely unchanged until the 120th day.

The ash weight of the C-parts on the nailed side was higher than on the control side throughout most of the experimental period(**). However, on the 100th day and on the 120th day no difference in ash weight was found between the two sides.

The activity of the C-parts (See Fig. 16 and Table) on the control side showed a tendency to be above normal during the first half of the experimental period. From about the 70th day the activity showed a falling tendency, and on the 100th day it was lower than normal(*).

The activity of the nailed C-parts on the 10th day was higher than normal(*) and then increased to reach a maximum about the 40th day. The activity then dropped and on the 80th day and during the rest of the experimental period it lay within the normal range of variation.

The decrease in activity on the control side in relation to normal was about 20 % on the 100th day. The increase in activity on the nailed side on the 10th day was about 50 % and on the 40th day it was about 90 %.

The activity of the C-parts on the nailed side was higher than on the control side throughout the experimental period(**). The increase in activity in relation to the control side on the 10th day was about 30 %, on the 40th day about 60 % and on the 120th day it was about 25 %

Estimation of mineral density of callus (Fig. 17 and Table). From day 10 the mineral density of the callus tended to increase on the nailed and on the unnailed side. The increase was initially fairly abrupt, but from the day 30 and during the rest of the experimental period it was more gentle. The mineral density on the nailed side on day 10 was about 20 % greater(*) and on day 20 about 40 % greater(***) than on the control side. During the rest of the experimental period there was no difference in the mineral density of the two sides.

The mineral density on day 10 on the nailed side was about 45 % of normal against about 35 % on the control side. On day 20 the mineral density rose to 55 % and 40 %, respectively. On day 60 the mineral density was about 70 % and on day 120 it was about 75 % of normal on both sides.

Results of statistical analysis. The qualitative analysis showed that apart from the 10-day group and for the nailed bones also the 20-day group during the first 50 days there was no covariation between the absolute tensile strength and the ash weight of the B-parts, the difference between

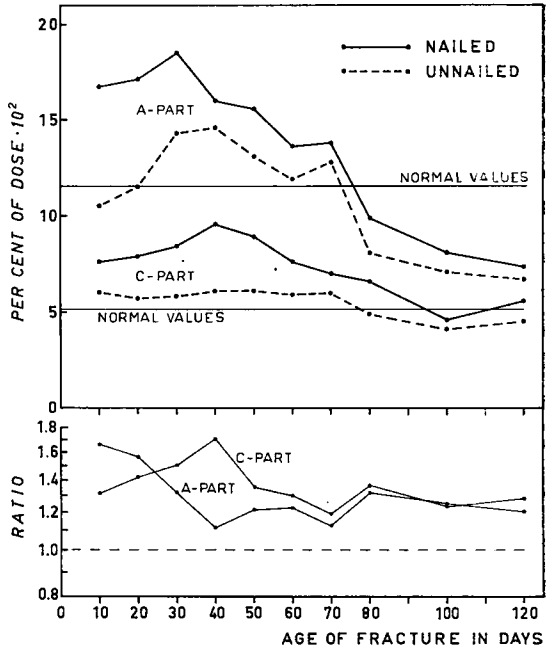

Fig. 16

Variation in activity of the A- and C-parts with age of fracture.

Below: Curve for ratio between the nailed and unnailed bones given in log. scale.

The data forming the basis of the curves are given in tabular form below.

age of fracture in days	No. of animals	Sr^{85} activity in % of dose × 10^2						ratio Sr^{85} activity nailed/unnailed			
		nailed			unnailed						
		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean	
10	17	16.7	5.6	1.37	10.5	3.9	0.94	1.66	0.36	0.086	A-parts
20	16	17.1	7.9	1.97	11.5	5.4	1.34	1.57	0.60	0.150	
30	15	18.5	9.7	2.50	14.3	6.8	1.76	1.32	0.41	0.105	
40	16	16.0	6.5	1.62	14.6	5.6	1.41	1.11	0.24	0.060	
50	16	15.6	5.7	1.41	13.1	4.6	1.15	1.21	0.32	0.081	
60	18	13.6	5.8	1.36	11.9	6.1	1.44	1.23	0.31	0.072	
70	17	13.8	5.7	1.38	12.8	6.1	1.48	1.13	0.26	0.063	
80	17	9.9	4.7	1.14	8.1	4.3	1.03	1.32	0.41	0.099	
100	24	8.1	3.9	0.80	7.1	4.1	0.83	1.25	0.42	0.086	
120	24	7.4	3.8	0.78	6.7	4.4	0.90	1.20	0.28	0.056	
mean normal values 64 A-parts		11.4	5.8	0.73				1.00	0.06	0.011	

10	17	7.6	2.5	0.62	6.0	1.9	0.46	1.31	0.29	0.070	C-parts
20	16	7.9	3.6	0.89	5.7	2.6	0.66	1.42	0.40	0.101	
30	15	8.4	3.6	0.93	5.8	2.5	0.63	1.50	0.45	0.115	
40	16	9.6	3.7	0.93	6.1	2.2	0.55	1.70	0.73	0.184	
50	16	8.9	7.3	1.82	6.1	2.4	0.61	1.36	0.54	0.134	
60	18	7.6	3.1	0.72	5.9	1.6	0.37	1.30	0.46	0.107	
70	17	7.0	2.5	0.60	6.0	1.9	0.46	1.19	0.30	0.073	
80	17	6.6	2.6	0.62	4.9	1.8	0.43	1.36	0.19	0.046	
100	24	4.6	1.7	0.34	4.1	1.4	0.28	1.13	0.19	0.038	
120	24	5.6	2.7	0.56	4.5	2.2	0.45	1.28	0.24	0.049	
mean normal values 64 C-parts		5.1	2.0	0.24				1.01	0.12	0.021	

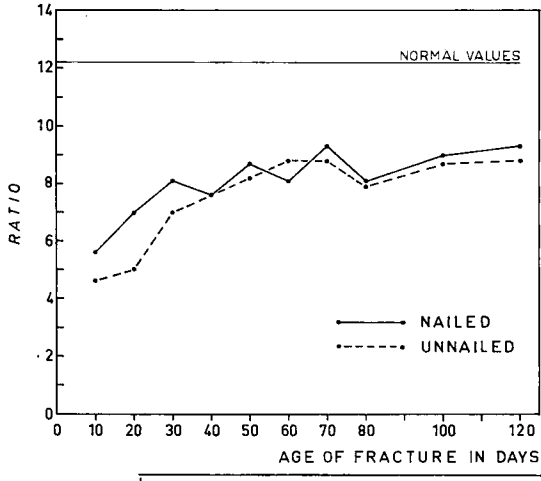

Fig. 17

Variation in ratio between ash weight in the B-parts and the cross sectional area of the callus with age of fracture.

The data forming the basis of the curves are given in tabular form below.

ratio wt. of bone ash in B-part/cross section of callus								
age of fracture in days	nailed				unnailed			
	No. of animals	mean	s. d.	error of mean	No. of animals	mean	s. d.	error of mean
10	17	5.6	1.6	0.39	17	4.6	0.9	0.23
20	20	7.0	1.7	0.37	20	5.0	1.1	0.25
30	15	8.1	0.8	0.20	15	7.0	1.2	0.31
40	16	7.6	1.0	0.25	16	7.6	1.1	0.27
50	16	8.7	1.5	0.37	16	8.2	2.0	0.51
60	18	8.1	1.2	0.29	18	8.8	1.5	0.35
70	17	9.3	0.9	0.21	17	8.8	1.3	0.31
80	17	8.1	1.0	0.23	17	7.9	0.9	0.21
100	21	9.0	1.6	0.34	24	8.7	1.9	0.40
120	23	9.3	1.0	0.22	24	8.8	1.8	0.36
mean normal values								
16 right		12.2	1.0	0.26				
16 left		12.1	0.6	0.16				
32 (right + left)		12.2	0.8	0.15				

the observed and the calculated values for n_{12} being alternately positive and negative and of the same order as the mean error. After 50 days the difference was positive and, as a rule, larger and sometimes more than twice the mean error and thus showed a correlation.

Quantitative evaluation of the covariation between the absolute tensile strength and the ash weight of the B-parts gave the following correlation coefficients (Table 3).

age of fracture in days	correlation-coefficients absolute tensile strength ashweight B-parts	
	unnailed	nailed
10	0.68	0.40
20	0.01	0.44
30	— 0.05	— 0.14
40	0.23	0.03
50	— 0.06	— 0.41
60	0.50	0.61
70	0,22	0.67
80	0.38	0.54
100	0.50	0.50
120	0.44	0.52

Table 3

During the first 50 days, apart from the 10-day group, and for the nailed bones also for the 20-day group, there was no correlation between the absolute strength and the ash weight of the B-parts. During this period, when the absolute tensile strength increased rapidly, while the ash weight decreased, some other factors must have influenced the variation in the values found for the tensile strength among the experimental animals. After the 60th day, on the other hand, a correlation appeared, which may, broadly speaking, be regarded as significant. Yet the relationship cannot be regarded as very strong, since the coefficients of correlation were on the average about 0.40.

Qualitative analysis of the absolute tensile strength and the ash weight of the A-parts, the activity of the B-parts and the mineral density showed no relationship between these data.

CHAPTER VII

DISCUSSION

The shapes of the curves for the various measurements made during the course of healing of the fractures were principally the same for the nailed as for the unnailed bones. The first part of the discussion will therefore be confined to fracture healing, as estimated from measurements of the control-bones, *i.e.* the unnailed bones, while the difference between the healing of the nailed and unnailed bones will be discussed in a separate section.

It is known from histological investigations that the healing of a fracture in the initial phase proceeds with great intensity (HERTZ 1936, URIST & MCLEAN 1941, PRITCHARD & RUZICKA 1950). Multiple fractures do not appear to influence the course of healing (MCLEAN & URIST 1950, BAUER 1952) and the calcification process of the callus closely resembles that in growing bone (MCLEAN & URIST 1951). URIST & MCLEAN (1941) found that the mass of the callus in the femur of the rat is maximal about the 10th—16th day and that the calcification of the callus is also greatest at that time (cf. *e.g.* BAUER 1954c). The callus then decreases in amount and healing proceeds with reorganization of the callus and subsequent formation of the cortex.

The histological descriptions of fracture healing deal mainly with the early phase of healing, and the literature on subsequent phases to definitive histological healing is scanty and contradictory. DOWN et al. (1932) found that fractures of the fibula of the rat heal with histologically normal cortex within about 50 days, while HERTZ (1936) still found remnants of necrotic cortical tissue in the new-formed cortex (fibula fractures of guinea-pigs) on the 50th day, and he claimed that definitive healing requires a long time, at least 1 year.

In the present investigation the biological reaction of bone to a fracture was studied by measuring the cross sectional area of the callus, the ash weight and the radioactivity of the radius. Further, repeated determination of the tensile strength of the callus was performed. It is clear from Figs. 11, 13, and 14 that the curves for the area of the callus and for the ash weight and radioactivity of the fracture region resemble one another in shape. After an initial ascent the curves for the area and the activity reach a peak about the 20th day. The ash weight appears to reach maximum

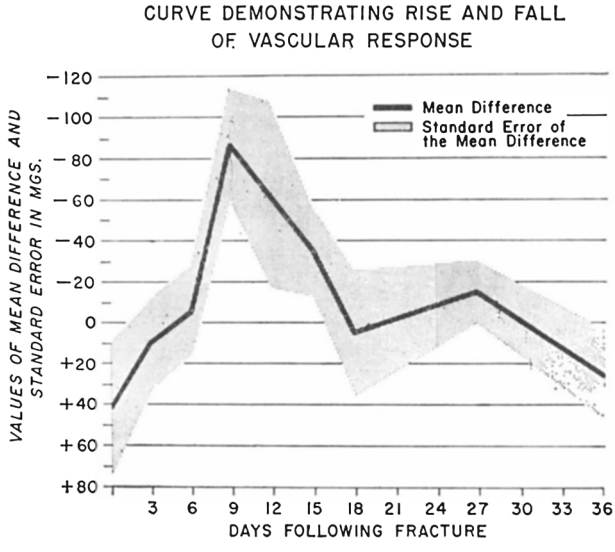

CHART I

Curve showing the rise and fall of the vascular response following fracture of the tibia in the rat. The values of the mean differences in milligrams are plotted against the number of days following fracture and are seen as a solid black line. The stippled band represents the range of the standard error of the mean differences.

Fig. 18

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about the 30th day. Afterwards the curves first rapidly fall, but from about the 50th—60th days the fall is slower, and at the end of the experimental period the values for the various measurements are still higher than normal.

WRAY & LYNCH (1959) determined the volume of the vascular bed in the hind legs of rats with fracture of the tibia. The curve in Fig. 18 illustrates the course of the traumatic hyperaemia during the healing period of the fractures. WRAY & LYNCH found that the peak of the curve coincided in time with that of the maximum of callus. The chronological lag of the peak of the curve in relation to the present experiments may be due to differences in the sizes of the animals (cf. URIST & MCLEAN 1941, BOHR & SØRENSEN 1950 and BAUER 1954c).

The curves in Figs. 11, 13 and 14 show the initial rate of callus formation. When the callus reached its peak on about the 20th day, the cross sectional area was more than 4 times normal. The ash weight in the fracture area had increased by 85 % and the accretion rate was 8—9 times normal. The increase in ash weight is the net increase because during the initial phase of healing the ash weight of the fracture fragments decreases because of resorption. Judging from histological examination the resorption is greatest

when the callus mass is maximal (URIST & MCLEAN 1941). Microradiographical examinations by NILSONNE (1959), however, appear to show that the resorption in the fracture ends occurs earlier and reachs maximum at the same time as the commending mineralization of the callus.

The rapid fall in the curve between the 20th and 60th days for all three measurements shows the rate of reorganization of the callus mass. During this period the area of the callus decreased by about 50 %, the ash weight by about 25 %, and the rate of accretion by about 65 %. During the rest of the experimental period the curves fell slowly, and even at the end of the experimental period the cross sectional area was still twice normal (see photo in appendix), while the ash weight had increased by about 20 % and the rate of accretion was more than 1.5 times normal.

My findings agree with the histological appearance of the initial stage of healing of fractures, and confirmed the results of BAUER (1954c). In his experiments on rats he found a similar increase in the ash weight and activity, while COPP & GREENBERG (1945) and BOHR (1950) in their isotope experiments found a similar but smaller increase in activity over the region of the fracture.

The results of the present investigation also showed that definitive healing of a fracture requires a long time and confirms the investigations of BAUER & CARLSSON (1955), BOHR (1955) and NILSONNE (1959) and is in agreement with the histological findings of HERTZ (1936).

Measurements in man after the injection of Sr^{85} have shown a similar increase in radioactivity over the fracture (BAUER & WENDEBERG 1959). WENDEBERG (1961) in his material of tibia fractures found the activity over the fracture region to be up to 30 times higher than that over the intact bone. The activity was found to be highest about 6—8 months after the fracture. The rise in activity persisted for a long time. WENDEBERG (1961) thus found an increased activity even in several year old fractures of the tibia.

Cross sectional area of marrow and cavities

The restoration of the marrow cavity and the decrease in the total mass of callus appears to be related to the formation of the cavities observed in the callus. The formation of such cavities has been described by BAST et al. (1925), HERTZ (1936) and ESKELUND & PLUM (1950) as a normal phase in the reorganization of callus. The cavities are first seen in the periphery of the callus, when the callus reaches its maximal size. (HERTZ, ESKELUND & PLUM.) The cavities increase in size during the healing process and later they are scattered more widely in the callus (HERTZ). The cavities are

largest about 3—4 weeks after fracture (ESKELUND & PLUM, fibula of rats), after which they decrease in size and number. The cavities contain osteogenetic tissue (BAST et al.) and marrow tissue (ESKELUND & PLUM). They gradually decrease in size and number on formation of new bone and with simultaneous reduction in the amount of inner and outer callus (BAST et al.).

The occurrence and the distribution of the cavities in the present material thus agree with these earlier observations (see Table 1 and photos in appendix).

The mineral density of callus

While the total ash weight of the callus is increased during the healing of the fracture, the mineral content of the callus expressed by the ratio ash weight B: cross sectional area of callus is decreased. The use of the ratio between the ash weight in the region of the fracture and the cross sectional area of the callus as an expression of the density of the mineral in the callus can be justified on the following grounds. In the region of the B-parts the normal rabbit radius is almost cylindrical in shape. When the amount of callus is greatest the B-parts take on the shape of a double truncated cone. As healing proceeds they again became cylindrical. Since there exists a constant ratio between the volume of a cylinder and that of a cone and their respective bases (provided the height is constant) it appears reasonable to assume that there is also a largely constant ratio between the volume of the B-parts and their crosssectional area. Fig. 17 illustrates the course of the curves of the mineral density of the callus during the experimental period.

It is seen from the curve of the unnailed bones in Fig. 17 that the mineral density in the callus on the 10th day was about 35 % of normal. The curve then rose fairly sharply until about the 30th day, when the mineral density was about 60 %. At the same time the ash weight in the fracture region was 85 % above normal. The rise in mineral density then gradually increased, and on the 120th day it was about 75 % of normal. The curve given for the mineral density in the callus (as expressed in the present investigation) corresponds in its course to that of the mineralization of the callus of the tibia of the rat and femur of the dog found by NILSONNE (1959) on quantitative microradiography.

Changes in the A- and C-parts

The effects caused by the fracture on the ends of the radius were most pronounced in the A-parts (Figs. 15 and 16), where the ash weight on about the 10th day was about 15 % below normal. At the same time the activity showed a rising tendency, but no deviation from normal values. It is clear from the course of the curve that the weight loss begins early during the first phase of healing and has passed its maximum already at the beginning of the observation period. At the same time the accretion does not deviate from normal.

The ash weight from the 10th day increased and reached normal values about the 30th day to remain within the normal range of variation until the 70th day. From about the 80th day the ash weight was significantly increased and remained increased until it returned towards normal at the end of the experimental period. The increase in ash weight from the 10th day was accompanied by a rise in the activity, and about the 40th day it was increased. Then the activity fell and on about the 100th and 120th days it was significantly lower than normal.

The changes in the C-parts were correspondingly less pronounced. During the first half of the experimental period the ash weight and the activity lay within the normal range. On about the 70th day a rise occurred in the ash weight and at the same time the activity fell. The ash weight then persisted significantly increased throughout the rest of the experimental period, while the activity around the 100th day was below normal and then again approached normal.

The changes in the activity and ash weight of the A-parts during the first half of the experimental period agree largely with those found in earlier experiments by BAUER (1954c) and BAUER & CARLSSON (1955), but in the present experiments the changes were less pronounced and particularly of shorter duration. The reason why it was not possible to demonstrate similar changes in the C-parts in the present investigation was presumably due to the C-parts consisting mainly of cortical bone, in which the mineral content, as shown by BAUER (1954d), is not so readily resorbed as the mineral in the A-parts representing the lower radius-meta-epiphysis.

The more pronounced changes in the ends of the fractured bones observed by BAUER (1954c) and BAUER & CARLSSON (1955) may be explained by the fact that these authors used small animals (rats), in which the general reaction of the skeleton is more pronounced than in larger animals (LACROIX 1956, NILSONNE 1959.)

WENDEBERG (1961) also found an increase in the activity over the knee and femur in human subjects with fracture of the tibia. In the present investigation the maximum of activity of the ends of the bones appeared

somewhat later during the course of healing than in the region of the fracture. This could not be confirmed by WENDEBERG's investigation.

From about the 80th day an increase was noted in the ash weight and a decrease in the activity of both end parts of the bones. These changes persisted during the rest of the experimental period, although the ash weight of the A-parts showed a tendency to a decrease about 120th day. In human beings with 4—5 year old fractures of the tibia WENDEBERG (1961) reported a similar decrease in the activity over the knee and femur on the fractured side, where the activity was lower than that over the control knee and femus.

Tensile strength

It is clear from Figs. 9 and 10 that until the 80th day the tensile strength curves were almost linear. Then they became flatter, particularly the curve for the absolute tensile strength. The flattening coincided with the time of appearance of the defects in the radius (see Table 2), which in the 100- and 120-day groups occurred in one half to three fourths of the experimental bones. The decreased absolute tensile strength of the defective bones must therefore have a decisive effect on the shape of the curve and will influence the evaluation of the course of healing, which is based on the tensile strength of normal intact radii.

In the curves for the absolute and specific strength (Figs. 9 and 10) is also given — in thin lines — for the 70-, 80-, 100- and 120-day groups, the values corrected according to the calculation described on page 33. In view of the above observations, the tensile strength in relation to the normal tensile strength in the last mentioned experimental groups, and particularly in the 100- and 120-day groups, must be evaluated with caution.

It is, however, reasonable to suppose that the corrected shape of the curves, which show an almost linear continuous ascent, is a more correct expression of the cumulative bone-forming process occurring in the callus during healing of a fracture.

It is difficult to explain the development of such fusion between the marrow cavities of the two bones. One might imagine the defect to be due to a lesion of the ulna during the operation. But such a lesion is less likely because the ulna is protected by an osteotomy hook during operation. In addition, it would be more reasonable to suppose that a lesion would heal instead of growing in size. Fusion of the radius and the ulna occurs so often that it seems to be a normal link in the healing process. A conditon necessary for such fusion may be the close contact present between the two bones, a connection that is augmented still more by the fact that callus to some extent encroaches upon the ulna. But why the cortex at the site of osteo-

tomy of the radius as well as the cortex of the ulna is resorbed with consequent communication between the marrow cavities of the two bones is still obscure.

The shape of the tensile strength curves showed good agreement with results obtained by the other measurements of the course of healing of the fracture in the present investigation. These curves also showed that the healing process was not concluded at the end of the experimental period.

Good agreement was found between the present results and those described by HÄBLER & REISS (1936) on experiments in which they loaded healing fractures of the radius, ulna and tibia of the dog. When measuring the breaking strength of 50—90 day old fractures they found the absolute strength to be decreased to 70—50 % of normal.

COPP & GREENBERG (1945) carried out similar experiments on fractures of the fibula of the rat and found the absolute strength to be normal after about 30 days. These fractures appeared to heal rather rapidly. Simultaneous measurements of the radioactivity over the region of the fracture after administration of Sr^{85} showed an increased uptake suggesting that the healing process at that point was not concluded.

The total and the specific strength characterize the healing process in two different ways. The absolute strength gives the total strength of the callus, while the specific strength is a measure of the quality of the callus tissue. A characteristic difference was found between the absolute and specific strength during the course of healing. While the absolute strength on the 10th day was about 4 % of normal, the specific strength was only about 1 %. On the 30th day the corresponding values were 20 % and 6 % and on the 80th day 50 % and 20 %. It is thus apparent that fracture healing is achieved in the first place by a relative rapid increase in the absolute strength of the callus, while the quality of the callus improves at a much slower rate.

In the treatment of fractures the time of clinical healing, *i.e.* when the callus is strong enough to permit weight bearing, is of greatest interest. PAUWELS (1946) stated that a bone is not normally loaded to more than about one seventh of what it can tolerate. If this be taken as a norm for clinical healing, it will be found that the absolute strength of the fractured rabbit radius attains such strength by about the 20th—30th days, *i.e.* at the time when the amount of callus was largest and when the ash weight and the radioactivity in the region of the fracture were maximal. Thus, clinical healing of a fracture occurs histologically and biologically in a relatively early stage.

This is in good agreement with the observation in my experiments that the animals soon moved about unhindered after the operation. These

observations also appear to be in accord with clinical experience. Fracture of the tibia in man will, as a rule, be clinically healed within 6—8 months, *i.e.* att the time when WENDEBERG (1961) found the radioactivity to be highest.

The shape of the curves for the absolute tensile and specific strength in the present experiments were largely linear and ascending. COPP & GREENBERG (1945) only studied the absolute strength in their experiments and found a similar rise. In identical experiments MCKEOWN et al. (1932) found a deviating course for the strength curve, which fell between the 15th and 20th days, coinciding with the time of restoration of the marrow cavity. These authors ascribed the fall in strength to the resorption of the endosteal callus. The decreasing strength in the experiments of MCKEOWN et al. is difficult to explain, but it could hardly be due to resorption of the endosteal callus because this process is a normal link in its reorganization.

Ash weight, mineral density of the callus and radioactivity in relation to strength of callus

HÄBLER & REISS (1936) found no relationship between the strength of the callus and the ash weight of the fracture region in dogs. BOHR (1955), on the other hand, was able to demonstrate such a relationship in his experiments from the 3rd week after the fracture.

In the present experiments a covariation was found between the absolute strength and the ash weight of the B-parts from about day 60 and during the rest of the experimental period. No such covariation could be found — except on day 10 — during the first half of the experimental period. While the strength of intact cortical bone increases with the mineral content (BELL, CHAMBERS & DAWSON 1947, WIER, BELL & CHAMBERS 1949, VOSE & KUBALA 1959) this was not found to hold for the callus until the latter had reached a certain stage of maturity. Therefore from day 20 to day 60 other factors must be responsible for the increasing strength of the callus.

It is clear from Fig. 13 that the ash weight of the callus between the 30th and 60th days fell from 197 mg. to 141 mg., *i.e.* by about 30 %. In the same interval the absolute strength rose from 18.5 kg. to 38.2 kg., *i.e.* about 100 % (Fig. 9). Despite a considerable reduction in the ash weight there was a strong increase in the absolute strength of the callus. The cause of this rise should be sought in the reorganization of the callus occurring during the healing process.

The correlation found between the absolute tensile strength and the ash weight of the B-parts on day 10 can be explained by the fact that the reorganization of the callus at this time is not yet so advanced as to exert any dominating effect on the healing of the fracture.

It is apparent from Fig. 17 that the mineral density of the callus from day 30 to day 60 increased from about 60 % to 70 % of normal. During the same period the specific strength rose from 0.68 kg./mm.^{2} to 2.44 kg./mm.^{2} (Fig. 10). At the same time as the mineral density increased by about 10 %, the specific strength rose by about 250 %. The reorganization of the callus thus seems to be of importance also for the rapid increase of the specific strength.

In contrast to what was found by BOHR (1955), it was not possible to demonstrate any relationship between the absolute strength and the ash weight of the A-parts — which consisted of the lower meta-epiphysis. This might be explained by the assumption that the variation in the degree of healing of the fractures in the different experimental groups in the present experiments was much smaller than in BOHR's experiments, in which the fractures were not fixed. As in BOHR's experiments no correlation was found between the absolute strength and the radioactivity in the region of the fracture. This is explained by the fact that the activity measured does not give any information on the amount of bone formed but only on the rate at which new bone is formed.

Discussion of healing of fracture in the nailed bones

It is clear from Fig. 11 that the callus formation in the nailed bones followed the same pattern as in the unnailed bones, but that the cross sectional area on the 20th and 30th days was about 50 % and 25 %, respectively, less than in the unnailed bones. This finding is in agreement with observations made by previous investigators in experiments in which the amount of callus was judged radiographically (TRUETA & CAVADIAS 1955, FITTS Jr. et al. 1949, GALUZZI & GIANELLI 1953). All of these research workers also found the callus to form somewhat earlier in nailed bones. This could not be confirmed in the present experiments.

While the amount of endosteal callus in unnailed bones is rapidly decreased by resorption, in nailed bones (Fig. 12) the amount of endosteal callus, as judged from the cross sectional area of the marrow (+ nail cavity) remained unchanged from the beginning of the experimental period until about the 60th day. Not until after the 60th day did the area of the marrow increase to reach normal value about the 70th day. The reorganization of the endosteal callus is thus retarded in the nailed fractures. This is also illustrated by the cavity formation. The cavities formed later and persisted longer in the nailed bones (See Table 1 and photographs in appendix). Delayed resorption of the endosteal callus of nailed bones has also been observed by GREISSMANN & REICH (1944) in experiments on dogs.

Also the formation of callus, as measured by the ash weight and the radioactivity in the B-parts (Figs. 13 and 14), was fundamentally the same for the nailed and unnailed bones, but both the ash weight and the activity (apart from the activity on the 10th day) during the initial active phase were less than the values noted for the control bones. After the 100th day the ash weight of the nailed fractures showed a tendency to increase, and on the 120th day it was significantly larger than that of the control bones. The activity after the 70th day accordingly showed a tendency to exceed that of the control bones, and on the 80th and 120th days it was higher than on the control side (Fig. 14).

Thus, in the last part of the experimental period the values found for ash weight and radioactivity of the nailed bones showed a tendency to exceed those of the control bones. This might reasonably in part be ascribed to the delayed reorganization of the endosteal callus.

In the end parts of the nailed bones the changes in ash weight and activity were more pronounced than in the control bones. The shape of the curves showing the changes in the end parts (see Figs. 15 and 16) were roughly parallel on both sides, which indicates that there was only a difference in degree of the changes.

The nail produced an increased accretion of bone salt in the ends of the radius from the very beginning of the experiment. This is in agreement with the histological changes observed in the periosteum, the cortex and the endosteum of nailed experimental fractures. Thus GRIESSMANN & REICH (1944), RAISCH (1943—44) and TRUETA & CAVADIAS (1955) observed the formation of periosteal new bone along the major part of the diaphysis in their experiments. This could not be observed on gross inspection of the experimental preparations in the present investigation, even though the callus in the nailed bones showed a tendency to extend further along the diaphysis. This can probably be ascribed to the fact that in the present experiments the animals were practically full-grown and, as shown by TRUETA & CAVADIAS (1955), for example, such animals show a less pronounced tendency to periosteal reaction than younger animals. TRUETA and CAVADIAS (1955) found that in unnailed fractured bones endosteal callus formed only in the proximaty of the fracture. Similar observations were made in the present investigation. In nailed bones, on the other hand, more or less continuous new-formed endosteal bone was seen along the entire length of the nail (GRIESSMANN & REICH 1944, RAISCH 1943—44). Similar changes have been described in human nailed fractures (ROTH 1945). In the present investigation such new-formed callus was also observed and was most pronounced on the radial side of the radius. The changes in the cortex proved to be necrosis in the inner part of the latter (TRUETA &

CAVADIAS 1955) or signs of reorganization in the cortex (GRIESSMANN & REICH 1944, HASCHE-KLÜNDER 1952). The reorganization of the cortex is a slow process. TRUETA & CAVADIAS (1955) found traces of necrosis in the cortex 6—8 months after the fracture.

The changes in the A- and C-parts of the nailed bones, like the changes in the callus during the first part of the experimental period, were characterized by a biphasic course. The initial phase with increasing activity and ash weight was followed by a decrease in both, indicating advancing reorganization of the new-formed bone tissue in the endosteum, periosteum and cortex. During the latter part of the experimental period the activity began to fall, as in the control groups, while the ash weight increased.

The values found for the absolute and specific tensile strength of the nailed fractures showed the same linear course found for the control side (Figs. 9 and 10). The cortical defects in the nailed bones began to occur at the same time as in the nailed bone and to the same extent (see Table 2). What was said previously about the significance of these defects for the absolute and specific tensile strength and for the determination of the area of the callus and marrow also holds for the nailed fractures.

The specific tensile strength found for nailed fractures between the 10th and 30th days was more than 50 % greater than that of the control fractures. No difference in absolute tensile strength was found between the two sides during this interval. From about the 40th day both the absolute and specific tensile strength of the nailed bone showed a tendency to be less than that of the unnailed bone and between the 50th and 70th days both the absolute and specific tensile strength were greater on the unnailed side. About the 60th day the absolute strength was about 30 % and the specific strength about 37 % greater.

The mineral density of the callus (given as ratio between the ash weight B and the area of the callus) between the 10th and 30th day was about 40 % greater on the nailed side than on the control side. The specific tensile strength as well as the mineral density of the callus expressed in the ratio given above is measure of the callus quality. Both showed that during the interval between the 10th and 30th days the callus was of better quality on the nailed side. The higher density of the callus found in the nailed fractures agreed with the finding of TRUETA & CAVADIAS (1955) and FITTS Jr. et al. (1949) who radiographically observed a more advanced filling of the fracture space on the nailed side. No difference was found in the absolute tensile strength between the callus on either side. This can be explained by the fact that about the 20th day the cross sectional area was about 50 % greater on the unnailed than on the nailed side.

In the interval between the 50th and 70th days there was no significant difference in the mineral density of the callus on either side, and no difference was found between the cross sectional areas of the callus. Nevertheless the absolute and specific tensile strength of the unnailed bones were found to be greater. This difference in strength coincided in time with a marked reduction of the endosteal callus in the nailed bone (see Fig. 12), and it may be ascribed in part to the delayed reorganization of the latter. After the 70th day no difference was found, but the absolute strength of the nailed bone tended to be less than that of the unnailed bone throughout the rest of the experimental period. This tendency was not so pronounced for the specific tensile strength, however. The difference in strength was so great and the endosteal callus represents such a small portion of the total mass of callus that it is reasonable to assume, that a delayed reorganization in the endosteal callus alone cannot by itself explain the differences in strength.

If the reduction in the amount of callus is taken as a measure of the rate at which the callus is reorganized, the reduction in the mass of callus on the unnailed side between the 20th and 60th days was about 55 % while the corresponding reduction on the nailed side was about 35 %. It therefore appears reasonable to assume that a delayed reorganization of the callus on the nailed side not only occurred in the endosteal callus, but also in other components of the callus mass.

Since the fractures were identical, it would appear that the difference in the amount of callus and in tensile strength between the nailed and the unnailed bones were due to the nail *per se*. The actual mechanism involved is obscure.

According to KÜNTSCHER, the nail serves not only to give good fixation of the fracture but also mechanically stimulates fracture callus formation so that the callus formed is more abundant (KÜNTSCHER 1955, 1958). The results of experimental nailing showed, however, that the fracture callus formed in less amount (FITTS Jr. et al. 1949, GALUZZI & GIANELLI 1953, TRUETA & CAVADIAS 1955). This was confirmed by the present investigation. It may thus be excluded that the nail has any stimulating effect on the amount of callus formed and some authors, such as FITTS Jr. et al. (1949), GRIESSMANN & REICH (1944), RAISCH (1943—44), also believed that the effect on the callus formation should be ascribed entirely to the good fixation of the fracture secured by the nail.

KÜNTSCHER (1958) does not believe the effect of the nail on the marrow circulation to have any appreciable influence on fracture healing. TRUETA & CAVADIAS (1955), on the other hand, feels that the injuries to the marrow vessels by the nail can explain its effect on the callus formation.

However, the vascular lesions alone do not seem to be able to explain

the effect of the nail. In fracture callus in nailed bones there is histologically a regularly radial arrangement of new-formed bone trabeculae, while in the callus of the control fractures these trabeculae are arranged irregularly. (KÜNTSCHER 1957, RAISCH 1943—44, GRIESSMANN & REICH 1944.) Experiments have also shown that in contrast to unnailed bones, the ossification in nailed bones occurs via pure fibrous callus without any intermediate cartilaginous phase (TRUETA & CAVADIAS 1955, RAISCH 1943—44, GRIESSMANN & REICH 1944). This course in the ossification cannot, however, be ascribed to any specific effect of the nail. A similar callus formation has been observed in unnailed fractures with ideal fixation (KAPSHAMMER 1898, MATZEN 1954), while even in nailed fractures with poor fixation cartilaginous callus formation has been reported (COURTOIS-SUFFIT 1952, GRANJON & SOEUR 1955).

According to PRITCHARD & RUZICKA (1950), the course of the ossification of the callus is determined by the vascularization of the latter. Cartilagious callus forms when vascularization is poor. PRITCHARD & RUZICKA claim that the significance of fracture fixation consists mainly in securing good conditions for vascularisation of the callus. It would therefore appear reasonable to suppose that the higher specific tensile strength found in nailed bones on about the 20th day was due mainly to the better fracture fixation secured by the nail. The smaller amount of callus found at that time in the nailed bones might also be explained by better fracture fixation, for clinical experience has shown that the amount of callus formed varies with the degree of fixation of the fracture.

The lower absolute and specific tensile strength found for the nailed bones on about the 60th day may most likely be ascribed to the slower reorganization observed in the callus. That this slower reorganization should be related to vascular changes caused by the nail appears less likely, because TRUETA & CAVADIAS (1955) found the vascularization of the callus in the nailed radii of the rabbit to be the same as for the control fractures. No satisfactory explanation can be offered for the delay, but it might possibly be due to mechanical factors. PAUWELS (1946), for example, claims that just as the shape and structure of bones is to a certain extent determined by mechanical forces (Wolff's law), the reorganization of the callus is due *inter alia* to the bending and traction forces which influence the callus during the healing process. In accordance with this it would not be unreasonable to imagine that the nail by its presence prevents or reduces the effect of these forces and that the reorganization of the callus in nailed bones therefore proceeds at a slower rate.

As mentioned, when loaded in the traction apparatus, 4 of the bones (3 in the 100-day group and 1 in the 120-day group) fractured outside the

site of osteotomy. All of these bones had been nailed and healed without defects. Though these findings do not allow of any valid conclusions, they are of interest in the light of the necrosis demonstrated by others in the inner cortex of the diaphysis of nailed bones. It cannot be excluded that this might reduce the strength of the cortex outside the site of the fracture during reorganization of the necrotic tissue. The decrease in the tensile strength compared with normal was on the average 30—35 %. Owing to the enormous strength of the bone in relation to the strain and stress to which it is normally subjected (PAUWELS 1946), this reduction in the tensile strength is of theoretic interest rather than of practical importance.

The decrease in the total strength of the nailed bones between the 50th and 70th days was about 25 % in relation to that of the unnailed bones. At first glance this difference seems considerable. Clinically, it appears in a relatively late stage of fracture healing and is only of temporary nature. With reference to what was said previously about clinical healing and the order of the physiological load, the decrease in the total strength of the callus cannot be of any appreciable importance.

The possible effect of early extraction of the nail on the decrease in the tensile strength was not studied in the present investigation. To achieve any such effect, the nail should be extracted as early as possible, *i.e.* about the 20th to 30th days, when the fracture is clinically healed.

In clinical practice the time of extraction is dictated by the radiographical appearance of the fracture and clinical experience. LAURITZEN (1949) extracts nails from humerus fractures after 3—5 months and from tibia fractures aftes 6—12 months. BÖHLER (1948) gave 6—7 months as a suitable time for extraction of nails. Clinical healing of a fracture, as shown in the present investigation, occurs fairly early in the course of healing, and the extraction, as shown above, is done so early that it should be possible to avoid or reduce the undesirable effect of the nail.

SUMMARY

The course of healing of unnailed and identical, nailed fractures in rabbits was studied from the 10th to the 120th day following open osteotomy of the radius on both sides. The absolute tensile strength of the callus was determined in a traction apparatus. The transverse area of the callus at the site of osteotomy was measured by planimetry of reproductions on photographic paper. Hence, the specific tensile strength of the callus was calculated. Most of the animals were given Sr^{85} 4 days before they were killed. Determinations were made of the ash weights and of the radioactivity in the region of the fracture and in the ends of the bone. The ratio between the ash weight in the region of the fracture and the transverse area of the callus was calculated to give the mineral density of the callus.

The following observations were made:

1. Fixation of the fracture on the nailed side was better than on the contralateral side.

2. During the course of healing gross cavities of different shape, size and number developed in the nailed and in the unnailed bones. The cavities appeared later and persisted longer in the nailed bones.

3. During the last third of the experimental period both the radius and the ulna in an increasing number of animals showed a cortical defect at the level of the osteotomy. At this level a connection arose between the marrow cavities of the two bones.

4. The periosteal callus tended to spread longer along the diaphysis on the nailed side than on the unnailed side. On the unnailed side endosteal callus formed only in the region of the osteotomy, but more or less continuously along the entire length of the nail on the other side.

5. The absolute as well as the specific tensile strength of the nailed and of the unnailed bones showed an almost even increase throughout most of the experimental period, but the increase of the absolute tensile strength was more rapid. While the absolute tensile strength of the unnailed bone was about 4 % of normal on the 10th day, about 20 % on the 30th day, and 50 % of normal on the 80th day, the corresponding values for the specific tensile strength were 1 %, 6 % and 20 %, respectively. The specific tensile strength on the nailed side was greatest about the 20th day, while the absolute tensile strength at that time was the same on both sides. After

the 40th day the absolute as well as the specific tensile strength of the unnailed bones showed a tendency to increase more than that of the nailed bones, and the absolute as well as the specific tensile strength of the unnailed bones was greatest about the 60th day. This difference afterwards disappeared.

6. The biological reaction of the bone in the region of the fracture, as reflected in the transverse area of the callus, the ash weight and the activity, showed largely the same course. After an initial increase with a maximum about the 20th day (for ash weight about the 30th day) a fall occurred, which was initially steep. From about the 50th to 60th day the fall was slower, but at the end of the experimental period the transverse area as well as the ash weight and the activity were still increased in relation to normal.

During the initial active phase the transverse area of the callus, the ash weight and the activity were greater on the unnailed side. When the callus was maximal the transverse area of the unnailed side was about 4 times, and on the nailed side about 3 times, greater than normal, the ash weight was increased by about 85 % and 65 %, respectively, and the activity was 8.3 and 5.8 times, respectively, greater than normal. No difference was found between the two sides after the 40th—50th day. At the end of the experimental period the transverse area of the radius on both sides was twice normal, the ash weight was increased by about 25 %, and the activity was almost twice normal. The reorganization processes in the callus, as measured by the variation in the transverse area of the callus, the ash weight and the activity in the region of the fracture thus showed a more rapid course on the unnailed side.

The amount of endosteal callus, as measured by the area of the bone marrow, showed largely the same variation as the total mass of callus. On the 20th day the marrow cavity on the unnailed side was filled with callus. On the nailed side the amount of endosteal callus was less. While the amount of endosteal callus on the unnailed side decreased rapidly so that the marrow cavity on the 60th day was of normal size, the amount of endosteal callus on the nailed side was unchanged in amount from the beginning of the experimental period until the 60th day. Not until the 70th day was the marrow cavity of normal size. At the end of the experimental period the marrow cavity was larger than normal on the unnailed side, while on the nailed side it tended to be larger.

7. The mineral density of the callus on the nailed and on the unnailed side increased from the beginning of the experimental period. The increase was initially relatively rapid but afterwards slower. On the 20th day it was about 55 % of normal on the nailed side and about 40 % of normal on the

unnailed side; afterwards no difference in mineral density was found between the two sides. At the end of the experimental period the mineral density of the callus was about 75 % of normal.

8. The end parts of the radius on the unnailed side showed changes which were most pronounced in the distal meta-epiphyses. At the beginning of the experimental period the ash weight on the unnailed side had decreased to about 85 % of normal and at the same time the activity showed no deviation from normal. After an increase to normal the ash weight increased further and from the 80th day it was above normal, while after an increase to above normal the activity again fell, and from the 80th day it was below normal. During the latter part of the experimental period similar changes were demonstrated in the proximal end part of the radius, while no variation from normal was found in that part during the first two thirds of the investigation period.

The changes in the ash weight and activity of the end parts of the nailed and unnailed bones were parallel throughout the experimental period, but both the ash weight and the activity were greater on the unnailed side.

9. From the 60th day and during the rest of the experimental period both the unnailed and the nailed bones showed a correlation between the absolute tensile strength and the ash weight of the fracture region. In the first half of the experimental period no such correlation was found for the unnailed side (apart from the 10th day) or the nailed side (apart from the 10th and 20th days).

These observations suggest the following conclusions:

1. During healing of a fracture the absolute tensile strength of the callus increases more rapidly than the specific tensile strength.

2. Definitive healing of a fracture requires a long time.

3. Changes in the mineral metabolism are not confined to the region of the fracture.

4. Not until a relatively late stage of healing does a correlation appear between the absolute tensile strength of the callus and the ash weight in the region of the fracture resembling that seen in intact cortical bone.

5. The course of healing is largely the same in nailed and unnailed bones, though nailing causes an increased mineral metabolism in the end parts of the nailed bones.

6. The amount of callus formed is less on the nailed side.

7. In the initial stage of healing the specific tensile strength and the mineral density of the callus are greater on the nailed side, while the absolute tensile strength is the same on both sides.

8. In the later stage of healing the absolute and the specific tensile strength are greater on the unnailed side.

9. The greater specific strength and mineral density of the nailed bones in the initial stage of healing is ascribed to the better fixation of the fractures. The smaller absolute and specific strength of the nailed bones found later appears to be related to the slower reorganization of the callus found in these bones.

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APPENDIX

Table 1. *Survey of material*

age of fracture in days	No. of animals	wt. at op. in kg.			wt. at death in kg.			length of unnailed radius in cm.			length of nailed radius in cm.		
		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean
10	24	2.4	0.2	0.04	2.3	0.2	0.05	6.6	0.2	0.05	6.6	0.2	0.05
20	28	2.5	0.3	0.06	2.3	0.3	0.06	6.5	0.3	0.06	6.5	0.3	0.06
30	24	2.5	0.3	0.05	2.7	0.3	0.05	6.7	0.2	0.05	6.7	0.2	0.05
40	24	2.5	0.4	0.08	2.5	0.3	0.07	6.6	0.2	0.04	6.6	0.2	0.04
50	24	2.3	0.1	0.03	2.4	0.2	0.04	6.6	0.2	0.04	6.6	0.2	0.04
60	24	2.2	0.1	0.03	2.4	0.3	0.05	6.6	0.2	0.05	6.6	0.2	0.05
70	24	2.3	0.1	0.02	2.5	0.3	0.05	6.7	0.2	0.04	6.7	0.2	0.05
80	24	2.4	0.2	0.03	2.6	0.2	0.03	6.7	0.2	0.05	6.7	0.2	0.04
100	24	2.2	0.1	0.03	2.6	0.3	0.06	6.8	0.2	0.03	6.7	0.2	0.04
120	24	2.2	0.2	0.03	2.6	0.3	0.06	6.8	0.2	0.05	6.8	0.2	0.05
mean normal values	32	2.5	0.2	0.03				6.6	0.2	0.04	6.6	0.2	0.04

age of fracture in days	No. of animals	distance of fracture from distal end of radius in cm. unnailed			distance of fracture from distal end of radius in cm. nailed			cross section of nail in mm^2.			length of nail in cm.		
		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean
10	24	3.1	0.5	0.10	3.1	0.4	0.08	1.4	0.3	0.07	5.1	0.6	0.12
20	28	3.2	0.5	0.09	3.2	0.6	0.10	1.6	0.3	0.05	5.1	0.8	0.15
30	24	3.3	0.4	0.08	3.3	0.4	0.08	1.4	0.3	0.06	5.5	0.9	0.17
40	24	3.2	0.5	0.10	3.2	0.5	0.11	1.5	0.3	0.05	5.1	0.7	0.14
50	24	3.0	0.3	0.05	3.0	0.3	0.06	1.5	0.3	0.07	5.0	0.4	0.08
60	24	3.0	0.3	0.05	3.0	0.3	0.05	1.4	0.3	0.07	4.9	0.5	0.09
70	24	3.1	0.3	0.05	3.0	0.3	0.06	1.3	0.3	0.05	5.0	0.6	0.12
80	24	3.1	0.3	0.06	3.0	0.3	0.06	1.5	0.3	0.06	5.0	0.5	0.10
100	24	3.1	0.2	0.05	3.1	0.2	0.05	1.7	0.2	0.04	4.8	0.3	0.06
120	24	3.1	0.3	0.05	3.1	0.2	0.04	1.5	0.4	0.07	4.8	0.3	0.06

Table 2 A. *Mean normal values.*

animals used for determination of normal values for strength													
No. of animals	wt. in kg.			No. of bones	length of radius in cm.			distance of fracture from distal end of radius in cm.			cross section of marrow in mm².		
	mean	s. d.	error of mean		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean
16	2.5	0.1	0.03	16 right	6.6	0.2	0.05	3.1	1.0	0.25	3.1	1.3	0.11
				16 left	6.6	0.2	0.05	3.1	0.8	0.21	2.6	0.9	0.24
				32(r.+l.)				3.1	0.9	0.16	2.9	1.2	0.21

Continued

animals used for determination of normal values for strength													
No. of animals	wt. in kg.			No of bones	cross section of bone in mm².			absolute tensile strength in kg.			specific tensile strength in kg/mm².		
	mean	s. d.	error of mean		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean
16	2.5	0.1	0.03	16 right	7.7	0.7	0.17	84.4	13.0	3.26	11.01	1.55	0.387
				16 left	7.5[1]	1.0	0.25	83.9	13.9	3.48	11.30[1]	1.45	0.376
				32 (r.+l.)	7.6	0.8	0.15	84.2	13.3	2.35	11.16	1.51	0.272

[1]) mean value for 15 bones only, one bone splintered and therefore excluded.

Table 2 B. *Mean normal values*

Continued

animals used for determination of normal values for cross section of bone and marrow													
No. of animals	wt. in kg.			No. of bones	length of radius in cm.			cross section of marrow in mm^2.			cross section of bone in mm^2.		
	mean	s. d.	error of mean		mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean
16	2.4	0.2	0.04	16 right	6.6	0.2	0.06	3.2	0.9	0.22	8.5	1.2	0.29
				16 left	6.6	0.2	0.06	3.3	0.9	0.23	8.6	1.2	0.31
				32(r.+1.)				3.3	0.9	0.16	8.6	1.2	0.21

Continued

animals used for determination of normal values of ash weight and activity																		
No. of bones	wt. of bone ash in mg.									Sr^{85} activity in % of dose $\times 10^2$								
	A-part			B-part			C-part			A-part			B-part			C-part		
	mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean	mean	s. d.	error of mean
32 r.	159	22	3.9	105	13	2.3	248	46	8.0	11.3	5.9	1.04	2.2	0.9	0.15	5.1	2.0	0.35
32 l.	161	21	3.8	108	15	2.6	248	46	8.1	11.4	5.9	1.04	2.2	0.8	0.15	5.1	2.0	0.35
64 (r.+1.)	160	21	2.8	107	14	1.8	248	45	5.6	11.4	5.8	0.73	2.2	0.8	0.10	5.1	2.0	0.24

Table 3. *Values noted for 10 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
103	0	2.9	23.1	16.8	2.3	1.2	0.10	0.07
104	0	2.5	20.5	16.6	3.5	3.5	0.17	0.21
105	0	3.1	26.5	33.4	2.0	3.2	0.08	0.10
106	0	2.5	24.5	21.6	2.7	2.7	0.11	0.13
110	0	2.6	22.3	19.0	1.8	—	0.08	— [1]
111	2.4	2.7	39.8	26.5	3.7	2.7	0.09	0.10
112	0	1.8	18.6	21.8	2.3	1.8	0.12	0.08
113	0.4	4.1	25.0	19.4	3.7	—	0.15	— [1]
160	0	2.6	20.7	22.5	3.5	3.2	0.17	0.14
161	0	2.6	23.1	22.7	3.2	4.0	0.14	0.18
162	0	2.6	26.1	17.1	4.0	4.0	0.15	0.23
163	0	1.0	33.3	26.6	5.5	4.2	0.17	0.16
240	0	2.1	25.8	24.7	2.2	5.0	0.09	0.20
241	0	3.7	33.0	35.8	3.0	2.5	0.09	0.07
242	3.3	3.2	24.4	17.7	2.2	2.0	0.09	0.11
243	0	2.2	30.8	35.1	2.5	2.5	0.08	0.07
244	0	2.1	31.3	18.2	3.5	3.2	0.11	0.18
32	0.4	0.5	24.6	27.8	4.2	2.7	0.17	0.10
33	0	0.5	20.2	30.0	2.3	3.5	0.11	0.12
34	0.1	1.6	21.5	16.4	4.5	4.5	0.21	0.27
35	2.1	3.0	18.8	15.1	2.0	2.0	0.11	0.14
36	0.7	1.4	25.8	20.2	4.2	2.3	0.16	0.11
37	0.3	1.1	13.6	14.9	3.7	3.0	0.27	0.20
38	0	0.6	26.4	26.9	3.5	4.2	0.13	0.16
mean	0.4	2.2	25.0	22.8	3.2	3.1	0.13	0.14
s. d.	0.9	1.0	5.6	6.3	1.0	1.0	0.05	0.06
error of mean	0.18	0.20	1.15	1.28	0.20	0.21	0.010	0.012

[1]) Fractured during preparation of specimen.

Table 4. *Values noted for 20 day old fractures.*

animal No.	cross section of marrow in mm^2.		cross section of callus in mm^2.		absolute tensile strength in kg.		specific tensile strength in kg/mm^2.	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
114	0	2.3	36.2	19.8	6.7	9.5	0.19	0.48
121	0	1.5	23.5	26.8	—	7.2	— [1]	0.27
122	0	1.1	42.1	25.9	7.5	3.5	0.18	0.14
123	0	3.6	36.5	29.2	7.0	8.5	0.19	0.29
152	0	4.1	32.5	23.2	7.2	8.8	0.22	0.38
153	0	4.1	46.4	25.8	7.2	9.8	0.16	0.38
154	0	1.5	32.6	18.8	7.2	9.8	0.22	0.52
155	0	4.6	34.4	20.4	8.8	7.2	0.26	0.35
204	0	4.3	31.8	19.3	5.4	—	0.17	— [1]
205	0	1.4	38.2	25.6	14.2	12.4	0.37	0.48
230	0	2.3	49.9	40.3	8.0	15.0	0.16	0.37
231	0	2.9	42.7	25.2	18.6	16.8	0.44	0.67
232	0	1.5	39.5	22.8	5.4	10.6	0.14	0.46
233	0	1.6	35.4	30.2	8.0	5.4	0.23	0.18
234	0	2.1	45.4	43.9	8.8	11.4	0.19	0.26
235	0	3.0	30.3	19.2	10.6	8.0	0.35	0.42
236	0	1.5	42.5	20.0	6.2	9.8	0.15	0.49
237	0	2.5	38.0	18.6	11.4	11.4	0.30	0.61
238	0	2.9	31.9	11.9	15.0	5.4	0.47	0.45
239	0	4.1	59.6	26.9	9.8	5.4	0.16	0.20
11	0	1.5	27.4	33.4	6.2	7.0	0.22	0.21
12	0	2.4	31.7	21.6	5.5	4.0	0.17	0.19
13	0	2.0	36.6	24.8	6.5	6.2	0.18	0.24
14	0	1.2	25.3	22.1	3.2	5.7	0.13	0.26
15	0	0.8	25.4	17.7	7.0	5.7	0.28	0.32
16	0	1.5	24.3	29.1	4.2	4.2	0.17	0.14
17	0	1.4	35.3	22.4	7.0	5.7	0.20	0.25
18	0	1.5	52.0	32.5	6.7	4.0	0.13	0.12
mean	0	2.3	36.7	24.9	8.1	8.1	0.22	0.34
s. d.	0	1.1	8.7	6.8	3.4	3.3	0.09	0.15
error of mean	0	0.21	1.64	1.29	0.65	0.63	0.017	0.029

[1]) Fractured during preparation of specimen.

Table. 5 *Values noted for 30 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
100	0	3.6	25.3	25.3	15.0	16.0	0.59	0.63
101	0	2.4	34.4	21.2	22.0	15.0	0.64	0.71
102	0	4.2	27.7	26.8	15.0	16.0	0.54	0.60
107	0	1.7	27.2	20.8	20.0	9.0	0.74	0.43[4]
108	0	2.3	29.4	26.1	16.0	20.0	0.54	0.77[4]
109	2.1	2.2	26.2	22.5	39.6	22.0	1.51	0.98[4]
136	1.8	2.4	21.5	17.8	23.0	30.0	1.07	1.69
137	1.7	1.8	28.8	21.1	19.5	13.2	0.68	0.63
138	0	2.2	22.9	26.2	24.6	9.8	1.07	0.37
139	0	2.8	23.8	19.3	12.4	6.2	0.52	0.32
206	0	3.6	31.2	21.2	11.5	21.2	0.37	1.00
207	0	1.4	36.9	23.1	15.0	23.0	0.41	1.00
208	0	3.2	30.8	17.9	9.8	11.5	0.32	0.64
209	0	2.6	42.5	23.5	8.8	24.6	0.21	1.05
265	0	2.5	22.5	13.1	30.0	20.2	1.33	1.54
31	0	2.1	22.8	25.4	13.2	19.5	0.58	0.77
39	0	2.3	27.5	26.0	16.0	13.2	0.58	0.51
40	0	2.2	30.0	27.5	16.0	11.5	0.53	0.42
41	0	1.0	29.3	17.7	24.6	18.6	0.84	1.05
42	0	0.9	25.1	27.4	21.2	21.2	0.84	0.77
43	0.3	1.8	27.0	27.8	29.0	19.5	1.07	0.70
44	0	0.7	29.6	21.3	7.2	19.5	0.24	0.92
45	0	2.7	38.2	34.3	15.0	18.6	0.39	0.54
47	0	3.0	27.0	18.6	19.5	11.5	0.72	0.62
mean	0.2	2.3	28.7	23.0	18.5	17.1	0.68	0.78
s. d.	0.6	0.9	5.2	4.6	7.4	5.6	0.33	0.33
error of mean	0.13	0.17	1.06	0.93	1.53	1.14	0.068	0.069

[4]) Bones with corrosion of nail.

Table 6. *Values noted for 40 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
84	1.1	1.8	13.1	16.2	20.0	33.0	1.53	2.04
85	2.7	3.7	20.3	14.7	28.0	9.5	1.38	0.65
87	1.9	2.9	25.2	15.6	16.0	9.5	0.63	0.61
88	1.1	2.0	18.1	17.8	33.6	36.0	1.82	2.02
89	2.3	4.8	20.8	26.2	12.0	10.5	0.58	0.40
91	2.0	3.2	33.5	16.1	28.0	19.0	0.84	1.18
92	1.7	2.1	25.6	20.9	38.5	26.5	1.50	1.27
93	2.1	2.6	23.6	24.8	33.0	29.5	1.40	1.19[4]
94	1.5	2.4	20.8	16.6	30.5	30.5	1.47	1.84[4]
266	0	3.1	22.4	16.1	25.0	10.5	1.12	0.65
267	2.5	2.6	22.9	16.5	28.0	29.5	1.22	1.79
268	1.1	2.0	20.5	22.7	33.0	25.0	1.61	1.10
269	1.7	1.9	17.3	18.1	41.0	25.0	2.37	1.38
270	1.7	1.8	21.7	24.5	17.5	24.0	0.81	0.98
271	4.4	2.1	21.9	21.0	42.5	29.5	1.94	1.40
272	0	2.7	24.1	21.1	20.0	24.0	0.83	1.14
21	0	1.9	27.1	25.4	22.5	12.0	0.83	0.47
24	0	1.2	28.4	28.2	22.5	21.0	0.79	0.74
25	0	1.9	21.5	14.0	16.0	12.0	0.74	0.86
26	0	1.7	26.6	15.2	22.5	22.5	0.85	1.48
27	1.5	1.9	22.4	16.7	19.0	28.0	0.85	1.68
28	0	1.0	23.0	30.8	30.5	20.0	1.33	0.65
29	0.7	1.2	29.5	32.2	16.0	26.5	0.54	0.82
30	2.1	1.9	36.5	21.1	13.5	17.5	0.37	0.83
mean	1.3	2.3	23.6	20.5	25.4	22.1	1.14	1.13
s. d.	1.1	0.8	5.0	5.3	8.7	8.0	0.50	0.49
error of mean	0.23	0.17	1.02	1.08	1.77	1.63	0.102	0.099

[4]) Bones with corrosion of nail.

Table 7. *Values noted for 50 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
95	4.1	3.4	24.4	26.2	30.0	12.5	1.23	0.48[4]
96	2.9	2.0	14.9	16.7	18.0	23.0	1.21	1.38
97	3.6	2.5	14.9	17.2	48.0	21.5	3.22	1.25
98	3.0	2.2	19.4	19.9	46.0	26.5	2.37	1.33
124	1.5	3.7	18.9	18.4	33.5	32.0	1.77	1.74
125	3.8	2.5	18.9	17.6	49.5	33.5	2.62	1.90
126	1.8	2.6	17.6	20.0	50.0	39.0	2.84	1.95
127	1.0	1.8	25.8	16.1	28.5	23.0	1.10	1.43
184	0.8	2.7	25.1	20.5	21.5	39.0	0.86	1.90
185	2.1	1.2	20.4	17.2	33.5	26.5	1.64	1.54
186	1.0	2.1	22.8	16.2	28.5	17.5	1.25	1.08
187	0	2.9	32.0	17.6	16.5	25.0	0.52	1.42
188	2.1	1.4	17.3	16.6	23.0	30.0	1.33	1.81
189	2.0	2.7	23.8	18.4	56.5	30.0	2.37	1.63
190	3.1	3.1	17.8	20.5	44.0	39.0	2.47	1.90
191	3.1	2.3	23.5	19.3	21.5	33.5	0.91	1.74
76	2.5	1.9	19.2	20.7	44.0	25.0	2.29	1.21
77	3.2	2.8	19.6	14.4	28.5	32.0	1.45	2.22[4]
78	1.7	1.1	13.7	14.6	32.0	32.0	2.34	2.19
79	1.8	0.7	26.0	15.6	41.0	13.0	1.58	0.83
80	1.3	1.2	17.0	12.1	37.5	28.5	2.21	2.36
81	0.9	1.3	23.7	15.2	30.0	20.0	1.27	1.32
82	1.9	1.2	16.0	18.3	24.0	18.0	1.50	0.98
83	2.6	1.7	20.4	20.2	41.0	20.0	2.01	0.99
mean	2.2	2.1	20.5	17.9	34.4	26.7	1.77	1.52
s. d.	1.1	0.8	4.4	2.8	11.2	7.7	0.70	0.47
error of mean	0.22	0.16	0.89	0.58	2.28	1.57	0.142	0.096

[4]) Bones with corrosion of nail.

Table 8. *Values noted for 60 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
116	1.8	1.0	23.1	14.6	44.5	37.5	1.93	2.57[4]
117	3.8	1.4	13.7	20.6	51.5	28.5	3.76	1.38
118	4.2	0.9	16.0	16.0	55.0	30.0	3.44	1.88
119	2.8	2.2	20.3	15.1	35.5	28.5	1.75	1.89
128	2.1	3.6	24.8	21.2	25.0	19.5	1.00	0.92[4]
130	1.5	2.0	22.8	23.3	56.5	56.5	2.48	2.42[4]
131	3.5	3.0	23.1	22.3	55.0	37.5	2.38	1.68
246	1.2	2.3	13.3	14.5	30.0	30.0	2.26	2.07
247	2.8	1.2	12.5	11.8	39.0	25.0	3.12	2.12
248	1.6	1.5	9.5	10.0	17.5	7.0	1.84	0.70
251	7.2	3.5	12.1	16.7	26.5	14.5	2.19	0.87
252	4.1	3.6	13.1	12.4	60.0	37.5	4.58	3.02
253	3.8	3.1	15.4	16.5	35.5	48.0	2.31	2.90
254	2.2	1.2	13.9	14.4	19.5	16.0	1.40	1.11
255	4.8	3.7	11.0	13.1	28.5	28.5	2.59	2.18
280	3.0	3.6	29.8	17.1	39.0	19.5	1.31	1.14
281	4.1	4.0	15.4	17.5	46.0	30.0	2.99	1.71
282	5.1	4.7	11.5	14.5	42.5	23.0	3.70	1.59
67	2.9	1.4	14.6	19.1	30.0	30.0	2.05	1.57
68	3.6	1.3	18.2	20.0	60.0	44.5	3.30	2.23
70	2.9	1.1	17.0	20.5	28.5	28.5	1.68	1.39
71	5.4	3.4	14.2	14.4	28.0	15.0	1.97	1.04
74	1.4	1.4	14.1	12.4	32.0	32.0	2.27	2.58
75	2.0	1.2	14.6	16.2	32.0	30.0	2.20	1.85[4]
mean	3.2	2.3	16.4	16.4	38.2	29.0	2.44	1.78
s. d.	1.5	1.2	5.1	3.5	12.8	11.2	0.86	0.65
error of mean	0.30	0.24	1.03	0.72	2.61	2.28	0.176	0.132

[4]) Bones with corrosion of nail.

Table 9. *Values noted for 70 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
132	2.0	1.3	19.5	17.1	41.0	56.5	2.11	3.32
133	3.3	1.8	22.8	21.7	30.0	49.5	1.33	2.29
134	3.2	2.9	22.1	17.2	53.0	32.0	2.44	1.85
135	3.3	2.7	18.8	20.5	49.5	60.0	2.67	2.96
140	6.9	4.0	19.1	15.8	44.5	30.0	2.36	1.90
141	3.9	3.8	18.4	15.4	44.5	44.5	2.41	2.93
142	4.7	6.9	20.3	17.1	44.5	51.5	2.19	3.00
143	5.3	3.6	22.6	17.0	55.0	26.5	2.44	1.56
256	5.9	5.6	21.4	12.5	35.5	26.5	1.66	2.12
257	5.1	2.1	12.5	14.8	32.0	19.5	2.56[2]	1.32[2]
258	3.4	3.5	11.1	11.1	26.5	23.0	2.39	2.07
259	5.1	3.5	9.7	11.7	42.5	32.0	4.38	2.74[2]
260	5.6	4.5	18.1	14.3	44.5	44.5	2.46	3.11
262	4.5	4.5	14.0	12.1	25.0	32.0	1.79	2.64
263	3.9	2.8	13.9	15.9	42.5	32.0	3.06	2.01
264	1.9	2.8	13.4	12.4	37.0	39.0	2.76[2]	3.15
283	3.9	1.8	13.0	17.1	46.0	32.0	3.54	1.87
58	6.3	1.5	14.1	20.8	32.0	32.0	2.28	1.54
59	9.2	3.2	19.0	15.8	35.0	—	1.84	— [1]
60	4.2	9.5	25.5	13.9	34.0	24.0	1.33	1.75
61	6.2	1.8	18.5	16.6	39.0	34.0	2.09	2.07
62	4.5	1.5	14.6	15.6	34.0	30.0	2.31	1.91
65	2.5	3.7	13.0	11.4	30.0	28.0	2.33	2.48
66	4.6	1.5	17.6	20.6	45.0	60.0	2.57	2.96
mean	4.6	3.4	17.2	15.8	39.3	36.5	2.39	2.33
s. d.	1.6	1.9	4.2	3.1	8.1	12.0	0.65	0.60
error of mean	0.33	0.38	0.85	0.62	1.64	2.49	0.132	0.124

[1]) Fractured during preparation of specimen.

[2]) Bones with cortical defect.

Table 10. *Values noted for 80 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
144	4.5	2.3	21.4	16.6	53.0	41.0	2.48	2.47
145	5.2	1.7	18.6	26.8	30.0	39.0	1.61	1.46
146	3.6	1.6	18.7	16.1	46.0	48.0	2.46	2.98
147	2.9	2.6	15.8	14.6	41.0	33.5	2.59	2.29
192	3.8	4.2	17.2	15.2	54.0	—	3.14	— [1]
193	4.4	4.0	18.6	18.9	41.0	—	2.20	— [1]
194	5.0	3.5	21.4	17.2	41.0	37.0	1.92	2.15
196	2.9	2.6	21.0	21.1	58.0	60.0	2.76	2.84
197	5.1	2.3	21.8	14.9	37.0	35.0	1.70[2]	2.35
198	4.6	3.0	25.0	20.5	52.0	48.0	2.08	2.34
199	5.0	4.1	14.9	19.0	20.0	52.0	1.34	2.74
200	4.2	5.6	13.8	21.5	41.0	41.0	2.97	1.91
202	4.6	1.5	17.7	17.4	37.0	52.0	2.o9	3.00
203	2.9	2.8	18.2	18.4	58.0	67.0	3.19	3.64
273	2.8	3.6	14.9	14.9	48.0	28.5	3.22	1.91
274	4.7	3.8	16.0	14.6	53.0	32.0	3.32[2]	2.19[2]
275	2.9	3.3	14.9	12.3	51.5	37.5	3.46	3.05
48	4.4	3.7	15.3	14.8	50.0	32.0	3.27	2.16
50	5.2	7.5	14.4	13.8	41.0	35.0	2.84	2.54
51	2.0	1.1	14.4	13.8	35.0	32.0	2.43	2.32
53	3.1	2.5	15.8	20.0	34.0	39.0	2.15[2]	1.95
54	4.7	1.4	12.9	15.5	26.0	30.0	2.02	1.94
56	3.2	1.7	14.0	12.8	39.0	26.0	2.79[2]	2.02
57	3.2	2.0	14.6	15.0	32.0	26.0	2.19	1.73
mean	4.0	3.0	17.1	16.9	42.4	39.6	2.51	2.36
s. d.	1.0	1.5	3.1	3.4	10.1	10.9	0.59	0.51
error of mean	0.19	0.30	0.64	0.69	2.07	2.31	0.121	0.109

[1]) Fractured during preparation of specimen.

[2]) Bones with cortical defect.

Table 11. *Values noted for 100 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
168	2.9	7.1	17.7	16.8	67.0	73.0	3.79[2]	4.34[2]
170	6.6	3.5	20.3	21.2	54.0	28.0	2.66[2]	1.32[2]
171	3.7	2.5	13.6	14.6	58.0	41.0	4.26[2]	2.81[2]
172	2.5	2.1	16.2	11.0	39.0	39.0	2.41[2]	3.55
173	2.8	5.2	17.6	14.6	43.0	32.0	2.44[2]	2.19
174	4.6	2.0	13.6	10.9	22.0	35.0	1.62[2]	3.21[2 4]
175	3.3	5.3	21.7	19.7	45.0	58.0	2.07[2]	2.94[4]
176	4.5	3.4	19.6	16.0	41.0	56.0	2.09[2]	3.50[2 4]
177	3.7	2.3	22.1	22.4	54.0	28.0	2.44[2]	1.25[2]
178	4.4	3.0 (5.7)	17.8	16.8(11.4)	43.0	48.0	2.42[2]	4.21[4]
179	6.7	4.5	18.7	17.8	48.0	71.0	2.57	4.00
180	2.8	1.6(2.9)	17.2	21.2(10.7)	35.0	60.0	2.03[2]	5.61[3]
181	4.5	3.4	10.5	11.3	78.0	58.0	7.43	5.13
182	5.5	5.1	21.0	20.5	75.0	56.0	3.57	2.73
183	4.8	2.9(6.0)	23.6	18.3(12.6)	43.0	63.0	1.82[2]	5.00[3]
222	4.0	4.6	11.1	10.6	41.0	37.0	3.69[2]	3.49[2]
224	4.6	3.4	16.5	14.6	26.0	54.0	1.58	3.70
225	4.4	4.3	13.0	13.2	32.0	45.0	2.46	3.41
226	5.6	3.8	10.8	10.2	50.0	41.0	4.63[2]	4.02[2]
227	6.5	2.7	19.0	12.7	57.0	53.0	3.00[2]	4.17[2]
228	6.1	6.0	13.1	15.7	33.5	30.0	2.56[2]	1.91[2]
229	2.7	3.7	10.1	10.2	32.0	50.0	3.17[2]	4.91[2]
276	3.4	4.0	12.3	13.8	67.0	41.0	5.45	2.97
277	5.5	3.8	15.0	16.1	63.0	35.0	4.20[2]	2.17[2]
mean	4.4	3.9	16.3	14.9	47.8	45.8	3.10	3.22
s. d.	1.3	1.3	4.0	3.8	14.9	13.3	1.36	1.05
error of mean	0.26	0.28	0.81	0.81	3.05	2.89	0.270	0.230

[2]) Bones with cortical defect.

[3]) Bones fractured outside callus area. Figures in brackets denote cross section of bone at site of fracture. These bones are not included in the analysis.

[4]) Bones with corrosion of nail.

Table 12. *Values noted for 120 day old fractures.*

animal No.	cross section of marrow in mm².		cross section of callus in mm².		absolute tensile strength in kg.		specific tensile strength in kg/mm².	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
148	4.9	7.6	19.1	15.3	22.0	39.0	1.15[2]	2.55[2]
149	4.3	3.5	22.3	21.3	58.0	39.0	2.60[2]	1.83[2]
150	6.6	4.2	16.0	17.5	60.0	41.0	3.75[2]	2.34
151	3.8	1.9	19.7	14.8	69.0	54.0	3.50	3.65
156	6.5	2.9(5.7)	18.6	18.8(12.3)	41.0	50.0	2.20	4.07[3]
157	4.1	3.3	16.2	18.3	58.0	63.0	3.58	3.44
158	4.6	4.3	13.8	17.0	41.0	65.0	2.97[2]	3.82[2]
159	8.2	7.7	21.0	24.1	—	65.0	—	2.70[1]
165	3.8	2.7	17.1	14.3	65.0	75.0	3.80[2]	5.25[2]
166	2.6	1.5	18.6	16.2	37.0	22.0	2.00[2]	1.36[2]
167	3.7	2.3	13.4	16.7	72.0	63.0	5.37[2]	3.77[2]
210	6.7	5.7	12.4	14.6	52.0	56.0	4.19[2]	3.42[2]
211	5.7	5.8	12.4	14.9	45.0	32.0	3.62	2.14[2]
212	4.8	3.8	11.9	11.4	41.0	30.0	3.45[2]	2.63[2]
213	4.0	2.6	14.4	13.7	48.0	58.0	3.33[2]	4.23[2]
214	4.3	2.6	12.4	15.4	45.0	39.0	3.63[2]	2.53[2]
215	5.3	2.5	13.0	13.7	48.0	54.0	3.69[2]	3.94[4]
216	6.2	4.8	13.9	13.4	52.0	41.0	3.74[2]	3.06[2]
218	4.5	2.5	15.6	13.4	32.0	37.0	2.05	2.76
219	4.3	2.4	9.3	10.1	45.0	43.0	4.84[2]	4.26[2]
220	3.2	3.1	10.8	11.7	28.0	26.0	2.59[2]	2.22
221	2.7	1.7	12.9	11.0	37.0	32.0	2.87[2]	2.90[2]
278	6.5	2.6	12.1	12.9	52.0	48.0	4.30[2]	3.72[2]
279	5.2	3.5	16.7	12.7	39.0	45.0	2.34[2]	3.54[2]
mean	4.9	3.6	15.2	15.0	47.3	46.4	3.29	3.13
s. d.	1.4	1.7	3.4	3.2	12.6	14.2	0.97	0.91
error of mean	0.28	0.35	0.69	0.67	2.63	2.95	0.203	0.189

[1]) Fractured during preparation of specimen.

[2]) Bones with cortical defect.

[3]) Bones fractured outside callus area. Figures in brackets denote cross section of bone at site of fracture. These bones are nor included in the analysis.

[4]) Bones with corrosion of nail.

Table 13. *Values noted for 10 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
103	144	168	107	99	198	231	16.4	24.6	9.9	9.3	7.2	10.4
104	144	178	80	61	199	227	14.3	22.8	7.2	4.6	7.1	11.2
105	151	169	96	116	268	288	12.0	18.5	5.2	7.7	6.1	7.7
106	166	188	100	89	260	288	15.0	21.2	5.4	4.6	8.0	11.2
110	141	165	83	106	243	235	12.6	19.0	6.6	7.7	9.1	9.0
111	154	180	129	113	227	244	14.9	25.8	9.1	11.1	8.9	8.3
112	149	167	108	94	374	365	8.0	13.9	5.8	5.1	5.0	5.9
113	173	203	111	107	321	346	11.6	17.6	6.4	6.2	5.3	9.3
160	127	139	133	122	253	266	6.1	10.6	3.9	4.3	3.7	3.3
161	107	120	139	146	254	270	8.0	12.7	6.5	8.1	5.6	5.7
162	103	106	129	124	230	253	3.3	6.7	4.2	4.5	3.5	3.9
163	151	198	195	220	300	289	8.4	8.1	8.8	9.7	5.0	6.8
240	138	143	130	134	290	291	8.8	20.5	6.7	12.0	8.0	8.2
241	117	139	135	147	300	330	4.5	10.9	4.0	5.6	2.8	4.1
242	118	164	124	121	212	229	8.9	14.5	6.1	6.8	4.2	5.8
243	132	155	128	142	191	200	11.8	19.7	8.7	11.5	5.7	7.4
244	129	144	129	130	270	318	14.1	17.3	9.5	9.4	7.0	10.6
mean	138	160	121	122	258	275	10.5	16.7	6.7	7.5	6.0	7.6
s. d.	19	26	26	34	49	46	3.9	5.6	1.9	2.6	1.9	2.5
error of mean	4.7	6.3	6.4	8.2	11.8	11.2	0.94	1.37	0.47	0.63	0.46	0.62

Table 14. *Values noted for 20 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
114	151	179	159	153	267	262	8.6	12.0	10.4	9.0	4.5	5.5
152	164	178	188	167	199	248	12.5	21.0	22.4	19.2	5.4	13.0
154	135	194	215	186	202	212	17.6	20.6	28.2	20.0	7.2	7.6
155	150	165	230	187	226	253	13.2	14.5	22.7	14.7	5.4	9.1
204	140	182	145	137	275	292	12.2	24.6	16.4	10.7	8.5	12.0
205	156	193	194	160	281	262	24.0	36.6	40.8	31.8	11.7	13.5
230	173	197	231	191	260	296	18.0	24.2	36.5	27.3	9.8	10.6
231	162	195	214	169	221	302	10.1	13.5	15.7	10.0	3.8	5.5
232	151	156	179	166	236	243	10.3	19.1	22.6	18.6	5.8	7.3
233	176	197	197	166	234	262	9.5	15.6	18.5	13.4	5.7	6.5
234	123	158	202	175	295	314	5.7	20.3	27.8	27.5	5.0	8.6
235	131	151	157	148	223	235	3.2	3.8	4.2	2.7	1.6	1.8
236	149	143	217	152	227	268	9.2	13.9	20.4	10.3	5.1	5.7
237	155	179	178	147	250	280	3.4	5.2	5.9	2.8	1.7	2.6
238	144	125	154	113	192	230	12.8	12.4	14.1	6.8	4.7	5.5
239	152	150	92	148	250	262	12.9	16.0	19.4	14.1	5.4	12.0
mean	151	171	184	160	240	264	11.5	17.1	20.4	14.9	5.7	7.9
s. d.	14	22	37	20	30	28	5.4	7.9	9.9	8.6	2.6	3.6
error of mean	3.6	5.6	9.2	5.0	7.6	6.9	1.34	1.97	2.47	2.16	0.66	0.89

Table 15. *Values noted for 30 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
100	132	190	164	169	296	357	4.6	11.6	8.7	8.7	3.1	7.9
101	187	187	294	183	238	286	16.6	20.8	25.6	18.5	6.5	10.3
102	167	147	177	241	223	225	18.6	23.8	19.3	27.0	7.3	9.0
107	191	181	173	189	215	240	23.4	24.4	18.9	23.8	7.1	9.1[4]
108	229	218	192	217	197	266	20.4	23.4	15.3	17.3	5.5	7.6[4]
109	184	223	182	165	208	220	28.7	41.7	28.4	24.6	11.9	18.2[4]
136	125	139	198	156	207	219	13.8	19.7	17.3	14.7	8.3	9.0
137	156	163	231	175	177	222	9.3	9.7	10.2	8.5	5.0	7.4
138	145	165	193	205	232	250	8.6	8.8	10.4	14.1	4.4	10.9
139	156	188	189	164	224	234	9.0	14.2	10.0	10.0	4.1	6.1
206	191	215	185	158	267	293	12.1	18.6	11.6	9.3	4.0	5.7
207	194	189	229	174	293	292	13.2	13.7	16.0	9.2	5.2	5.6
208	141	148	165	130	224	252	19.5	31.8	26.6	15.6	8.5	11.6
209	155	170	222	183	362	396	10.3	10.1	14.8	9.1	4.0	5.1
265	174	165	166	123	298	282	5.9	5.2	6.3	4.7	2.5	2.9
mean	168	179	197	175	244	269	14.3	18.5	16.0	14.3	5.8	8.4
s. d.	28	26	35	30	49	52	6.8	9.7	6.8	6.8	2.5	3·6
error of mean	7.3	6.7	8.9	7.9	12.7	13.3	1.76	2.50	1.76	1.75	0.63	0.93

[4]) Bones with corrosion of nail.

Table 16. *Values noted for 40 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
84	133	130	108	95	291	381	9.4	10.1	6.0	5.9	4.3	10.9
85	174	129	156	111	290	380	20.8	21.0	15.2	10.7	7.9	21.4
87	163	189	141	126	352	338	9.4	11.3	9.8	6.2	5.1	7.3
88	116	158	139	120	326	335	5.8	6.6	7.0	5.9	4.3	7.3
89	189	183	176	197	242	284	11.6	13.1	6.2	8.7	4.6	5.4
91	135	171	178	118	225	266	13.1	17.0	14.5	7.6	4.3	6.1
92	160	206	252	178	203	283	11.9	22.0	14.6	11.2	4.0	8.2
93	159	177	195	213	240	251	14.0	13.7	15.0	17.6	7.5	9.4[4]
94	143	141	166	161	261	372	7.6	8.4	7.5	6.2	3.1	11.4[4]
266	149	137	157	137	295	317	12.2	9.7	15.1	11.8	4.8	9.1
267	169	159	162	144	237	250	17.7	17.7	9.2	8.6	7.0	7.5
268	172	199	151	149	215	246	22.9	28.3	11.5	12.8	10.3	9.9
269	170	169	149	143	210	231	21.0	23.6	10.9	12.2	8.0	10.4
270	165	158	157	164	257	268	19.6	19.9	10.7	12.3	9.9	11.6
271	186	161	159	139	234	255	23.8	23.6	12.2	14.3	7.3	11.3
272	149	143	184	170	319	347	13.0	10.5	13.3	12.5	5.0	6.3
mean	158	163	164	148	262	300	14.6	16.0	11.2	10.3	6.1	9.6
s. d.	20	24	31	32	45	52	5.6	6.5	3.3	3.4	2.2	3.7
error of mean	5.0	5.9	7.7	7.9	11.2	13.0	1.41	1.62	0.82	0.86	0.55	0.93

[4]) Bones with corrosion of nail.

Table 17. *Values noted for 50 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
95	178	183	262	251	277	352	18.9	24.1	22.2	30.0	11.4	31.0[4]
96	154	167	172	187	298	279	9.9	6.7	7.1	6.6	4.5	6.3
97	132	132	173	202	260	276	9.1	11.1	8.5	12.4	6.4	8.4
98	132	145	199	190	223	256	16.8	23.8	15.4	20.3	9.9	21.6
124	242	190	176	130	182	290	17.5	17.5	8.7	8.8	5.1	9.5
125	189	192	165	133	288	316	10.7	11.4	6.3	5.4	5.1	7.2
126	214	275	158	194	326	352	8.5	17.5	4.6	8.3	5.3	6.1
127	141	137	152	138	261	285	8.9	11.8	8.4	8.5	6.1	3.0
184	118	165	168	167	287	297	10.5	14.8	12.9	13.4	10.0	7.3
185	123	147	122	113	246	249	8.5	13.0	6.2	6.0	3.5	4.2
186	128	153	158	161	238	244	7.3	5.2	7.2	5.8	2.6	3.2
187	125	163	177	159	269	290	11.4	14.7	14.1	9.8	4.5	5.7
188	161	165	121	120	204	188	13.8	16.2	8.2	8.4	4.6	4.3
189	174	196	157	142	251	242	19.0	20.2	9.0	11.5	5.7	6.0
190	184	180	146	150	245	293	19.8	22.2	9.6	9.5	7.0	9.0
191	175	230	172	156	275	328	19.0	20.1	13.1	10.7	5.5	9.0
mean	160	176	167	162	258	283	13.1	15.6	10.1	11.0	6.1	8.9
s. d.	36	37	32	36	36	43	4.6	5.7	4.5	6.3	2.4	7.3
error of mean	8.9	9.2	8.0	8.9	9.0	10.6	1.15	1.41	1.11	1.57	0.61	1.82

[4]) Bones with corrosion of nail.

Table 18. *Values noted for 60 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
116	160	152	146	140	234	316	8.7	10.8	9.5	8.1	6.2	14.6[4]
117	147	195	133	130	303	267	12.7	15.0	6.8	5.6	6.1	6.7
118	183	180	175	144	248	280	10.6	12.1	7.2	5.4	5.0	5.9
119	150	149	150	143	276	292	5.0	9.1	6.4	6.4	4.7	11.4
128	152	162	192	164	206	267	8.7	12.4	15.6	12.3	5.5	7.9[4]
130	191	192	231	199	362	456	6.1	10.6	10.5	10.8	6.4	10.1[4]
131	239	227	192	184	270	293	18.3	17.0	8.8	8.5	7.0	10.9
246	163	161	115	97	206	226	16.0	15.5	4.2	4.1	5.7	5.7
247	170	149	116	89	194	203	23.0	20.0	8.3	5.0	7.6	7.9
248	105	120	85	98	189	202	10.1	9.5	3.3	4.3	5.0	4.7
251	145	183	107	99	225	222	22.0	28.1	10.3	7.3	9.2	10.0
252	141	140	126	101	210	225	8.1	8.1	4.1	3.5	3.8	3.8
253	120	172	133	156	359	354	6.5	10.0	7.5	6.8	5.8	5.8
254	126	149	125	135	313	321	3.0	5.4	3.5	4.4	3.3	4.1
255	104	116	112	113	239	245	6.7	6.8	4.1	3.7	3.2	3.6
280	177	179	149	114	274	280	16.3	16.6	5.7	7.7	7.1	10.0
281	144	162	133	138	235	269	20.4	22.0	7.2	7.6	8.0	7.5
282	157	161	124	108	253	289	12.2	15.0	5.5	8.3	5.8	5.4
mean	154	164	141	131	255	278	11.9	13.6	7.1	6.7	5.9	7.6
s. d.	32	27	36	31	52	61	6.1	5.8	3.1	2.4	1.6	3.1
error of mean	7.6	6.3	8.5	7.4	12.2	14.3	1.44	1.36	0.73	0.57	0.37	0.72

[4]) Bones with corrosion of nail.

Table 19. *Values noted for 70 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
132	173	192	155	159	271	309	4.7	8.1	5.3	7.6	3.6	5.3
133	186	204	193	205	291	326	11.2	15.2	11.5	10.7	7.9	9.3
134	172	176	182	185	325	382	5.9	9.2	8.8	8.5	6.7	7.5
135	148	144	159	189	318	354	6.4	8.1	8.8	11.6	7.4	10.9
140	176	206	135	124	257	243	12.9	15.8	5.6	6.3	5.8	7.6
141	194	217	148	166	277	265	12.4	15.8	5.4	6.2	5.0	7.2
142	236	225	173	169	272	344	13.9	11.4	5.4	6.5	5.6	10.1
143	180	235	145	146	286	255	10.3	12.7	4.6	4.1	4.8	4.5
256	179	189	142	130	227	241	27.2	26.2	13.8	8.7	9.2	10.3
257	157	139	118	127	260	301	16.5	15.8	7.9	5.6	6.5	10.1
258	152	152	111	100	214	221	17.3	20.2	4.9	4.2	8.0	6.0
259	141	161	103	109	249	210	18.2	12.8	5.9	5.5	7.5	5.8
260	190	218	146	131	228	235	21.8	23.7	7.7	8.2	8.6	8.0
262	161	168	142	119	241	268	8.4	7.7	5.4	4.9	4.2	3.4
263	173	181	143	131	235	258	5.2	5.0	3.2	2.6	2.8	3.2
264	203	221	129	118	224	226	13.2	14.8	4.3	3.7	4.2	5.5
283	165	166	125	138	244	255	12.6	12.1	5.2	7.6	4.5	5.0
mean	175	188	144	144	260	276	12.8	13.8	6.7	6.6	6.0	7.0
s. d.	23	30	24	30	32	51	6.1	5.7	2.8	2.5	1.9	2.5
error of mean	5.5	7.3	5.8	7.3	7.8	12.4	1.48	1.38	0.67	0.60	0.46	0.60

Table 20. *Values noted for 80 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
144	150	180	144	149	299	290	2.7	6.5	4.6	4.6	2.7	4.2
145	240	256	149	167	233	260	13.5	15.0	4.4	5.8	4.9	5.2
146	144	163	123	139	306	322	2.0	3.6	3.1	4.0	2.9	3.3
147	179	156	129	113	258	305	6.7	6.7	3.7	4.1	3.2	4.6
192	228	179	140	108	280	370	13.6	11.9	4.3	4.0	6.0	9.6
193	239	271	149	131	305	319	14.5	14.2	5.1	4.3	5.5	6.3
194	245	239	173	156	278	317	5.1	5.5	3.2	3.4	3.3	5.2
196	195	223	175	172	288	341	6.1	8.0	5.3	6.1	4.6	6.3
197	196	199	130	136	251	249	12.7	12.8	5.1	5.5	6.0	6.7
198	201	254	165	152	280	294	14.5	18.2	8.6	7.6	7.3	8.7
199	143	176	125	140	278	317	9.9	18.3	8.4	10.7	8.2	12.5
200	155	198	119	182	284	310	4.6	8.0	2.9	8.5	3.6	6.0
202	156	164	147	155	250	267	6.2	9.7	6.8	9.2	5.7	7.2
203	167	196	157	156	324	326	9.4	13.0	9.0	10.8	7.9	11.1
273	165	132	129	120	311	311	4.4	4.5	2.2	3.1	3.2	4.3
274	171	149	141	114	325	346	4.9	5.2	3.5	2.9	3.4	4.5
275	135	140	129	123	330	327	6.6	7.1	4.6	4.3	4.3	6.2
mean	183	192	143	142	287	310	8.1	9.9	5.0	5.8	4.9	6.6
s. d.	37	43	17	22	28	31	4.3	4.7	2.1	2.6	1.8	2.6
error of mean	8.9	10.3	4.2	5.3	6.8	7.5	1.03	1.14	0.50	0.63	0.43	0.62

Table 21. *Values noted for 100 day old fractures.*

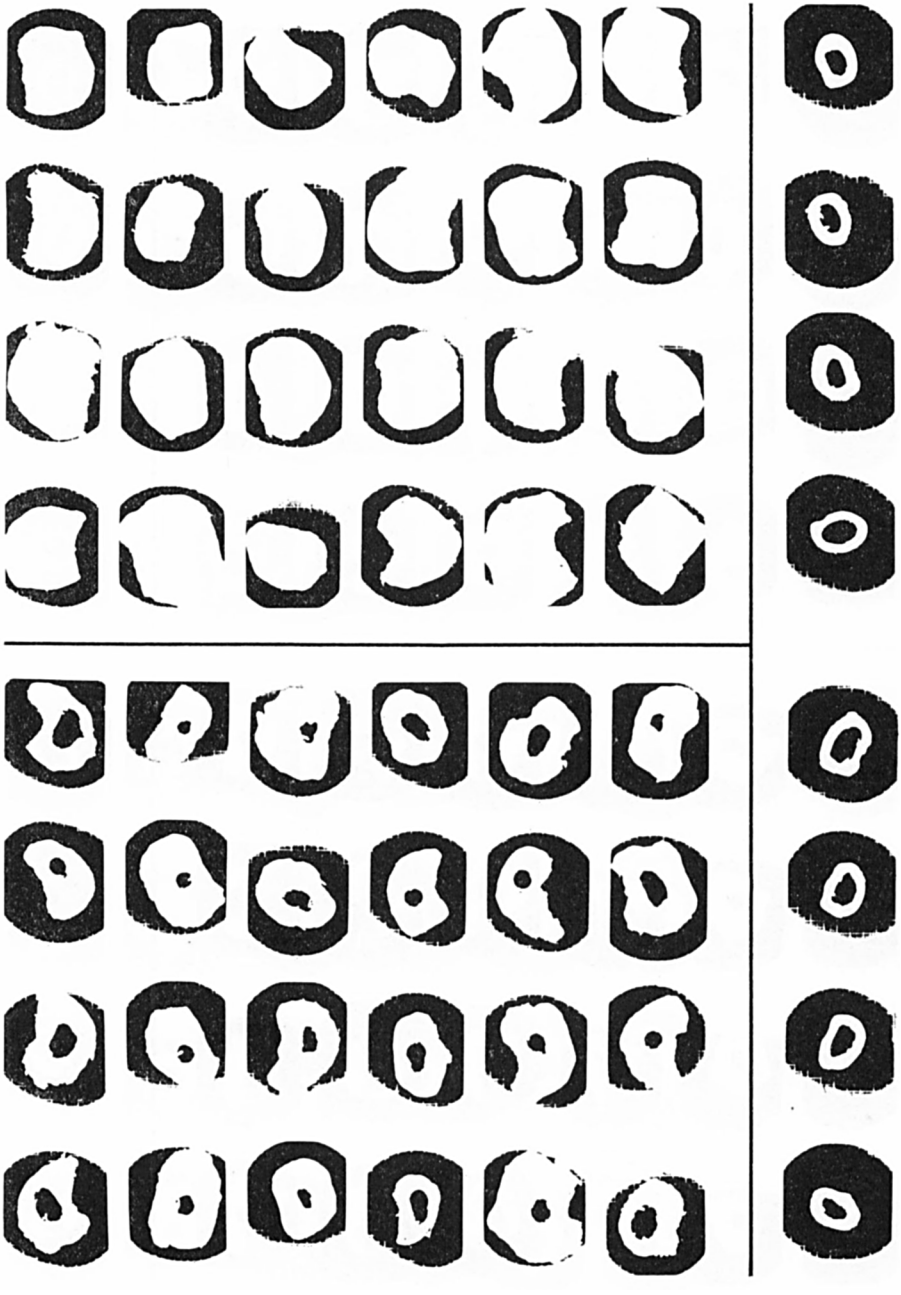
animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
168	255	288	147	154	260	276	11.5	11.5	4.0	4.4	5.1	5.9
170	208	264	151	156	227	227	8.3	15.0	5.4	5.3	4.1	5.0
171	170	176	133	126	234	300	5.4	5.4	3.3	4.7	3.8	5.0
172	162	156	111	98	241	218	4.5	5.4	2.6	1.7	3.6	3.2
173	207	172	137	148	239	278	5.9	4.7	2.0	2.5	2.6	3.0
174	164	150	114	98	192	187	7.9	7.5	2.3	2.0	2.7	2.7
175	198	197	139	137	252	246	7.4	9.1	3.2	2.9	3.4	3.4[4]
176	164	192	134	140	246	277	2.8	3.4	1.8	1.8	2.2	2.8[4]
177	195	258	133	128	324	312	9.4	11.0	3.5	4.0	4.5	5.4
178	184	162	133	147	270	278	15.2	14.4	7.0	7.7	8.0	8.9[4]
179	235	237	145	190	341	334	6.8	6.8	3.0	3.8	5.1	4.3
180	197	234	137	149	291	239	12.1	13.4	5.1	4.0	4.1	4.2
181	127	192	159	150	334	311	3.1	4.9	3.5	3.1	3.2	3.0
182	185	215	177	160	374	364	6.3	8.8	5.8	5.9	6.0	7.1
183	231	200	161	172	329	376	17.4	16.4	6.1	5.6	6.7	8.1
222	116	126	114	104	294	307	2.6	3.7	2.2	2.1	3.7	4.6
224	202	204	162	132	305	321	4.8	7.1	3.0	3.4	2.8	3.7
225	117	159	121	120	289	293	3.7	4.4	2.7	2.3	4.0	3.7
226	123	152	100	98	253	253	9.3	10.8	3.6	3.6	5.4	5.7
227	190	154	161	136	372	274	4.0	9.2	2.7	4.3	2.9	4.8
228	139	186	103	136	280	354	8.9	7.4	3.8	2.3	4.2	3.4
229	165	211	107	97	238	275	9.7	8.0	3.1	3.1	4.1	5.4
276	169	151	139	121	390	402	1.7	4.1	1.8	2.1	3.3	3.6
277	142	138	140	118	279	280	2.6	2.9	2.1	2.3	2.3	2.7
mean	177	190	136	134	285	291	7.1	8.1	3.5	3.5	4.1	4.6
s. d.	38	42	21	25	52	51	4.1	3.9	1.4	1.5	1.4	1.7
error of mean	7.7	8.7	4.2	5.0	10.5	10.5	0.83	0.80	0.29	0.31	0.28	0.34

[4]) Bones with corrosion of nail.

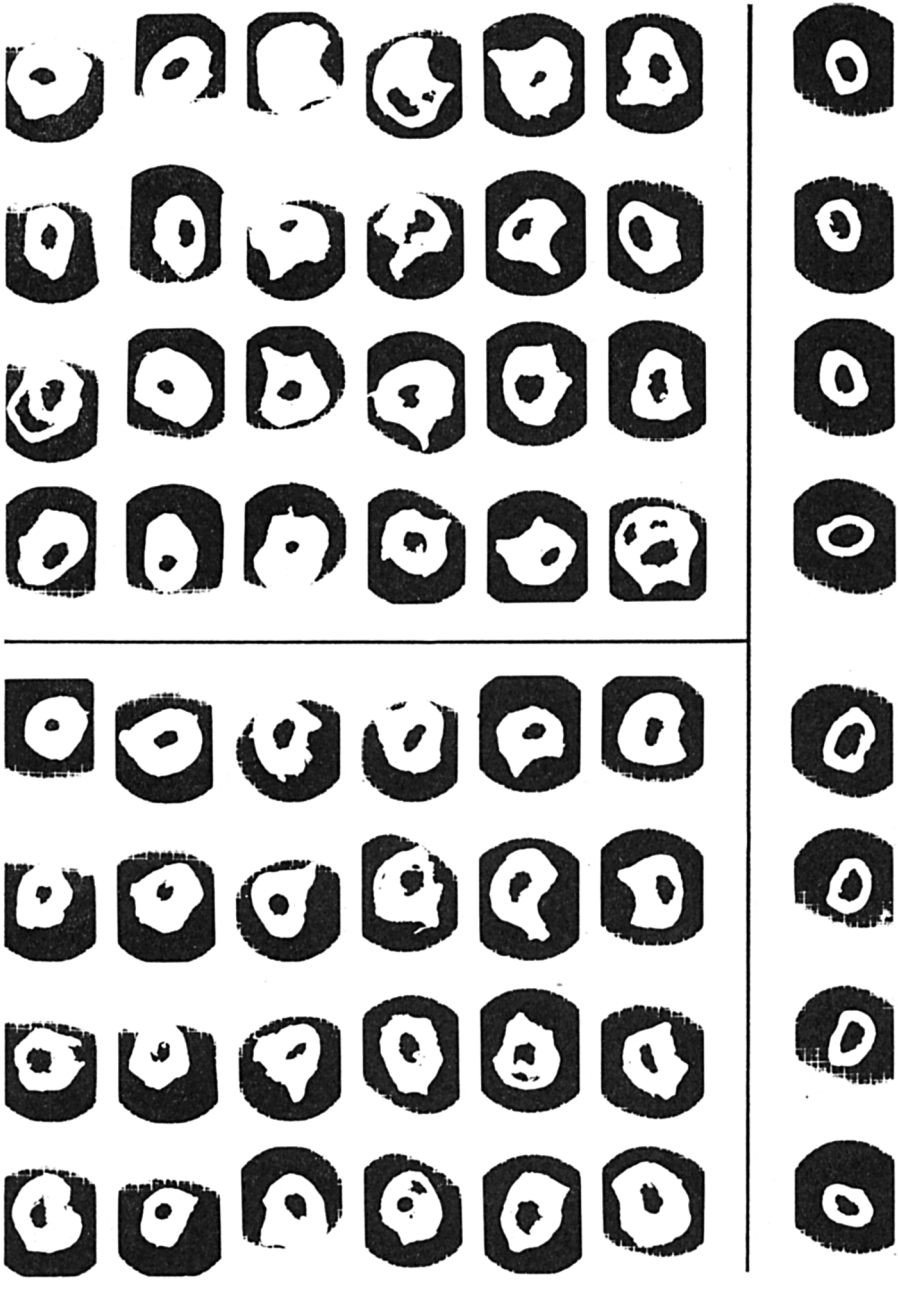
Table 22. *Values noted for 120 day old fractures.*

animal No.	wt. of bone ash in mg.						Sr^{85} activity in % of dose × 10^2					
	A-part		B-part		C-part		A-part		B-part		C-part	
	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed	unnailed	nailed
148	170	164	111	135	298	339	13.1	10.4	4.1	5.6	5.6	6.8
149	162	202	156	183	328	374	1.8	2.9	2.4	2.7	2.1	2.7
150	229	265	141	159	336	351	8.0	9.2	2.3	2.8	3.8	4.4
151	154	163	150	138	282	308	3.4	5.7	3.4	3.2	3.3	4.7
156	285	214	157	190	292	396	8.4	7.1	3.2	4.5	3.6	6.9
157	227	262	133	194	311	316	5.5	7.1	2.1	3.1	3.5	4.2
158	189	236	164	175	311	322	3.8	4.4	2.2	2.8	2.0	2.4
159	223	266	148	206	307	330	4.0	4.5	1.9	2.2	2.1	2.4
165	187	171	153	145	255	289	4.1	5.0	4.2	4.2	3.5	4.4
166	154	149	123	115	258	274	5.8	8.2	5.1	5.0	6.3	8.0
167	125	143	110	116	318	313	2.6	4.0	1.9	2.4	3.3	3.7
210	152	189	132	140	355	326	15.3	15.0	10.6	8.3	7.1	12.4
211	170	187	92	130	292	290	20.6	19.1	4.5	6.4	8.0	11.1
212	119	152	119	119	265	260	7.9	10.1	4.5	4.3	6.6	6.7
213	123	139	122	121	261	269	8.2	9.7	5.5	5.9	7.7	9.2
214	178	164	152	131	265	284	4.0	3.8	2.3	2.7	2.5	3.3
215	162	159	119	138	258	269	4.6	4.2	2.0	2.5	3.6	3.7[4]
216	121	142	141	121	327	195	5.7	7.9	6.0	5.2	9.3	7.7
218	125	155	97	132	312	317	3.1	5.9	3.0	4.0	3.2	4.5
219	199	140	103	108	279	287	3.5	3.5	1.6	2.1	2.7	3.3
220	144	134	99	106	258	280	4.6	4.4	2.3	3.0	2.5	4.2
221	115	149	117	107	296	273	5.9	7.1	3.3	3.3	3.0	3.8
278	196	210	138	143	290	298	10.4	10.7	5.6	6.2	7.4	8.5
279	173	188	144	119	274	273	7.4	7.4	3.7	2.8	4.6	5.4
mean	170	181	130	140	293	301	6.7	7.4	3.7	4.0	4.5	5.6
s. d.	42	42	21	29	28	41	4.4	3.8	1.8	1.6	2.2	2.7
error of mean	8.6	8.5	4.3	6.0	5.8	8.4	0.90	0.78	0.38	0.33	0.45	0.56

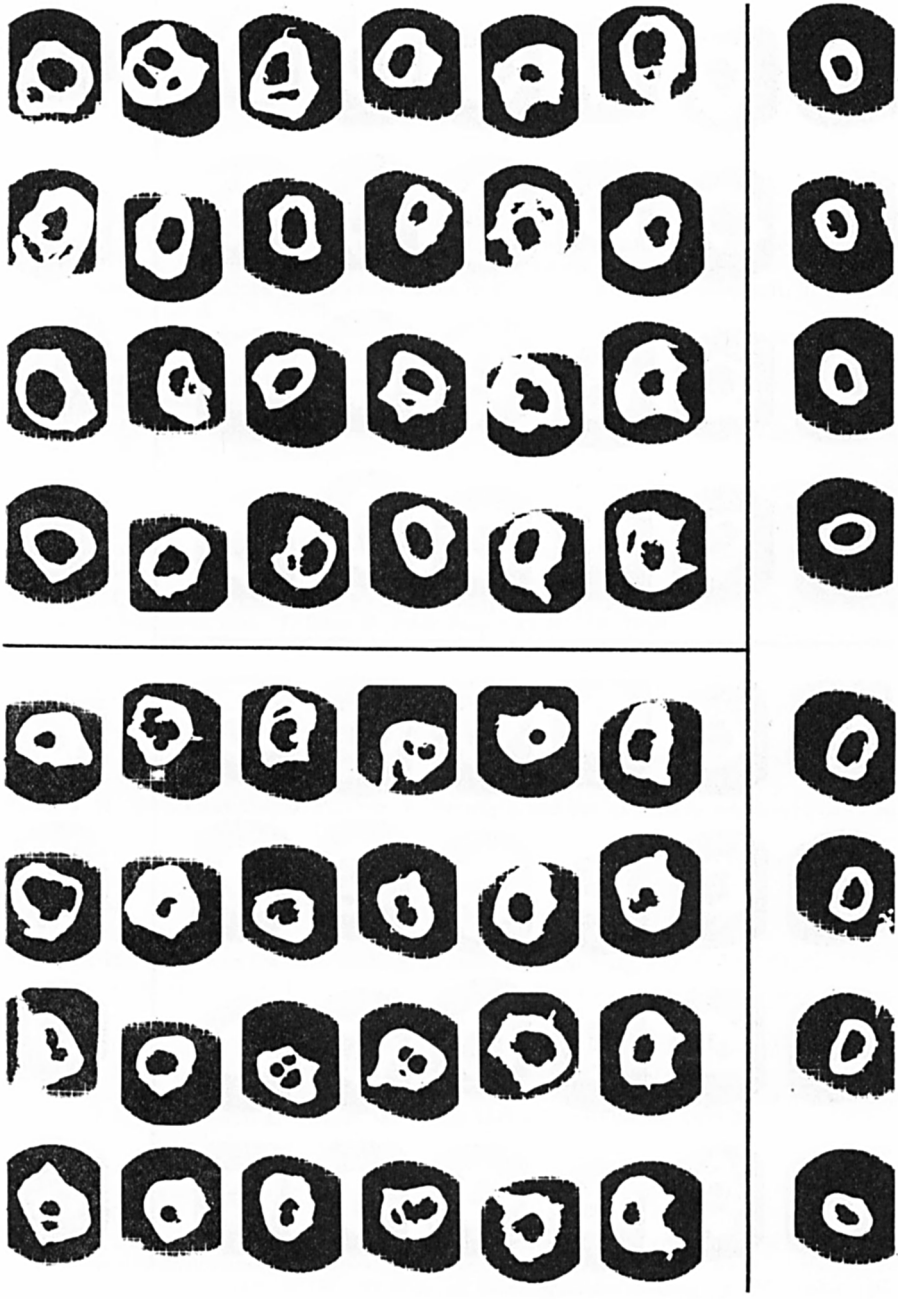
[4]) Bones with corrosion of nail.



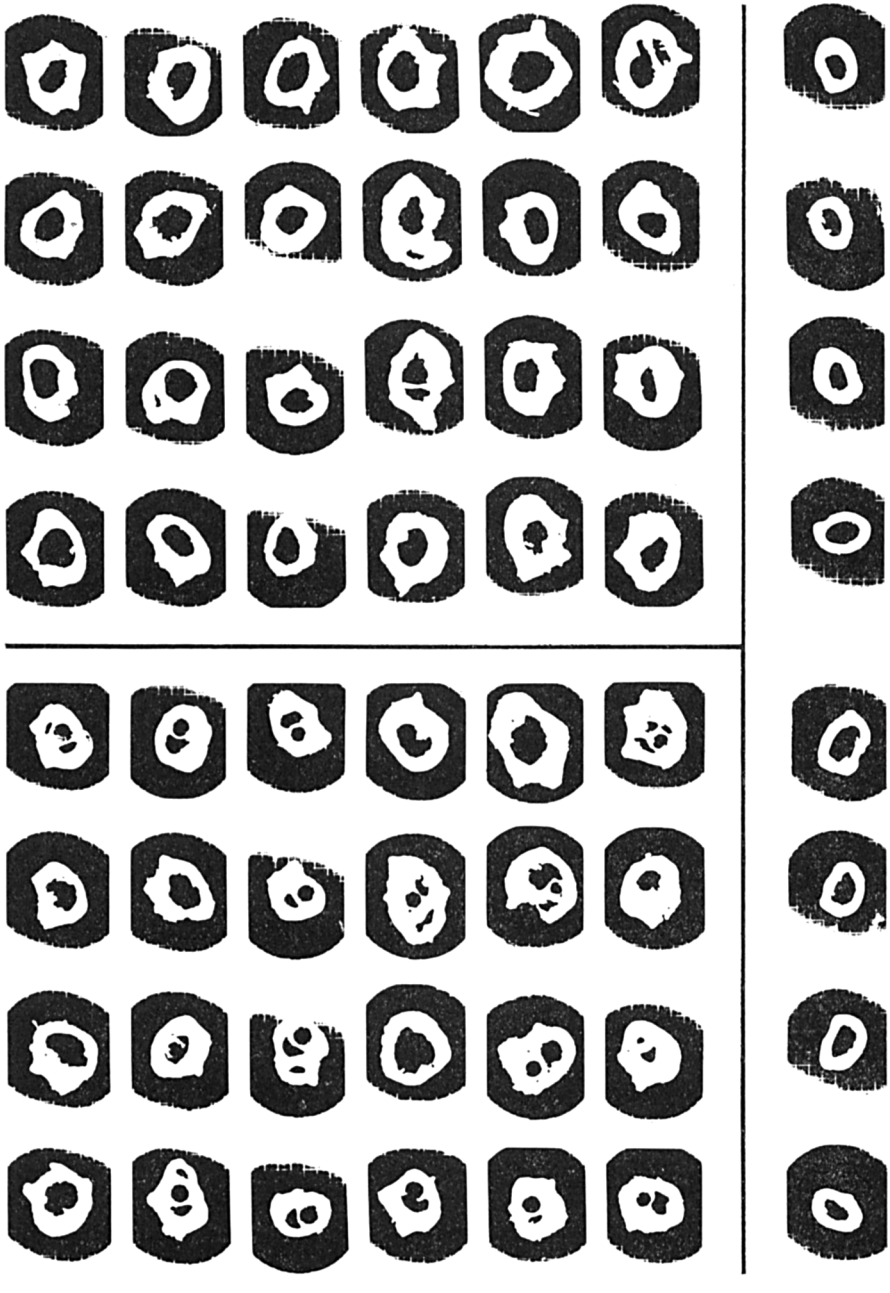
Cross-sectional area of callus in 20 day old fractures. Above: unnailed. Below: nailed. Row to extreme right: normal radius.



Cross-sectional area of callus in 50 day old fractures. Above: unnailed. Bolow: nailed. Row to extreme right: normal radius.



Cross-sectional area of callus in 70 day old fractures. Above: unnailed. Below: nailed. Row to extreme right: normal radius.



Cross-sectional area of callus in 120 day old fractures. Above: unnailed. Below: nailed. Row to extreme right: normal radius.

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