ACTA ORTHOPAEDICA SCANDINAVICA
SUPPLEMENTUM NO. 134

From the Departments of Surgery and Orthopedics
University Hospital, Uppsala

INTRAMEDULLARY NAILING AFTER REAMING

An investigation on the healing process in osteotomized rabbit tibias

By

GÖRAN DANCKWARDT-LILLIESTRÖM

GIAN LORENZO LORENZI *

and

SVEN OLERUD

MUNKSGAARD
Copenhagen 1970

* Ass. Professor, Visiting Guest from the Clinic of Orthopedics and Traumatology, University of Turin, Italy

Translated by Maud Marsden

This work was supported by grants
from the Swedish Medical Research Council.

B 68 -17X-2026-3: S. Olerud and G. Danckwardt-Lillieström

B 69 -17X-2026-4: S. Olerud and G. Danckwardt-Lillieström

B 70 17R-2050: S. Olerud

ISBN 87 16 00181 8

Printed in Italy by "Monograf" - Bologna - Maggio 1970

CONTENTS

Introduction . . . . page 1

Literature Review . . . . » 3

Blood supply of the diaphyseal bone on nailing . . . . . » 3

Periosteal bone reaction after nailing . . . . » 4

Reaming of the medullary cavity . . . . » 5

Fracture stability on nailing . . . . » 6

Fracture stability and healing pattern . . . . » 7

Nailing and reaming in relation to fat embolism . . . . . » 8

Material and Methods . . . . » 13

Premises . . . . » 13

Material . . . . » 15

Methods . . . . » 16

Operative procedure . . . . » 18

Recording methods . . . . » 22

Results . . . . » 25

Remarks on the operative procedure . . . . » 25

Postoperative complications . . . . » 25

Genèral body reaction to operation . . . . » 26

Local reactions . . . . » 26

Roentgenological findings . . . . » 26

Microscopical observations . . . . » 36

Vascularity and rebuilding of cortex . . . . » 36

Periosteal bone formation . . . . » 44

Intramedullary reaction . . . . » 49

The nail and the bone formation . . . . » 56

Osteotomy line . . . . » 56

Discussion . . . . » 67

Conclusions . . . . » 73

Bibliography . . . . » 75

FOREWORD

Medullary nailing is used throughout the world in all technically advanced countries. This method has defended its position extremely well through thirty years of experience and its use is increasing all the time. From the manufacturers we know that millions of these « medullary rods » have been sold.

The strength of the nail depends on its diameter. It increases with about the 4th potential of the transverse measurement. The medullary cavity is frequently too narrow to allow the introduction of a medullary nail of sufficient weight-bearing capacity. Not until *the method of widening the bone canal* with long drills was used, was it possible to produce a mechanically stable intramedullary osteosynthesis.

Since 1950 many surgeons engaged in traumatology, including members of the Swiss Arbeitsgemeinschaft für Osteosynthesefragen (A.O.), have used this technique. However, in many countries, for example U.S.A., the method is strongly opposed on the basis that it can cause considerable injury. Strangely enough *not one single experimental investigation has been published on this extremely important question* of reaming and nailing, in spite of the fact that this method has been used clinically for more than twenty years. The authors, S. Olerud, G. L. Lorenzi and G. Dankwardt-Lillieström, deserve great merit for the present research work and we owe them appreciation for penetrating the problem in such an extensive, precise and thorough way.

Gerhard Küntscher

INTRODUCTION

From the mechanical point of view it is of obvious advantage, as many surgeons realise, to treat certain diaphyseal fractures by the intramedullary nailing method. In earlier years, several different authors advocated various techniques of intramedullary fixation (Lambott 1913, Hey Groves 1918, Rush & Rush 1937). The method of Küntscher, however, has had the greatest success, and nowadays intramedullary nailing is generally linked with his name. It was in 1939 at a meeting of the Medical Society of Kiel that Küntscher first presented his concept of this procedure and introduced the spring-acting clover leaf shaped nail.

Eleven years later, in 1950, Küntscher proposed an important modification of this original method by introducing reaming of the medullary cavity. This meant that large contact surfaces between the nail and the inner cortex could be obtained, permitting the use of bigger and stronger nails. The size of the reamer used could also serve as a guide as to the most suitable diameter of the nail, and the risk of the nail getting locked was eliminated. Increased stability added to the value of this method and extended its use. The Küntscher type of intramedullary nailing, both with open and closed techniques and with different characteristics of the nail (Uffreduzzi 1942, Kaessman 1966, Weseley 1968, Schneider 1968), is still gaining increasing interest all over the world, 30 years after its introduction.

The principles of Küntscher-nailing are largely known and have often been emphasized by other authors, including Lorenz and Jörg Böhler. It seems surprising, however, that intramedullary nailing with reaming of the medullary cavity, which, though technically more extensive, is more stable and more efficient from the mechanical point of view, has not been more generally accepted by orthopaedic surgeons. But we consider that this relatively new idea, of reaming of the medullary canal, deserves deeper research in the experimental field. Danckwardt-Lillieström (1969*a*) found, on reaming, that marrow from the cavity easily caused blockage of the intracortical circulation. The effect of this on fracture healing after nailing is not known. The healing pattern, especially the peripheral bone reaction, seems at times to be contradictory—in spite of complete stability a large amount of callus formation is sometimes seen.

Our interest in the Küntscher nailing method inspired us to the present experimental studies. Although we realise that results from investigations on rabbits cannot be referred directly to man, our findings will make us more aware of the problems involved when we face clinical decisions.

There are still many unsolved problems concerning intramedullary nailing, and we hope that with this work we can give some answers to the following questions:

1. What kind and grade of damage do osteotomy and nailing produce in the cortical bone when the medullary cavity has been reamed?
2. How is revascularization of the cortical bone accomplished with a stable nail well fitting the marrow cavity?
3. How does the periosteal bone formation behave under these conditions?
4. How does repair take place in the fracture gap under these conditions?

LITERATURE REVIEW

Since 1940, after publication of Küntscher's first reports, nailing of shaft fractures has become an accepted method of internal fixation. Although nailing had been tried by several surgeons earlier, it was the principles of Küntscher which made it practically acceptable. His development of the method in 1950 by the reaming procedure must be considered very important, because of the possibility of primary weight bearing. During recent years, though very slowly, this change in the method has been accepted increasingly by many surgeons.

Although several studies have been published concerning the problem of nailing in different long bones of various animals, no report appears to have been made dealing with the problems arising on fracture treatment with true reaming of the medullary cavity including the inner part of the cortex. The reaming procedure involves complete destruction of the medullary circulation and gives rise to new problems regarding the blood supply to the bone as a whole and to the fracture site in particular.

The literature concerning these problems deals with such different and well defined questions that they can be suitably divided as follows:

1. Blood supply of the diaphyseal bone on nailing.
2. Periosteal bone reaction after nailing.
3. Reaming of the medullary cavity.
4. Fracture stability on nailing.
5. Fracture stability and healing pattern.
6. Nailing and reaming in relation to fat embolism.

1. Blood supply of the diaphyseal bone on nailing

As pointed out by several authors in the last 15 years, the blood supply of the shaft of long bones comprises three systems: 1. Periosteal vessels, 2. Nutrient arteries, 3. Metaphyseal vessels. The importance ascribed to these different pathways has varied.

Trueta and Cavadias (1964), in a study of the blood supply of long bones, arrived at the conclusion that (under their experimental conditions) the periosteal vessels were able to nourish only the outer third of the cortex. The same authors had stated in 1955 that the nutrient artery was normally responsible for the blood supply to the largest part of the cortex. De Marneffe (1951 and 1953) considered the proximal third of the tibia to be supplied mostly from the marrow canal. The distal third got its blood supply mostly from periosteal vessels and the middle third from both sources.

Brooks and Harrison (1957) believed that, perhaps because of the connection between the two systems, the circulation of the cortex would not be severely affected by suppression of one of the two systems (Koeckenberg 1963, Rhinelander 1968).

The damage that nailing of a long bone can produce in the medullary vascular system has been widely studied.

Trueta and Cavadias (1955), who were the first to study the small vessels in experimental nailed fractures, found, on microangiography, that even if part of the nutrient artery could escape damage, numerous branches were destroyed by the nail. In Göthman's experiments (1960*a*) with nailing alone, the arterial system was less severely damaged. When nailing was combined with fracture, he found more extensive damage to the intramedullary vessels (1960*c*).

The avascularity in the cortex that can sometimes result from nailing is obviously the reason for the cortical necrosis that some authors, e.g. Trueta and Cavadias, have shown to be very extensive and to persist partly even 8 months after the surgical procedure.

The inner avascular cortex, together with still viable bone, will undergo more or less extensive resorption and rebuilding activity, with formation of cavities. This rebuilding process has been described in recent literature by Koeckenberg (1963), Trueta & Cavadias (1964), Richany et al. (1965), Johnson (1966) and Danckwardt-Lilieström (1969*b*).

2. Periosteal bone reaction after nailing

The extensive periosteal bone formation so frequently observed by different authors, both clinically and under experimental conditions, has been given various explanations.

Küntscher (1940*b*-1941) considered that callus was formed as a normal phlogistic response to the injury. Griessman (1944), Silani & Amanta (1949) and Maatz (1951) described in a clinical study the new bone formation all along the diaphysis. Their respective explanations were: the result of chemical or physical irritation, pressure of the nail against the bone, and vascular damage.

Trueta and Cavadias (1955) considered bone marrow ischaemia as a cause of the periosteal bone proliferation.

Göthman (1960*b*), in rabbits, found only an occasional profuse periosteal vascular reaction, and this was not accompanied by any new bone formation.

Koeckenberg (1963), like Trueta, considers that it may be due to damage to the intramedullary vessels.

Mital & Cohen (1966), in a study on rats, found that only with maximal injury in the medullary cavity was there any significant subperiosteal bone deposition.

Richany et al. (1965), in an investigation on cat femurs, destroyed the medullary cavity by introducing a pin into the canal. With further brushing and flushing the cavity was cleaned. In these experiments he found marked periosteal bone formation which he considered to be due to stasis in the periosteal vessels and oedema resulting from destruction of the medullary venous system. He remarked that the picture resembled that in hypertrophic pulmonary osteoarthropathy.

Zucman et al. (1968) and Danckwardt-Lillieström (1969*c*) also observed periosteal bone formation, but because of their particular experimental conditions and of their original observations, their findings will be discussed under the next heading.

3. Reaming of the medullary cavity

Zucman et al (1968) destroyed the marrow tissue in the medullary cavity with a reamer in experiments on the rabbit tibia. He gave a very clear description of the occurrence of bone marrow fragments under the periosteal layer during the reaming, and named this « medullo hematoma ».

Zucman considered that bone marrow, pressed through the cortical channels to the subperiosteal space, played an important role as a bone marrow auto-transplant in promoting callus formation.

One of the present authors (Danckwardt-Lillieström, 1967 and 1969*c*) has also studied problems arising from reaming of the medullary canal. Differently from Zucman et al., but also in the rabbit tibia.

he reamed in addition the inner part of the cortex, in an attempt to reproduce the same conditions as found in clinical practice.

Danckwardt-Lillieström (1969*a*, 1969*c*) confirmed the finding of Zucman of a subperiosteal « medullo hematoma », but he also demonstrated the intracortical and subperiosteal pathways of bone marrow by lipid staining methods.

Danckwardt-Lillieström (1969*c*) studied the correlation between periosteal bone formation and cortical avascularity. He showed that this was due to massive embolism of intracortical canals by bone marrow and fat.

The extent of the intracortical fat embolism and consequently of bone avascularity, is dependent upon the way in which the reaming is performed.

Danckwardt-Lillieström's studies (1969*c*) of the pressure in the medullary cavity during reaming of the rabbit tibia revealed wide variations from the normal value (30 mm Hg). With vigorous reaming, values up to 300 mm Hg could easily be obtained in the positive field. Negative values of about 100 mm Hg were recorded during withdrawal of the reamer.

It can be expected that reaming of a closed system such as the bone marrow cavity will result in such pressure changes.

The high pressure can easily explain the intracortical and subperiosteal presence of fat observed by Danckwardt-Lillieström (1969*c*) and Zucman et al. (1968), respectively.

We have demonstrated that as a consequence of reaming of the rabbit tibia, marrow fat particles can very easily appear in the femoral vein (Olerud et al. 1969).

4. Fracture stability on nailing

The aim of fracture treatment with intramedullary fixation has changed during the last few decades.

In previous years the only intention was to maintain the axial direction of the shaft fragments (Uffreduzzi 1942), and this always required further fixation with a plaster case. In time, however, this view altered, and more rigid stability with the avoidance of any complementary fixation became the main goal. Andersson (1962 and 1965) describes the two types of nails involved as « loose-fitting » and « tight-fitting ». We consider that in most cases the Rush pin method (1949) belongs to the loose-fitting type. The same is true of the Kirschner pin (Landelius 1951), which was used extensively some years ago in the treatment of some diaphyseal fractures.

Satisfactory intramedullary fixation can be obtained by using a fascicle of metal pins (Hackethaı 1961), with which the medullary cavity is filled completely.

In 1940 Küntscher developed a new nail, which in the transverse section worked as a spring. The aim was to obtain a nail which completely fitted the marrow canal. Küntscher found that much more stability was achieved by transforming the hour-glass shape of the medullary cavity into a cylindrical shape by reaming the inner cortex and using a wider and stronger nail (1950); at the same time the number of fractures that could be treated by this method increased.

Kaessman (1966 and 1969) describes a nail with still greater stabilizing properties especially concerning the rotatory forces, and with which compression can be applied to the fracture site.

Similar devices have also been described by Fitzgerald (1966) and Vinditti and Benini (1962).

Experimental studies of loose-fitting nails have been made by Göthman (1961), Gustilo et al. (1964) and Rhinelander et al. (1967). Andersson (1965) compared the healing of experimental osteotomies in dogs with loose-fitting and tight-fitting nails. Also Varma and Metha (1967) observed differences in healing between loose and tight fitting nails.

5. Fracture stability and healing pattern

Since 1949, when Danis first proposed his compression plates, many authors have devoted their attention to problems of stability in the healing of fractures (Friedenberg et al. 1952, Yamagishi et al. 1955, Bagby et al. 1958 and Petrokof 1962).

After the first reports from the AO-group with the paper of Schenck and Willenegger (1963), interest in this particular problem of osteosynthesis became intense and gave rise to considerable experimental and clinical research.

Schenck & Willenegger (1963 and 1965), after stable compression plating of osteotomized dog radii, observed secondary osteones crossing the closely adapted fracture line. They considered this an ideal form of bone healing (1967).

Geiser (1963), on the contrary, considered that the cortical fracture ends became rebuilt by « creeping substitution » from the endosteal and periosteal sides. The same conclusion was drawn by Andersson (1965) and Rhinelander et al. (1967).

Two of the present authors, Olerud and Danckwardt-Lillieström (1968 and 1970) also found the primary bone healing described by Schenk et al. possible in fractures fixed with compression plates in the dog tibia. This pattern of healing was only considered feasible with absolute contact of the fracture ends, where there was no room for transverse bone formation in the gap. In clinical practice it would therefore seem almost exceptional, according to these authors.

In those cases where there is a small fracture gap, the orientation of the new lamellar bone will initially be transverse. Later, it will assume a longitudinal direction as a result of the formation of longitudinal, secondary osteones traversing the fracture area.

The healing of a fracture treated with a loose-fitting nail, as studied experimentally by Göthman (1961), Andersson (1965) and Rhinelander et al. (1967), is usually delayed in comparison with tight-fitting nails, owing to severe necrosis of the fracture ends, with frequent non-union and an abundant formation of cartilage. Similar findings have been made by many other authors under almost similar experimental conditions (Silani et al. 1949, Trueta and Cavadias 1955, Koeckenberg 1963, among others).

Andersson (1965) planned his experiments with the purpose of comparing the healing of a fracture under the different conditions created by treatment with a loose-fitting and a fully-fitting nail. With the latter type of nail he noted more rapid healing with smaller areas of necrosis, only an occasional occurrence of cartilage and frequent direct bone formation.

Trueta et al. (1955) probably also obtained very stable fixation in many cases in his studies of intramedullary nailing of the rabbit radius, and in these cases, as is evident by his photographs, he always obtained the same results as Andersson. The choice of the radius for the osteotomy obviously ensured good stability because of the integrity of the ulna and the special connections between these two bones in the rabbit.

As far as clinical experience is concerned, Küntscher (1950) considered that the more stability that could be obtained the better healing would be achieved. Reaming of the canal before nailing, to make possible the use of a stronger nail, therefore seemed to him logical.

Nailing and reaming in relation to fat embolism

Heavy trauma, especially when resulting in fractures, always causes emboli of marrow fat in the lungs (Backer-Grondahl 1911, Lehman

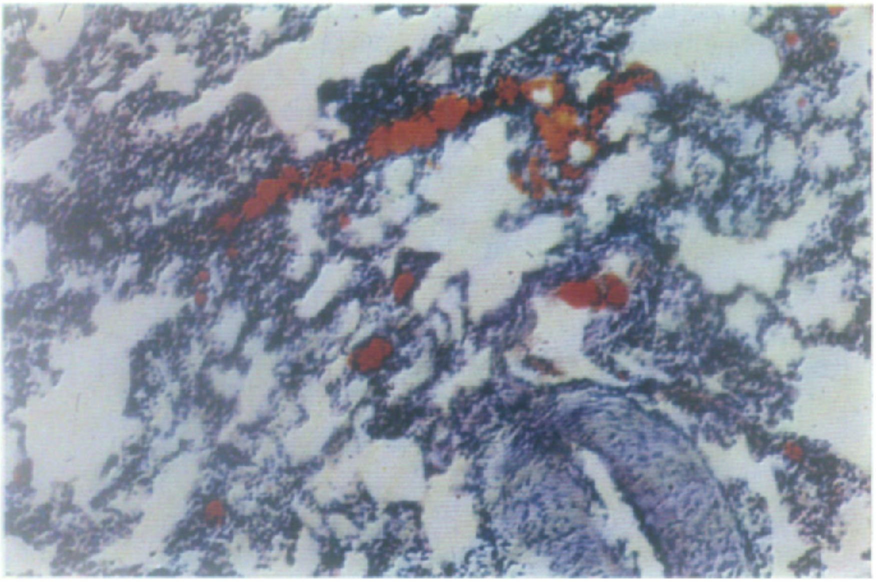


FIG. 1. - Group NS. Fat-stained marrow embolus in the lung.

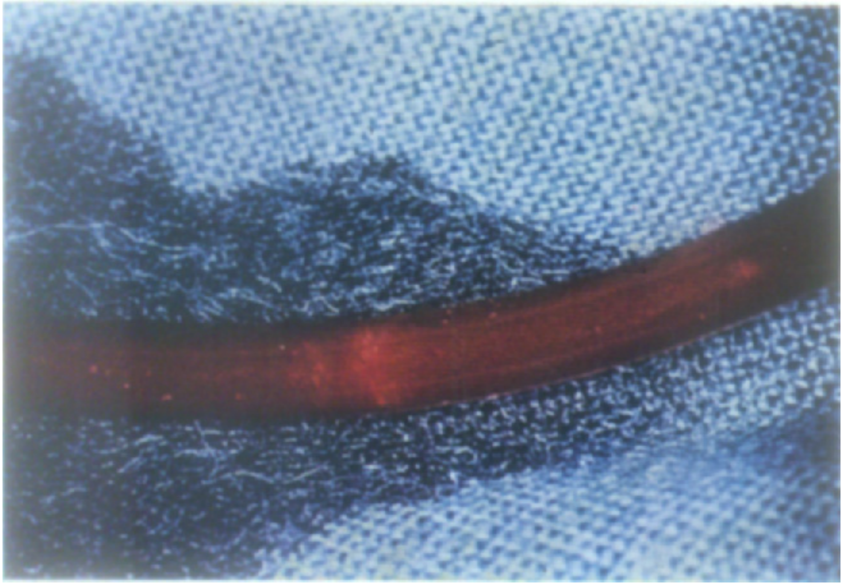


FIG. 2. - Bone marrow appearing in the transparent catheter connected to the femoral vein during reaming.

& Mc Nattin 1928, Grant & Reeve 1951). The liberation of fat in this way, and the biochemical and enzymatic effects of the traumatized fat tissue, which give the clinical entity of fat embolism, have been interpreted in different ways by different authors (Peltier 1956, Bergentz

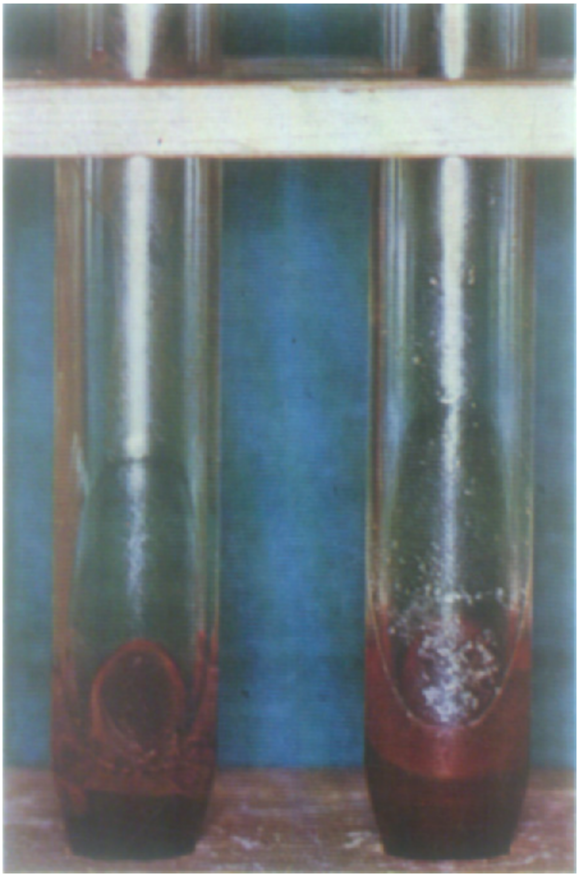


FIG. 3. - Fat supernatant seen as white flecks after centrifugation of blood collected from the femoral vein. Note also the fat deposits on the walls of the test tube (to the right).

1961, Wehner 1968, Kerstell 1969, Saldeen 1969). It is conceivable that a large marrow embolus in the lungs might directly diminish the pulmonary circulation with a fatal outcome.

Kerstell found, in experimental fractures in dogs followed by retrograde flushing of the lungs, that pulmonary fat embobi consisted only of tissue fat and no plasma fat component. Küntscher is certainly aware of the risk of embolism and advocates very careful hammering of the intramedullary nail. Hackethal (1961) considers that the use of a tourniquet is always extremely important for the avoidance of

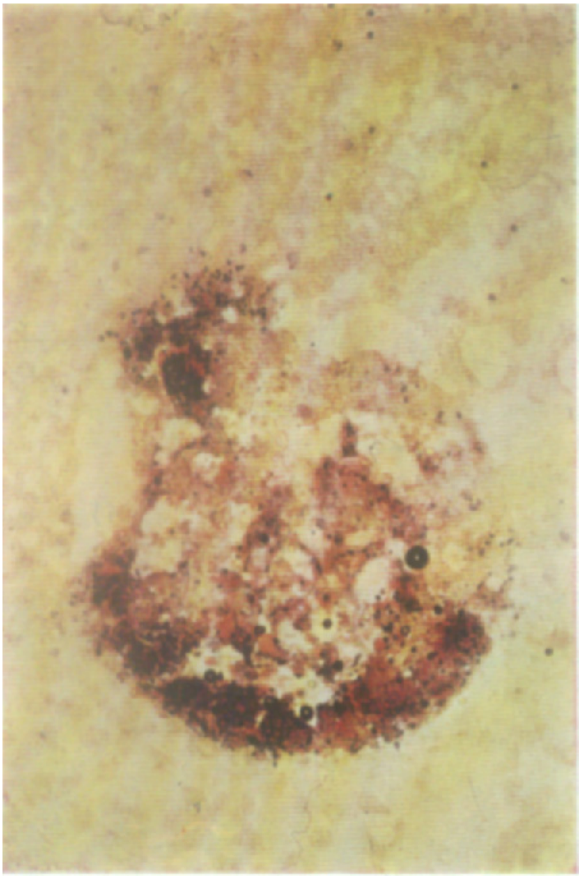


FIG. 4. - May Grünvald-Giemsa staining of blood smear. Marrow conglomerates in the peripheral blood.

fat emboli with the Bündelnagelungmethod. Peltier (1956) found a tourniquet useful in preventing fat emboli in orthopedic surgery.

Palmer (1951) and Böhler (1968) suggest that nailing should be avoided in all cases with signs of the fat embolism syndrome, so as not to develop it further.

Lange (1954) and Lechner and Schuster (1963) reported fatal cases, as also did Mörl (1967), who described 9 cases of fat embolism among 17 deaths out of 452 patients subjected to intramedullary nailing. Rokkanin et al. (1969) found cases of fat embolism, verified histologically by skin biopsies, among 116 cases of medullary nailing.

On reaming in clinical work Wehner (1968) observed a remarkable pressure rise in the medullary cavity.

On reaming under experimental conditions, Danckwardt-Lillieström (1969*a-c*) observed fat emboli caused by increased intramedullary pressure within the intracortical canals as well as in pulmonary tissue (Fig. 1).

Zucman (1968) describes the superiosteal medullo-hematoma after reaming of the medullary cavity.

On cannulating the femoral vein, Olerud et al. (1969) observed marrow tissue components in blood samples during a reaming procedure (Figs. 2, 3 and 4).

MATERIAL AND METHODS

PREMISES

The studies of Danckwardt-Lillieström (1969*a-c*) mentioned above, with reaming of the rabbit tibia, showed that large areas of avascular cortex were produced, with considerable variation between different animals. The reason for this was found to be that marrow particles liberated by mechanical forces were pressed into the cortical canal due to an increase in intramedullary pressure which was produced during the reaming procedure, causing embolism and blockage of the cortical circulation (Fig. 5) and subperiosteal fat deposition (Fig. 6). In the following this investigation is referred to as experiment NS (Exp. NS).

In order to avoid such a pressure increase and to reduce the extent of marrow embolism, the medullary contents were evacuated by suction before and during the reaming through a drill-hole made in the ventral part of the distal tibial metaphysis (Danckwardt-Lilliestrom et al.,

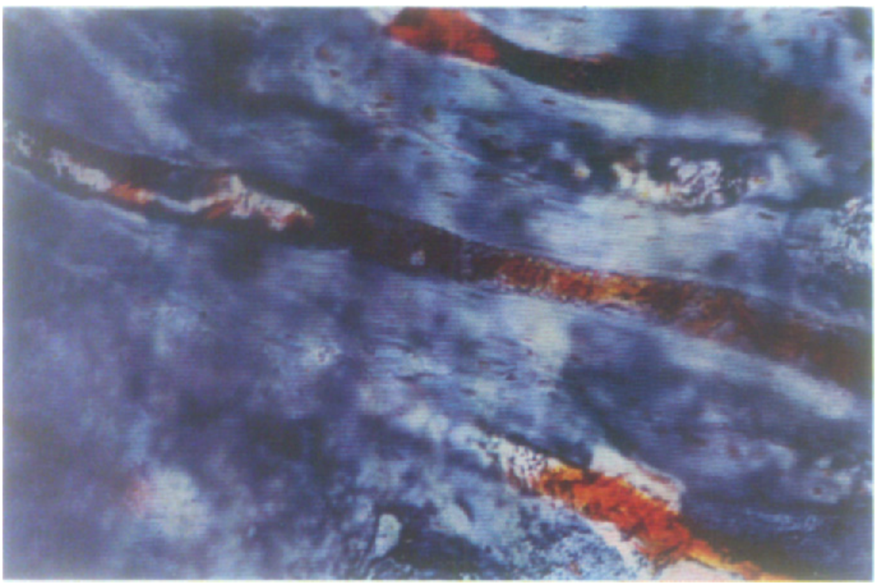


Fig. 5. - Fat stained material filling the intracortical canals.

1970). Under these conditions, in the following referred to as experiment S (Exp. S), the extent of intracortical avascularity, studied with Indian Ink microangiography on transverse tibial sections, was significantly smaller. A comparison was made between the findings in the two different experiments and the results are presented in Table I.

FIG. 6. - Fat stained transverse section. Intracortical and subperiosteal fat is separating the periosteum from the cortex.

The table gives the mean value and the standard difference for the percentage of avascular cortex in the two experimental groups after observation times of one to eight weeks. The difference between the values for the two series is also given for the different observation times. The degree of significance is denoted by asterisks.

TABLE I.

Mean values, with standard deviations, of percentage of avascular cortex (PAC) in groups NS (non-suction group) and S (suction group), and also the differences in PAC between the groups, and their significance. The table also shows the number of animals in the respective groups.

Obs.	Group *NS*			Group *S*			Difference *NS* — *S*	
time weeks	No. of animals	PAC *M*	PAC ± *SD*	No. of animals	PAC *M*	PAC ± *SD*	*M*	*t*-value
1	11	21.5	15.68	5	6.2	3.40	15.3	3.22 **
2	15	20.7	14.33	5	7.1	1.95	17.6	3.54 **
4	14	16.1	12.50	2	1.6	0.79	15.4	4.33 ***

The table shows that the standard difference was very high in Exp. NS and very low in Exp. S. The figures for Exp. S show that revascularization took place between the second and fourth weeks. This process was completed more quickly in Exp. S than in Exp. NS. In the latter experiment similar values for revascularization were not attained until after eight weeks.

The investigation described above thus showed important differences within the cortical circulation between Exp. NS and Exp. S. In view of this finding it was considered important for the present investigation to distinguish between rabbits in which reaming was performed without previous evacuation of marrow tissue (Group NS) and those in which evacuation of marrow tissue preceded the reaming (Group S). In all the latter cases the reaming was performed with the utmost care and with continuous suction.

With these premises as a basis we started our experimental model.

MATERIAL

The investigation was carried out on 134 male and non-pregnant female albino rabbits, 7-8 months old and weighing 2.7-3.2 kg, with a mean weight of 3.00 kg. Experience had shown this size of rabbit to be ideal because of the thickness of the cortex and the width of the marrow cavity.

Our study concerned mainly the conditions of ideal healing of a stable osteotomy after reaming and nailing. For various reasons 86 of the 134 rabbits operated on had to be excluded from the main study, and therefore only 48 comprise the main material upon which the results are based.

The reasons for exclusion of the 86 rabbits will be discussed below under « Remarks on Operative Procedure » (Page 25) and « Post-operative complications » (Page 25).

The main material was grouped as follows:

Group S: Osteotomy and nailing after reaming during suction of the marrow cavity. This group consisted of 33 animals and was subdivided into 9 groups with observation times between 1 and 16 weeks.

Group NS: Osteotomy and nailing after reaming without suction. This group consisted of 15 rabbits, subdivided into 6 groups with observation times between 2 and 16 weeks.

The grouping and subgrouping of the 38 animals can be seen in Table II.

METHODS

After weighing, the rabbits were anaesthetized with Nembutal diluted in physiological saline in the proportion of 1:1; 1 ml of this

FIG. 7. - The rabbit's leg fixed on the special sledge.

solution (= approx. 30 mg Nembutal) per kg of body weight was injected into one aural vein and the needle was left in place for further maintenance doses during surgery if required. The animal was then fixed in position on a special sled-shaped operation table, as illustrated in Fig. 7.

TABLE II.

Observation time in weeks		Number of animals		Mean weight of each group before nailing (gram)		Change in weight at the end of observation time-mean value for each group (gram)	
S	NS	S	NS	S	NS	S	NS
1	—	4	—	2700	—	—330	—
2	—	5	—	3100	—	00	—
—	2	—	2	—	3200	—	00
3	—	4	—	3100	—	100	—
4	—	4 **	—	2900	—	200	—
—	4	—	3	—	3300	—	300
6	—	3	—	2800	—	270	—
—	6	—	2	—	3100	—	140
8	—	3	—	2900	—	270	—
10	—	4 **	—	3000	—	950	—
—	10	—	3 *	—	3200	—	550
13	—	3	—	3100	—	100	—
—	13	—	4 *	—	2800	—	400
16	—	3 *	—	2700	—	1000	—
—	16	—	1	—	2800	—	(1500)
		Total number 33 + 15 = 48		Variation range 2500-3600			

* = indicates one rabbit treated with « Cerclage ».
S = medullary cavity suctioned.
NS = medullary cavity not suctioned.

The fur was cut away and the skin cleaned and disinfected with antiseptic alcoholic solution. A curved incision was made, with a medial concavity extending from the upper part of the knee to the most distal part of the tibia, in this way exposing the entire anterior aspect of the tibia and the patellar ligament.

Group S (Evacuation of marrow before and during reaming).

Using a drill 0.5 mm in diameter, a hole was made through the anterior aspect of the distal cortex in the tibia. A plastic transparent catheter with an inner diameter of 0.4 mm, connected to a suction apparatus was then inserted through the hole into the medullary cavity (Fig. 8*a*). During suction the catheter was repeatedly pushed up to the upper metaphysis, and at the same time physiological saline was poured over the distal hole. When no more bone marrow was

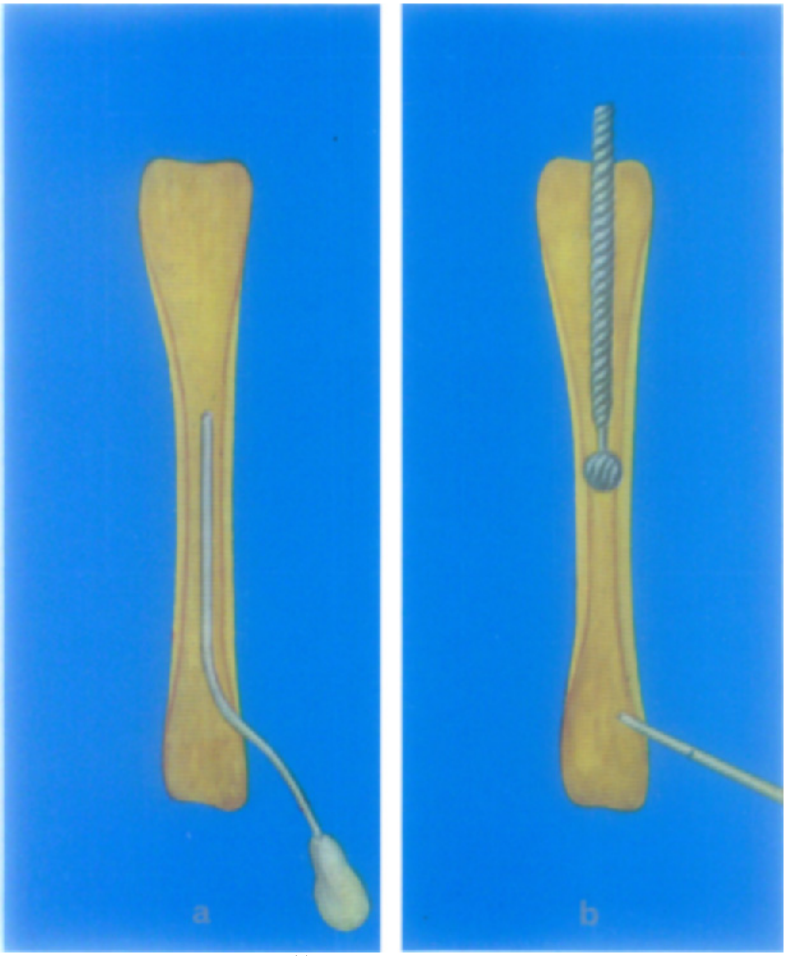


Fig. 8. - *a*) Suction through a catheter in the distal hole. *b*) Suction when reaming.

seen to be sucked through the transparent catheter, this was again pushed up as far as possible and left there (Fig. 8*b*).

The patellar ligament was then divided longitudinally, and the precondylar space of the upper tibial epiphysis was exposed. A quadrangular awl was then inserted manually below the patellar ligament, through the metaphysis and into the upper end of the marrow cavity where the tip of the catheter was located.

Group NS (Direct reaming).

The same approach was made to the medullary cavity through the proximal tibia as in group S. No distal hole was made and no suction of the medullary cavity was performed prior to reaming.

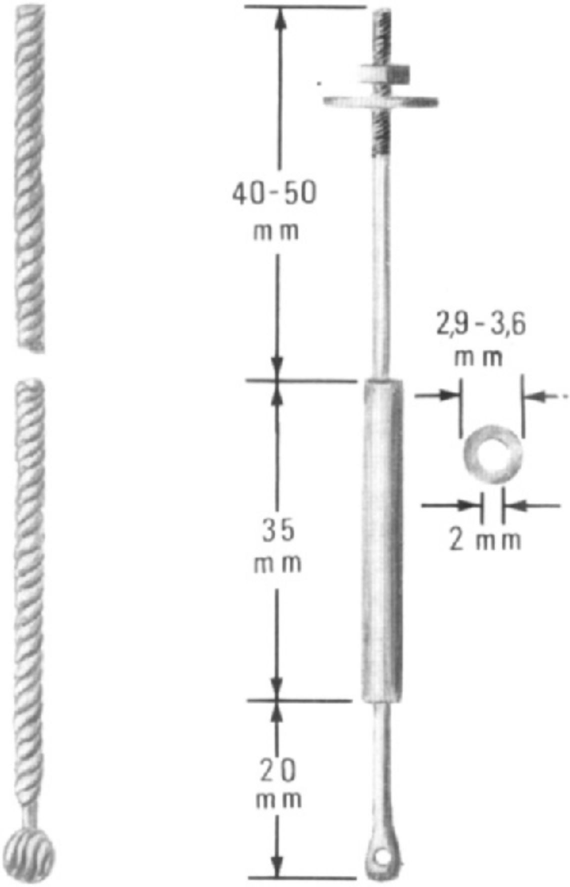


FIG. 9. - The characteristics of the reamer and the nail.

Reaming was then done in the same way in both experimental groups through the proximal hole, using ball reamers for dental surgery of diameters increasing from 1.3 mm to 3.7 mm. (For further details of the reaming technique, see Danckwardt-Lillieström 1969*c*). The reamers were specially adapted and firmly mounted on a special steel spring shaft, 0.3 mm smaller in diameter than the reamer (Fig. 9). They were connected via a Jacob's chuck to an electric motor with a rotation rate of 300 r.p.m. The internal diameter of the marrow canal varies greatly in different animals even when they are of the same body weight and size.

After the first bone had been removed, two further reamers were used, of diameters increasing by 0.1 and 0.3 mm. This was done in an attempt to obtain as identical experimental conditions as possible.

In this way the amount of cortical bone removed by reaming was estimated to correspond to about 8% of the total bone surface (in the transverse section and the middle third of the tibia).

During the reaming procedure it was common in group NS to find the formation of a medullo-hematoma in the layer between the bone and the intact periosteum, as described by Zucman et al. (1968) and by Danckwardt-Lillistrom (1969*c*). This subperiosteal medullo-hematoma, in which Danckwardt-Lilliestrom observed large amounts of fat, can occur almost anywhere around the tibia, but is more extensive just outside the openings for the nutrient arteries and emissary veins in the posterior, fibular part of the tibia.

Always during suction in group S, washing of the medullary canal was accomplished by pouring physiological saline through the upper precondylar hole, while the catheter was withdrawn to the level of the distal hole in the tibia but not taken out. This procedure with the catheter was also carried out during reaming. In fact, all reaming in this group was done with a negative pressure in front of the reamer head.

With this technique temperature increases produced by the reamer were also avoided. No medullo-hematomas were ever seen in group S.

After reaming, the periosteum was divided transversally 0.5 cm distal to the tibio-fibular junction, leaving untouched only the anterior part covering the tibial crest, which was separated finally during the osteotomy.

The osteotomy was performed at the same level with a goldsmith saw, the blade of which was 200 μ thick. To avoid rotation the osteotomy had to be done in the form of a curve with the convexity directed upward like a « dome ». During sawing, the bone was always kept moistened with physiological saline, and great care was taken to avoid as far as possible any damage or stripping of the periosteum.

The nail was especially made from V.4.A. stainless steel (AISI 316). It was constructed as a compression nail for stability reasons (Fig. 9).

The nail had to be designed in such a way as to satisfy the following conditions:

a) The curved shape of the rabbit's tibia and the need for a certain degree of elasticity demanded that the nail be constructed in three different pieces.

b) The need for a nail which would completely fit the reamed cavity, at least at the fracture site, demanded a large cylindrical intermediate section with a diameter 100 μ smaller than that of the last-used reamer. Nails with different intermediate diameters were thus used in different animals.

c) The high rotatory forces in the rabbit's leg demanded that the curved dome shaped osteotomy should be stabilized with compression.

The osteotomy stumps were then apposed and the nail was inserted from the upper prespinal epiphyseal hole, with careful hammering on its head.

When the thicker part of the nail had engaged and fixed the osteotomy line, in group NS a hole was made 2-2.5 cm distal to the osteotomy line in the anterior aspect of the tibia.

Through this hole, and in that already existing in group S, it was possible to see the location of the end of the nail during hammering. A short pin was then passed through the cortical hole and through the distal hole in the nail and drilled into the posterior distal cortex of the tibia to fix and stabilize the nail.

The upper threaded head of the nail was then adjusted beside the patellar ligament and close to the epiphyseal plate. The nut at the top of the nail was tightened until complete stability was observed in the osteotomy line under intentional stresses.

The distal transverse pin was cut at the level of the outer cortex with a pair of steel scissors.

The patellar ligament was then sutured with single silk sutures. Only one suture was used for the tibial fascia. The skin was sewn with a continuous silk suture.

No dressings were applied to the wound, apart from a double layer of plastic spray. In no case was plaster applied, nor any prophylactic antibiotic treatment given.

Recording methods

With special « Cristallite » Kodak X-ray film, roentgenograms were usually taken immediately after surgery and again at the end of the experiment after killing of the animal but before removal of the nail. Roentgenograms were also taken in most cases after removal of the nail. Only in the long term experiments were intermediate films taken, in order to check from time to time the healing of the osteotomy, the stability of the nail and the conditions of the bone. In all animals, at different times during the observation period, triple fluorochrome labelling was performed with Tetracycline, Hematoporphyrine and DCA Fluorescein, using the technique described elsewhere (Olerud and Lorenzi 1969 and 1970).

As shown in Table III, which gives the times of administration of the fluorochromes, the labelling of the newly formed bone covered 28 out of a total of 70 days of observation. At the end of the observation time the animals were anaesthetized again as described previously, and through a longitudinal midline laparotomy incision the abdominal aorta was exposed. This was cannulated with a plastic catheter 0.5 mm in diameter. Indian ink infusion was then performed

TABLE III.

Labelling code (L.C.) according to which the rabbits were labelled with Tetracycline, Hematoporphyrin and DCAF [(*N, N' di*) *carbomethyl, aminoethyl fluorescene*] *respectively.*

Observation time in weeks	Labelling day after the operative procedure		
	Tetracycline	Haematoporphyrin	DCAF
1	1	4	7
2	6	10	14
3	10	15	21
4	16	22	28
6	26	34	42
8	36	46	56
10	46	58	70
13	47	69	91
16	52	82	112

according to the technique described previously (Danckwardt-Lillieström 1969 c).

The treated left leg and the right leg were then removed and immediately deep-frozen. The greater part of the soft tissues was then removed without disturbing the periosteum, and the nail was withdrawn. The proximal and distal epiphyses were cut away and the specimens were freeze-dried until a constant weight was obtained (usually 3 days). Sections were then prepared by three different processes for examination:

1. Formalin fixation, nitric acid decalcification. Paraffin embedding, sectioning and preparation by the Spalteholz (1911) process for observation in a three-dimensional microscope.
2. Formalin fixation, nitric acid decalcification. (Paraffin embedding, sectioning and staining with the Masson technique.) Parts of the preparation were cut as frozen sections and stained with Sudan III and hematoxylin.
3. Methacrylate embedding. Sawing in longitudinal and transverse sections 0.5 mm thick, and grinding of these sections down to a thickness of between 20 and 60 μ for fluorescent light observation according to the technique described elsewhere (Olerud and Lorenzi 1969). To these undecalcified slide sections, the Goldner staining technique was also applied.

   The undecalcified ground sections were also studied with polarized light as well as by a microradiographic technique.

RESULTS

Remarks on the operative procedure

Of the total 134 rabbits operated on, 6 died under anaesthesia, (no pulmonary biopsies were taken in these cases).

Forty animals were needed for trial operations to obtain the most suitable level and shape of the osteotomy. A curved osteotomy line was used to prevent rotation, which otherwise easily occurred. Owing to the tendency of the concave surface to become fractured, the concavity was made on the proximal fragment, which was mechanically stronger than the distal one, partly because of the greater extent of reaming in the distal fragment.

A level just below the tibio-fibular synostosis was chosen for the osteotomy. In this area the inner layer of cortex was always reamed, and therefore the nail always fit closely in both fragments.

Owing to longitudinal infractions in 7 rabbits, occurring in the proximal segment of the tibia during compression, a cerclage wire was added in these cases (5 in group S and 2 in group NS). No difference was observed in the healing pattern in these animals in comparison with the remainder. These 7 animals were therefore included in the main material.

Postoperative complications

Fifteen rabbits sustained secondary fractures, mostly longitudinal in the upper part of the tibia, during the first days after operation, and they were therefore excluded from the material.

During the observation period 19 rabbits died of epidemic gastrointestinal infection with diarrhoea.

In group S no local infection occurred, nor any deaths from fat emboli.

In group NS there were 2 deaths from massive local infections and also 4 deaths from massive fat emboli, verified histologically. Of these latter 4 rabbits, one died just before the end of the operation and 3 during the first hours postoperatively. These deaths from fat emboli, which thus occurred only in group NS in which reaming was performed without suction, comprised 11 % of the total operated on in this group. During operation in this group a further 4 animals developed sudden dyspnoea and cyanosis. It seems highly likely that pulmonary fat emboli occurred also in these animals, which later recovered spontaneously.

General body reaction to the operation

The change in the mean body weight was calculated in each subgroup of groups S and NS (see Table II, p. 17). During the first week the body weight decreased in both groups. After the third week the animals in group S showed a fairly even and continuous weight increase. In group NS the body weight increase was usually slower than in group S. Also the death rate indicates that the animals in group NS were more severely affected than those in group S.

Local reactions

During the first 24 hours after operation, the rabbits held the treated leg close to their body, but after this time they seemed to use their legs in the normal way.

In group S the local reaction in the undisplaced osteotomized legs was characterized by a small spool-shaped swelling which decreased after 2-3 weeks and developed into a very small bony prominence. In group NS the swelling was more pronounced and the spool shape more elongated. After the 2nd to 3rd week the swelling was still considerable and became indurated. The time it took for the swelling to decrease was much longer in group NS.

Roentgenological findings

In most of the rabbits a good fit of the nail in the reamed cavity was seen (Fig. 4). The curved osteotomy line was hardly visible even in the short-term experiments. In the distal part of the tibia it was also possible to compare the thickness of the reamed cortex and the non-reamed cortex, and the amount of cortical bone removed could be roughly estimated (Fig. 10). Figure 11 demonstrates the shape and level of the osteotomy line in an animal observed after the 2nd week, where the gap is widened because of the absence of callus and the movement during withdrawal of the nail. The cerclage-treated animals showed no difference in the roentgenological findings from the unfractured cases (Fig. 12).

The roentgenological healing pattern differed regularly in groups S and NS (Fig. 13). In the animals with late secondary fractures (Fig. 14) it was more difficult to distinguish between the two groups.

Group S (with suction)

The peripheral osseous formation in this group was, as a rule, very thin and was observed only at the level of the osteotomy and never along the whole tibia (Fig. 15).

The fracture line was only slightly visible after 4 weeks and in most cases had completely disappeared after 8 weeks (Fig. 16*a-b*). Endosteal bone formation was nearly always present and locked the nail. This could be regarded as a sure sign of complete stability (Fig. 17).

The porosity of the cortical bone as a sign of cortical remodelling which took place in the later stages of the healing can be seen in Fig. 17.

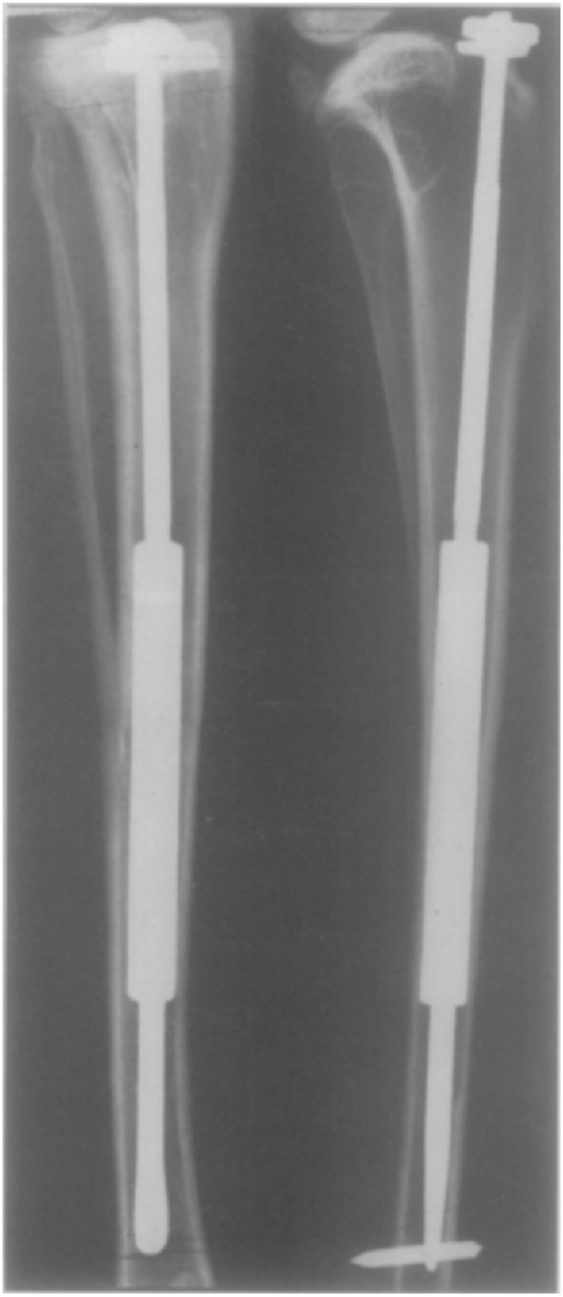


FIG. 10. - X-ray appearance just after operative procedure.

FIG. 11. - X-ray. The osteotomy line 2 weeks after operation.

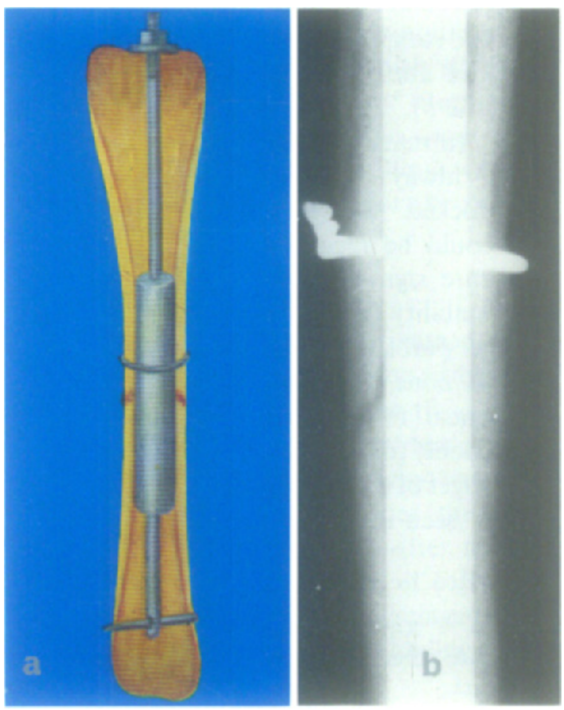
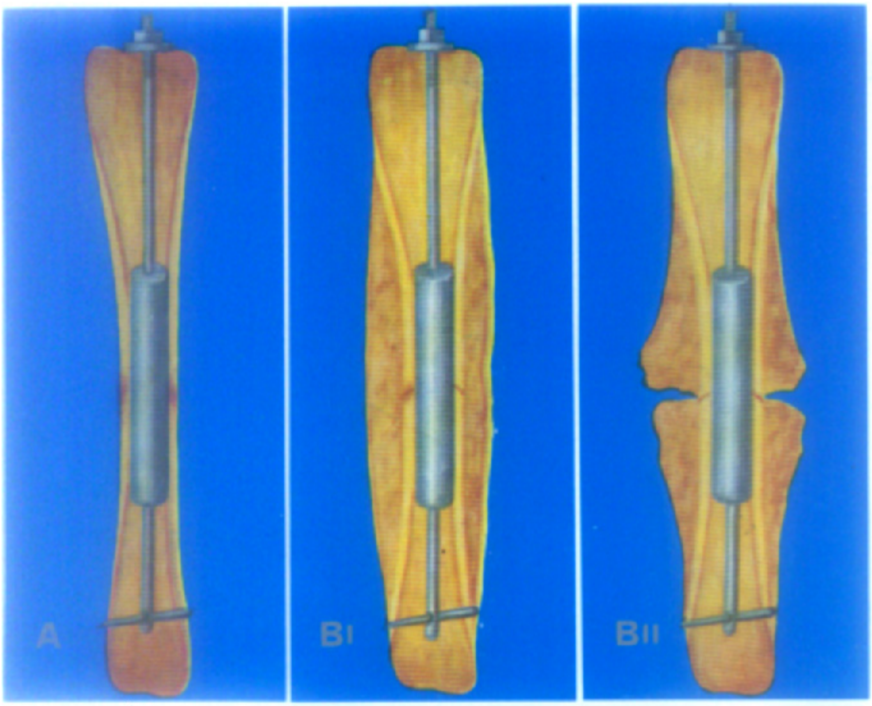
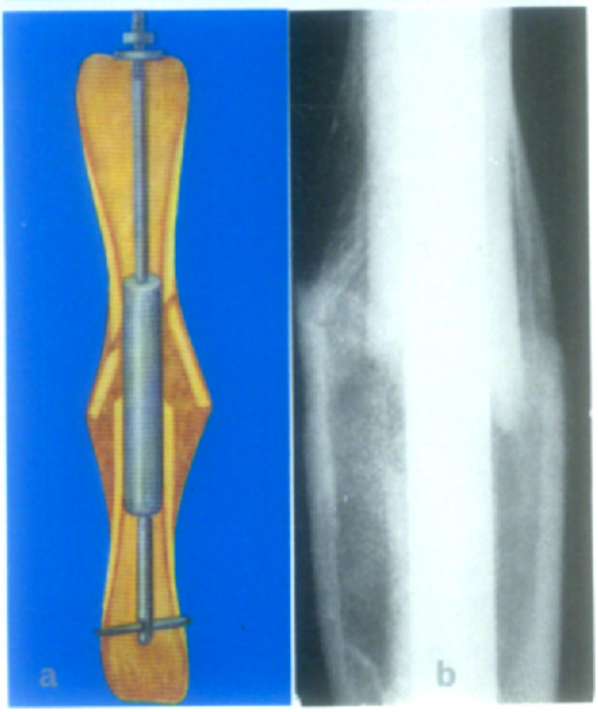


FIG. 12. - *a)* Schematic illustration of the healing after nailing and « cerclage ». *b)* X-ray of rabbit in group S 10 weeks after nailing.



Fɪɢ. 13. - Schematic illustration of the roentgenological observations. *A* refers to the observations in group S. *B*I and II refer to the observations in group NS.



Fɪɢ. 14. - *a*) Schematic illustration of healing after secondary fracture. *b*) X-ray 6 weeks after nailing.

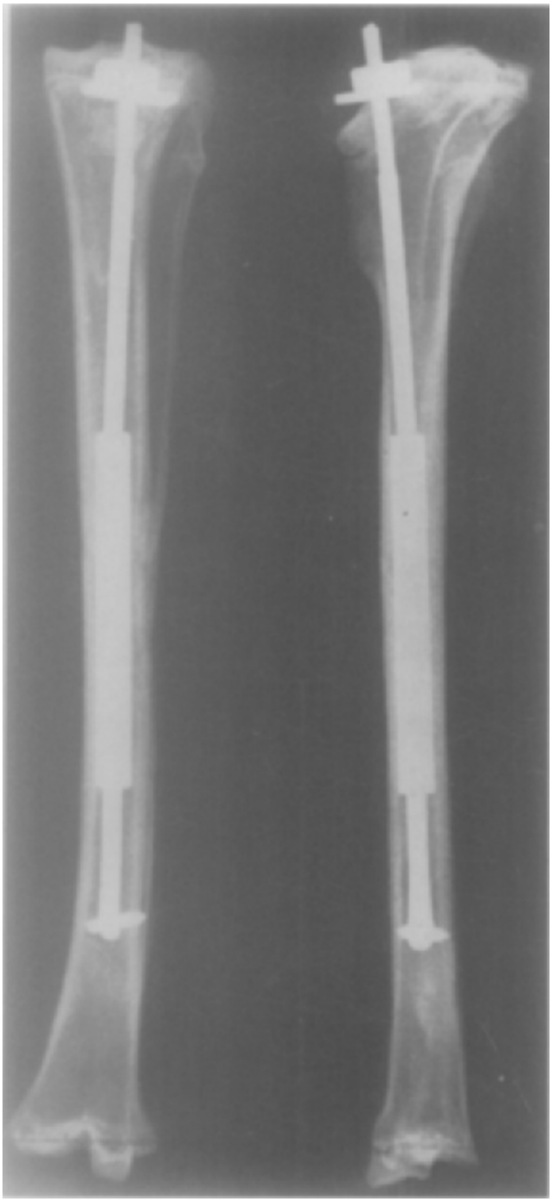


FIG. 15. - Group S. X-ray 8 weeks after nailing, showing a small thickening of the bone at the osteotomy site.

Groups NS (*without suction*)

The peripheral osseous formation, illustrated in Fig. 18, was often considerable and extended along the entire diaphysis. Sometimes it was interrupted at the fracture level (Fig. 20). A similar, but not quite so extensive peripheral bone reaction is shown in Fig. 19. Condensation of the new peripheral osseous tissue, which had the appearance of a new cortex, was observed in this group (Fig. 18). The original cortex appeared to be sequestrated and this was most pronounced close to the fracture line. The resorption of cortex was more pronounced far away from the osteotomy line.

The cortical ends, in contact at the osteotomy line, seemed to be practically unaffected by resorption. In some cases (Fig. 21) the peripheral new bone did not bridge the osteotomy line in spite of the

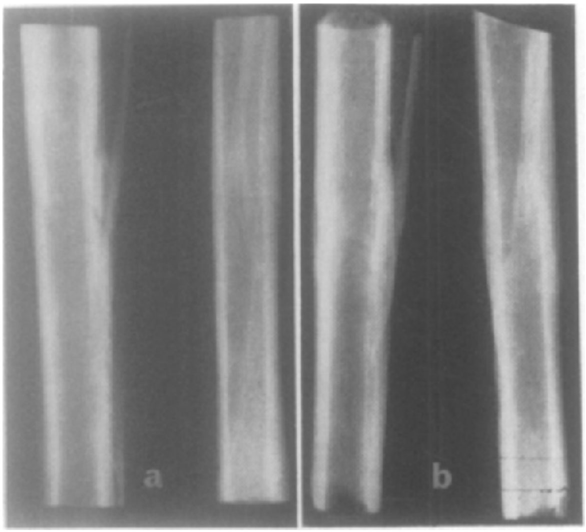


FIG. 16. - Group S. X-ray 4 weeks after nailing. Almost no peripheral reaction. Osteotomy line is hardly visible (*a*). 8 weeks after nailing: Osteotomy line still less visible (*b*).

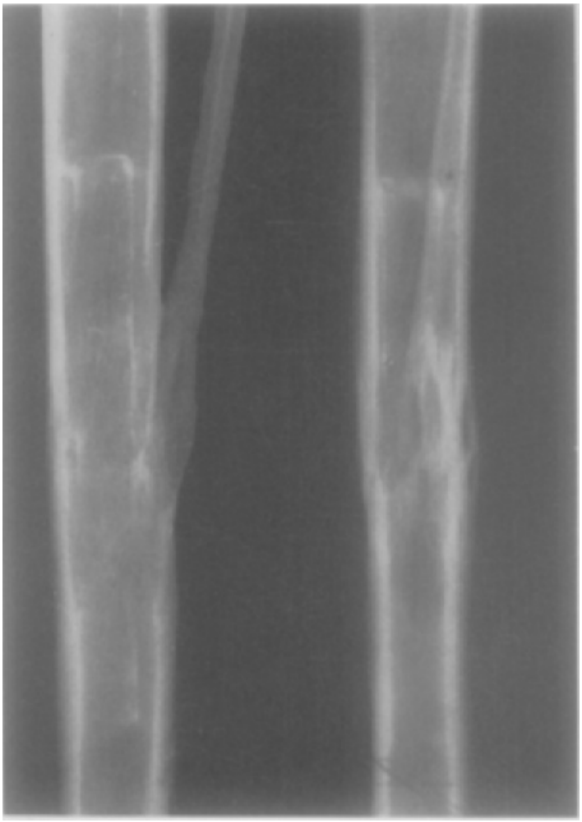


FIG. 17. - Group S. X-ray 10 weeks after nailing: a bone cast around the nail gives a negative image of the nail. The porosity of the cortex in the later stages can be seen here.

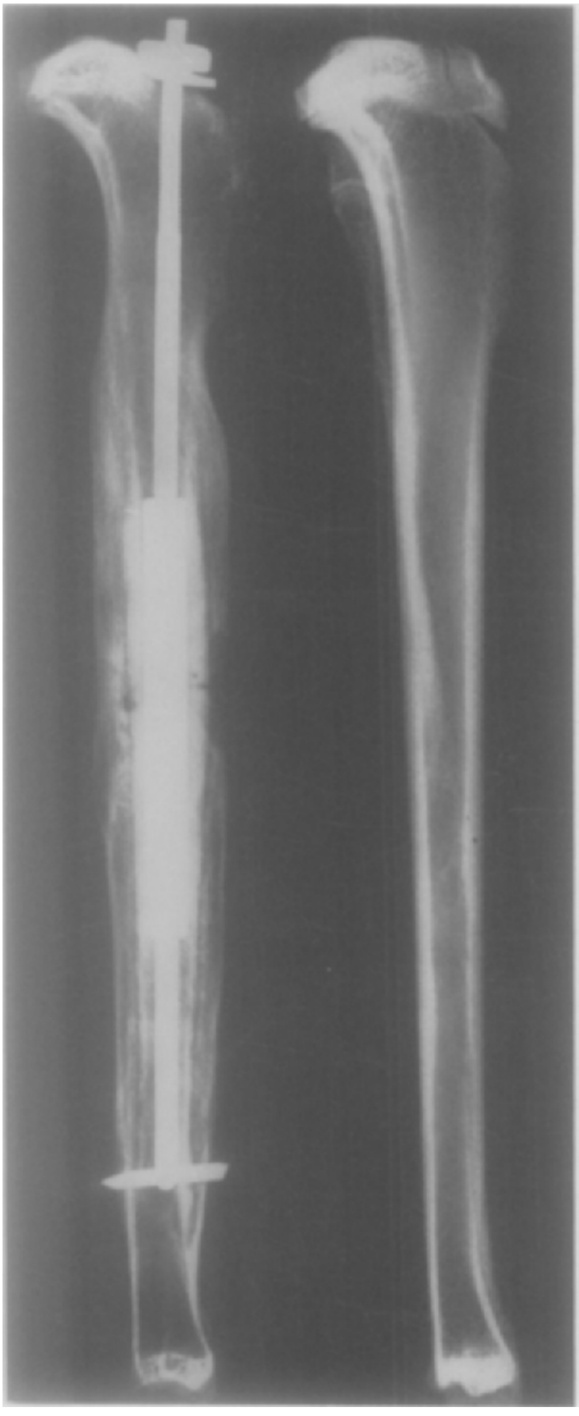


FIG. 18. - Group NS. X-ray 6 weeks after nailing: A considerable peripheral reaction is visible all along the diaphysis, which is undergoing corticalization while the old cortex seems to be sequestrated. On the right the contralateral tibia.

good stability which still seemed to exist, as indicated by the relatively unaffected cortical ends. In spite of the good apposition and stability achieved during surgery and which was still effective even after 10

FIG. 19. - Group NS. X-ray 10 weeks after nailing: the extensive peripheral reaction is larger at the osteotomy site. A pseudarthrosis is developing, and in this case the stability appears to be poor.

weeks in most cases, there was no satisfactory bridging across the osteotomy line.

Almost all animals in group NS (BI and BII in Fig. 13) could be considered to show delayed union, at least, even if not true non-union (Fig. 21).

FIG. 20. - Group NS. X-ray 13 weeks after nailing: another extensive, less mature, peripheral reaction and delayed union. On the right the contralateral tibia.

FIG. 21 A. - Group NS. X-ray 10 weeks after nailing. *a)* Pseudarthrosis. The old sequestrated cortex appears to be still in contact and well adapted. Note the corticalization of the peripheral osseous reaction. *b)* and *c)* Transverse section of upper and lower diaphysis. The central part of the cortex is sequestrated.

FIG. 21 B. - Group S. X-ray 10 weeks after nailing. *a)* Well healed osteotomy. *b)* and *c)* Transverse section of upper and lower diaphysis.


b
b
a
a
c
c
A
B

MICROSCOPICAL OBSERVATIONS

Vascularity and rebuilding of cortex

The experimental procedure always resulted in total damage to the intramedullary circulation, and close to the osteotomy line also in periosteal damage. This damage, due to stripping of the periosteum around the osteotomy, was estimated to extend about 1 cm above and 1 cm below the osteotomy line. This meant total primary avascularity of the osteotomy area.

Group S

In one preparation observed after one week the cortical ends were completely avascular (Fig. 22). In the distal and also, mostly, in the upper part of the diaphyseal cortex, far away from the osteotomy

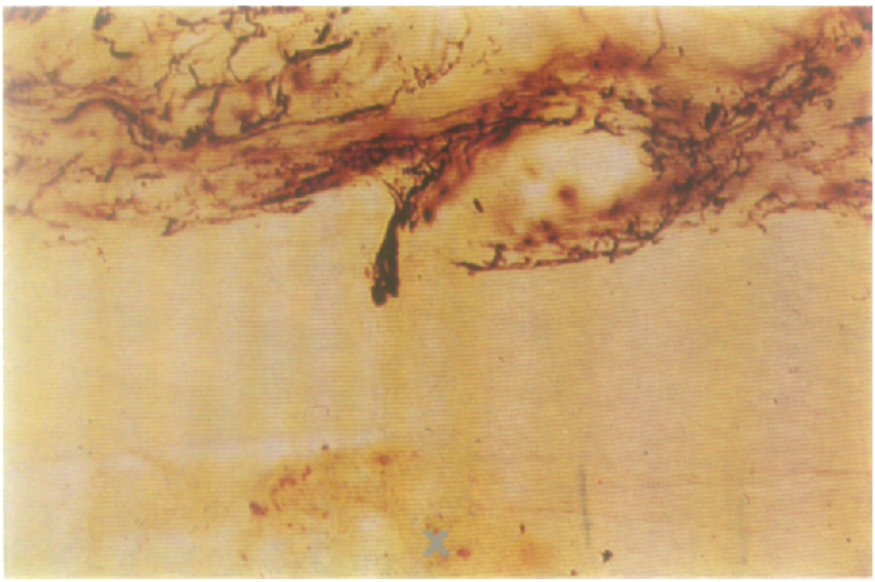


FIG. 22. - Group S. Spalteholz preparation 1 week after nailing. Complete avascularity of the cortical ends. A vascular loop is entering the osteotomy line. × Medullary cavity.

line, it was common to observe an almost normal intracortical circulation (Fig. 23). During the first week the intracortical vassels became wider. The vascular front was located at the level of the damaged and undamaged periosteum.

The first vessels very soon grew into the peripheral avascular part of the cortex, however, even at the level of the osteotomy line where the periosteum had been separated from the cortex during surgery and been replaced before closure of the wound. Around the vessels

FIG. 23. - Group S. Spalteholz preparation 4 weeks after nailing. Almost normal intracortical circulation at the upper nail level, where the endosteal circulation is also well re-established.

penetrating the avascular cortex there was progressing resorption, seen mainly in the third and fourth weeks (Fig. 24*a* and *b*). Later in the healing process the revascularization activities involved the development of many cutter heads which usually passed through the cortex in the direction towards the osteotomy line (Fig. 25). Sometimes

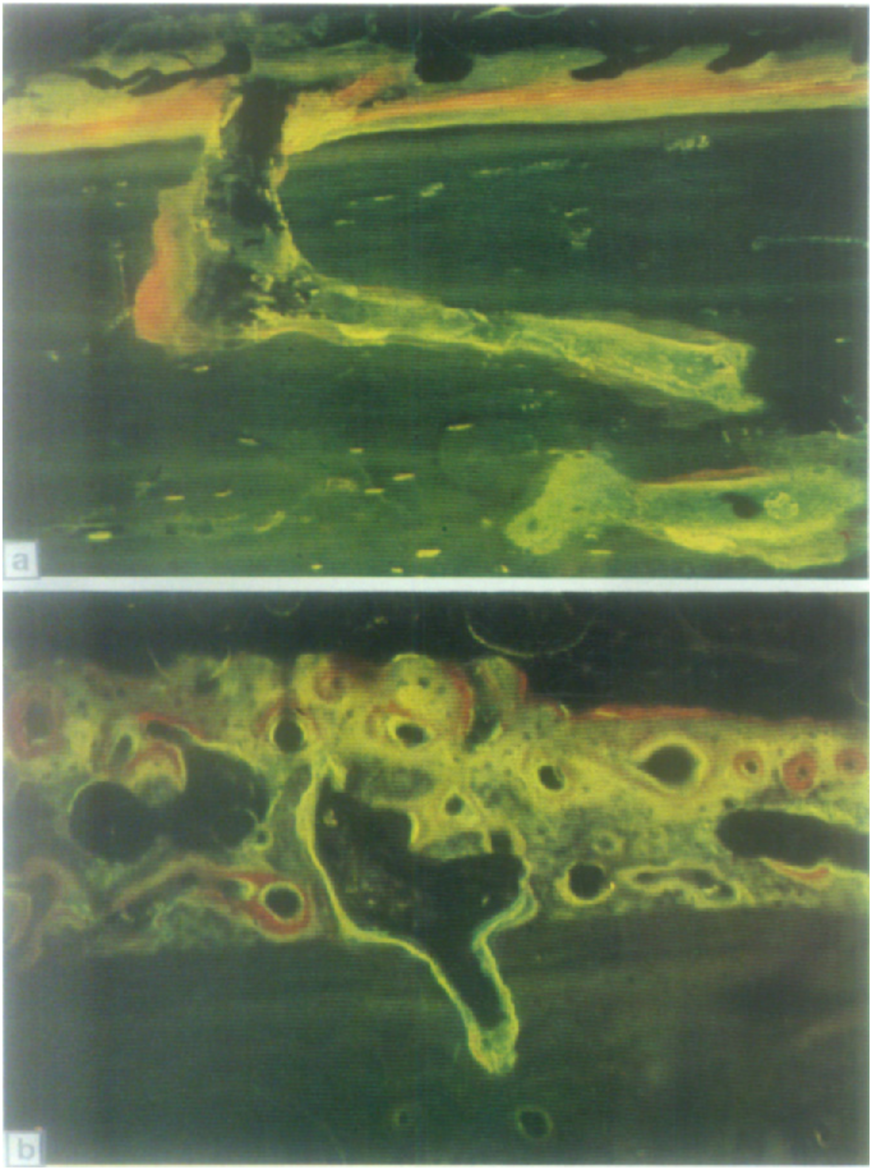


FIG. 24. - Group S. Fluorescence preparation 3 weeks after nailing (L.C. 10-15-21) *a*) Penetration and widening of vascular canals from the periosteal area. The vessels are directed towards the nearby osteotomy line located to the right. *b*) The same appearance in a transverse section.

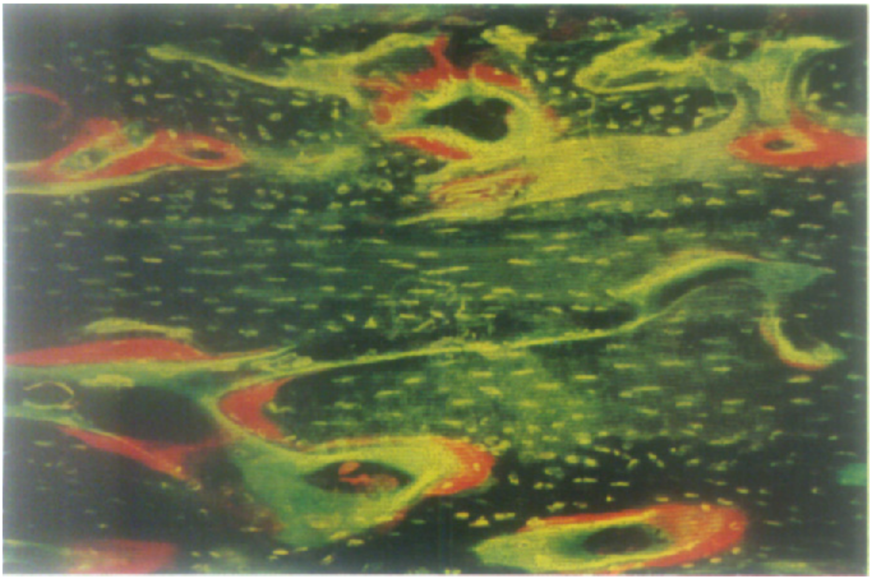


FIG. 25. - Group S. Fluorescence preparation 4 weeks after nailing (L.C. 16-22-28). Cutter heads are remodelling the cortex and progressing towards the osteotomy line.

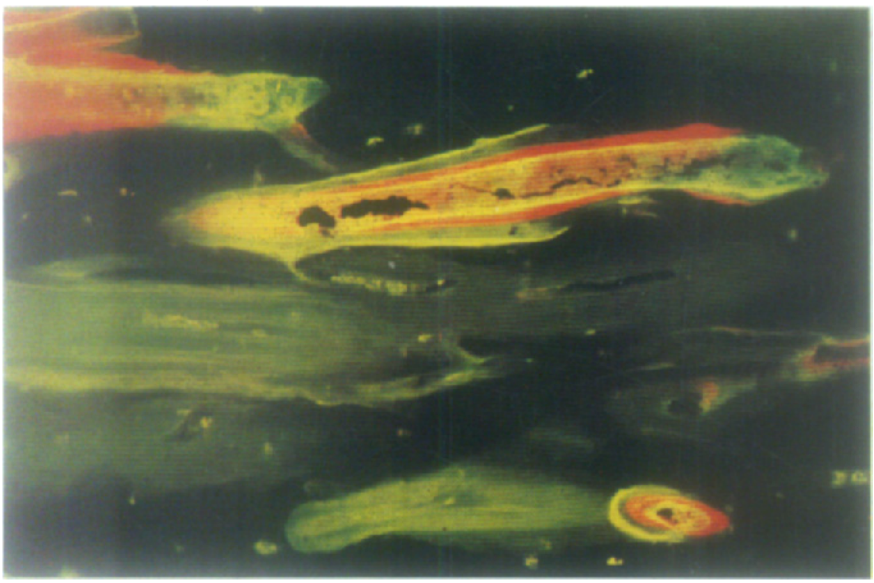


FIG. 26. - Group S. Fluorescence preparation 8 weeks after nailing (L.C. 36-45-56). Remodelling of the cortex. From resorption cavities (red and green) new canals (green) are moving along the cortex.

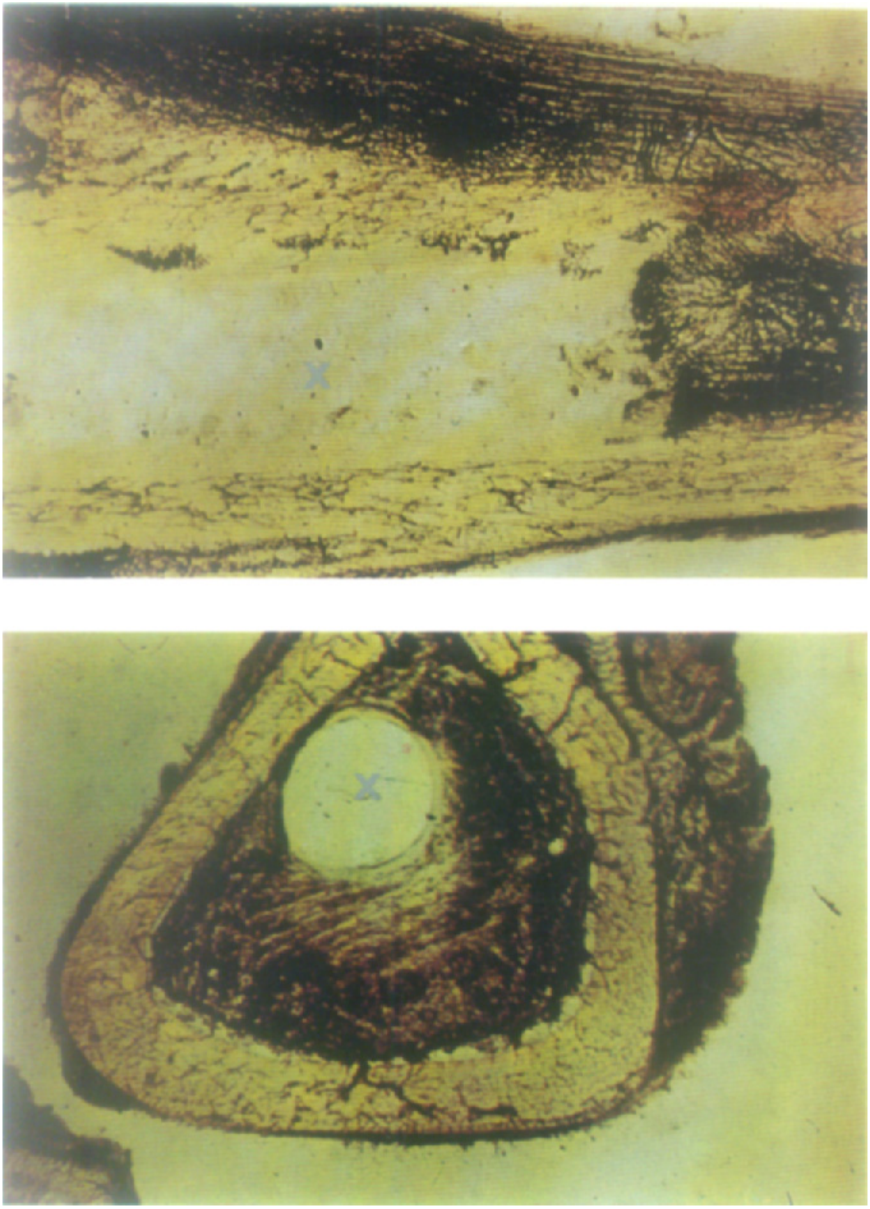


FIG. 27. - Group S. Spalteholz preparation 6 weeks after nailing. *a*) Abundant intramedullary vascularization has reached the upper part of the nail. The vessels are beginning to supply the inner cortex and to join the peripheral circulation. *b*) The transverse section also shows the small upper nail pin embraced by the new bone. · indicates the site of the nail.

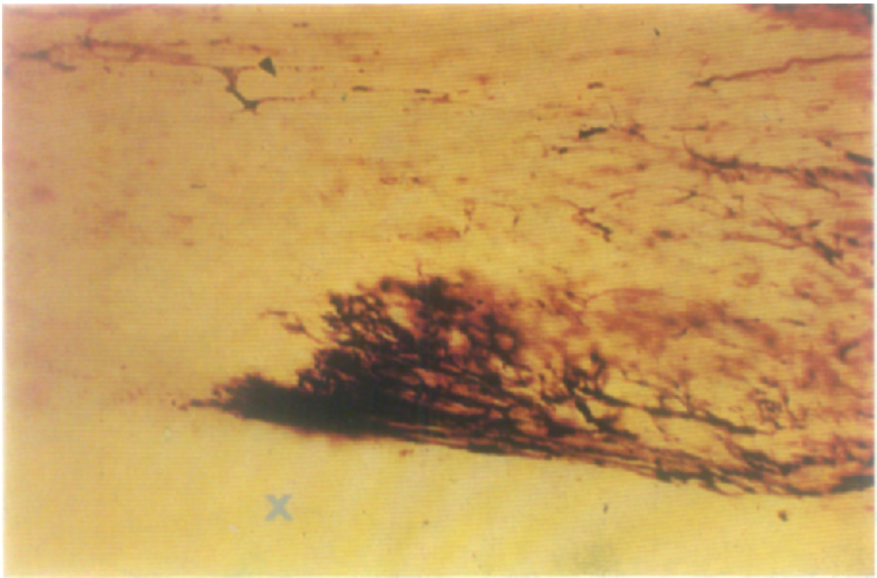


FIG. 28. - Group S. Spalteholz preparation 6 weeks after nailing. Abundance of vessels attacking the inner avascular cortex just adjacent to the nail.

these cutter heads, supplied by vessels coming from the periosteum, seemed via resorption lacunae to excavate the cortex, often the middle part (Fig. 26). The cortex could be revascularized from endosteal vessels in some cases as early as in the 2nd and 3rd weeks, but the 4th week was more usual for revascularization from this direction. These vessels penetrated the cortex especially in the region above the upper end of the nail (Fig. 27*a* and *b*). They often gave rise to resorption at the inner wall of the cortex and revascularized the inner part of it (Fig. 28).

Group NS

The avascularity of the cortex in this group was often very extensive. It was caused not only by the rupture of marrow vessels but also by marrow fat particles which had been forced out into the intracortical canal system. The avascularity lasted for a very long time. In a preparation six weeks after osteotomy there were still large areas without any Indian-ink filled vessels (Fig. 29).

The revascularization process of the cortex appeared to be quite different from that in group S, although in some cases the invasion of blood vessels from the periosteum close to the osteotomy line was similar.

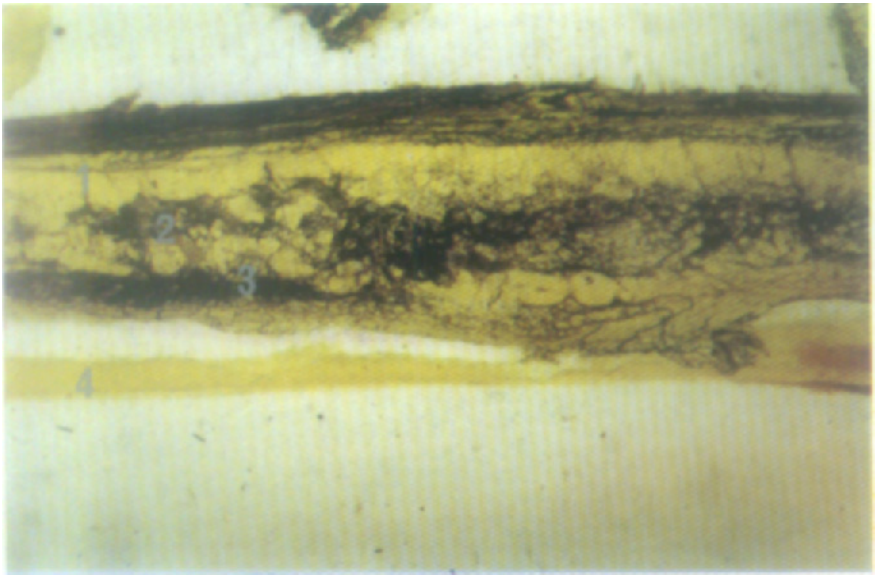


FIG. 29*a*. - Group NS. Spalteholz preparation 6 weeks after nailing. Revascularization pattern. From top to bottom. 1) Outer corticalized peripheral layer; 2) large vascular lacunae; 3) vascular communications with outer revascularized cortical layer; 4) sequestrated inner cortex.

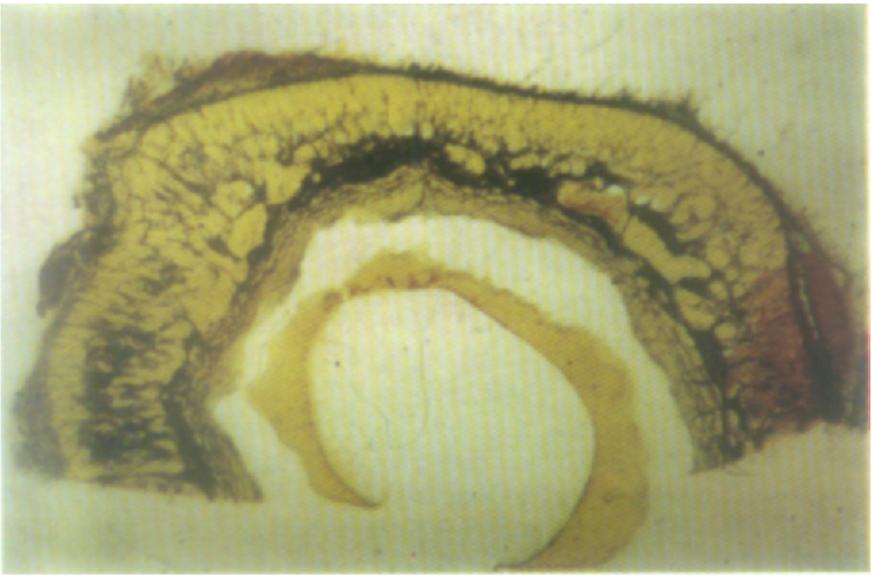


FIG. 29*b*. - Transverse section of preparation in Fig. 29*a*.

In comparison with group S, only a few vessels seemed to enter the cortex. Other vessels joined in cavities to form wider sinusoids often located in the middle part of the diaphyseal cortex. These vascular cavities increased in size and became more elongated along the cortex, forming a kind of reticular system. The cortical bone seemed to become « dissolved » or « melted down » in a peculiar way. This resorption procedure did not present the typical appearance of pure osteoclastic activity.

In its most pronounced form this « melting » activity would divide the cortex into one central layer which in some cases was sequestrated

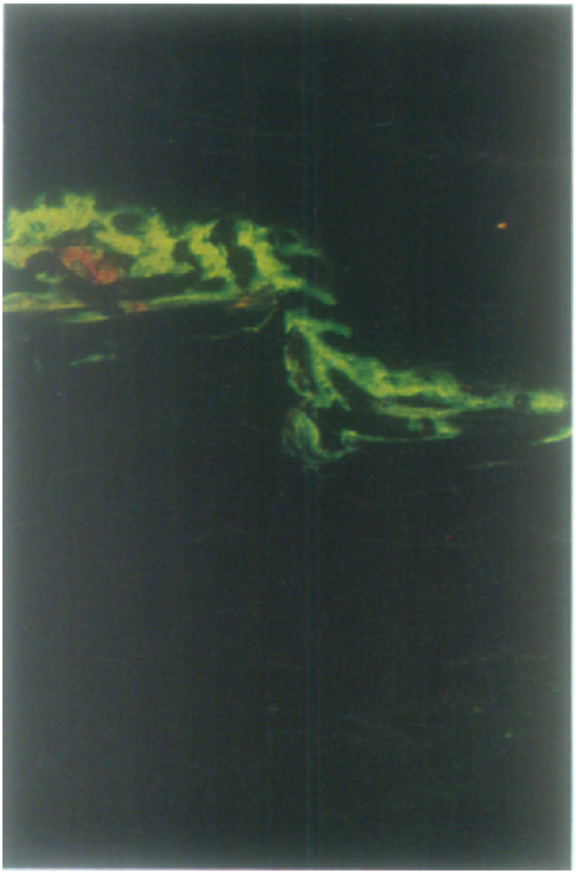


FIG. 30. - Group S. Fluorescence preparation 2 weeks after nailing (L.C. 6-10-14). The red labelling shows the first bone deposition under the stripped periosteum after ten days. The activity has increased very rapidly during the next days and the bone is labelled with green on the 14th day.

completely (Fig. 29) and one outer layer which would later be included in the remodelling of the new cortex in one way or another (Fig. 29).

Periosteal bone formation

Close to the gap, where the periosteum had been incised, ingrowing vessels and cells from surrounding tissues contributed to bone

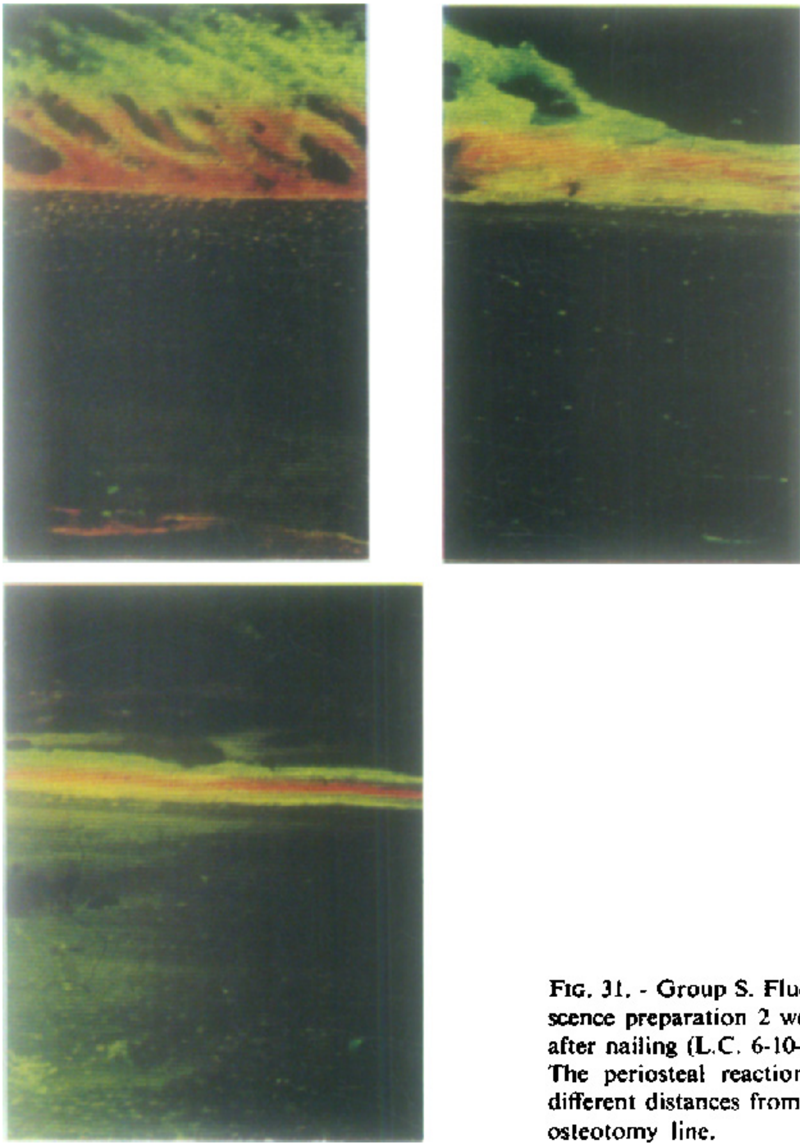


FIG. 31. - Group S. Fluorescence preparation 2 weeks after nailing (L.C. 6-10-14). The periosteal reaction at different distances from the osteotomy line.

formation. Away from the osteotomy line the bone was only formed subperiosteally.

Group S

In this experimental group the new bone reached a limited thickness only close to the level of the osteotomy line. The first periosteal reaction was seen to have occurred on the 3rd to 4th day in the hematoporphyrin-labelled bone, up to a distance of 0.5 cm from the osteotomy line. This newly formed bone often bridged the osteotomy line after the first week (Fig. 30). In the 1st and 2nd weeks it had the typical appearance of trabecular bone, later usually forming primary osteones in several layers. From the level of the osteotomy line, these osteones decreased in number and thickness along the diaphysis and finally ended in a layer of superficial lamellar bone far away from the osteotomy line (Fig. 31). Later, in the 6th to 8th weeks, the outer layer of trabecular bone underwent remodelling by superficial resorption of the ridges and by lamellar bone formation around the vessels in the intertrabecular spaces, a process which resulted in condensation, or corticalization, of the outer layer of the periosteally formed bone (Figs. 32 and 33). In the innermost layer just outside the cortical bone and close to the osteotomy line, resorption activities predominated, with typical Howship's lacunae eroding the outer cortex and resorption of the inner part of the newly formed trabecular bone (Fig. 33). This process terminated in the formation of limited cavities which then tended to unite. The tendency of these cavities was to move slowly into the cortex as a result of resorption from the central cortical wall and accretion of bone to the inner side of the peripheral wall.

Group NS

The periosteal bone formation was always very pronounced all along the diaphysis (Fig. 34). In comparison with group S, the bone formation began some days later. In some cases it showed even distribution along the diaphysis, but in the early stages it was also possible to see parts of the bone without any subperiosteal bone formation. Close to the osteotomy line, newly formed bone was seldom seen on the surface or in the gap. This was observed, however, in one preparation after 2 weeks (Fig. 35). During the time up to the 4th week the newly formed periosteal bone could reach enormous proportions, in some cases up to 8 times as much as observed in group S (Fig. 34).

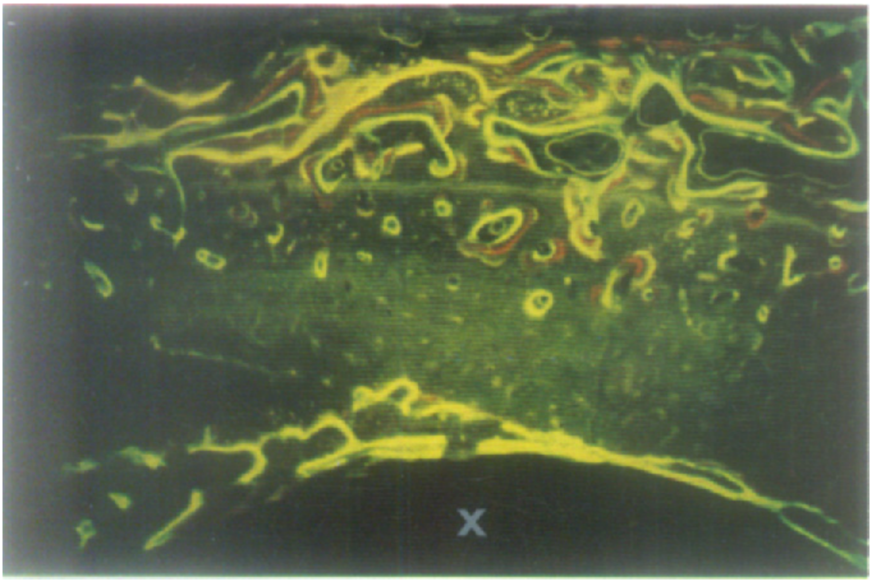


FIG. 32. - Group S. Fluorescence preparation 6 weeks after nailing (L.C. 26-34-42). The outer peripheral reaction is undergoing resorption. Condensation is clearly demonstrated by the triple fluorochrome linear labelling. In the inner part just in contact with the nail a layer of green labelled bone can be seen.

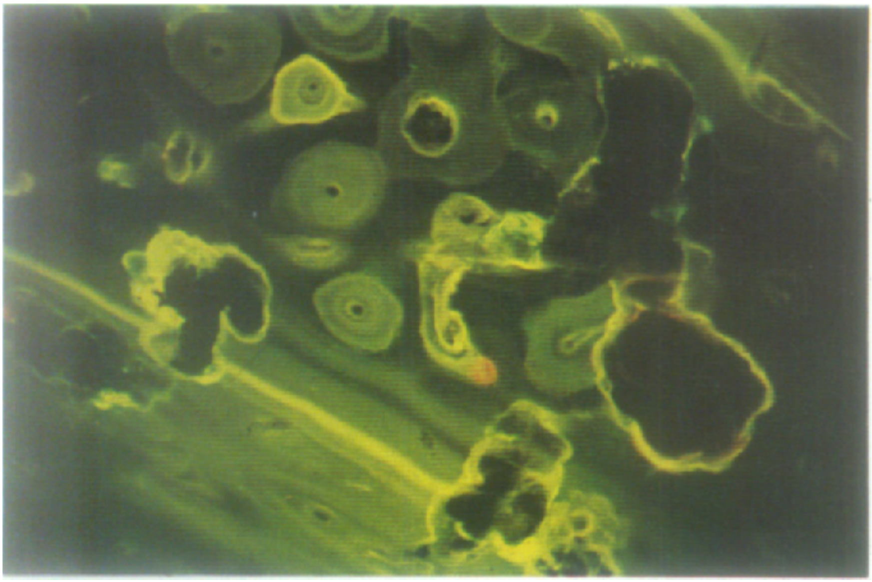


FIG. 33. - Group S. Fluorescence preparation 6 weeks after nailing (L.C. 26-34-42). Resorption cavities in the inner part of the peripheral bone.

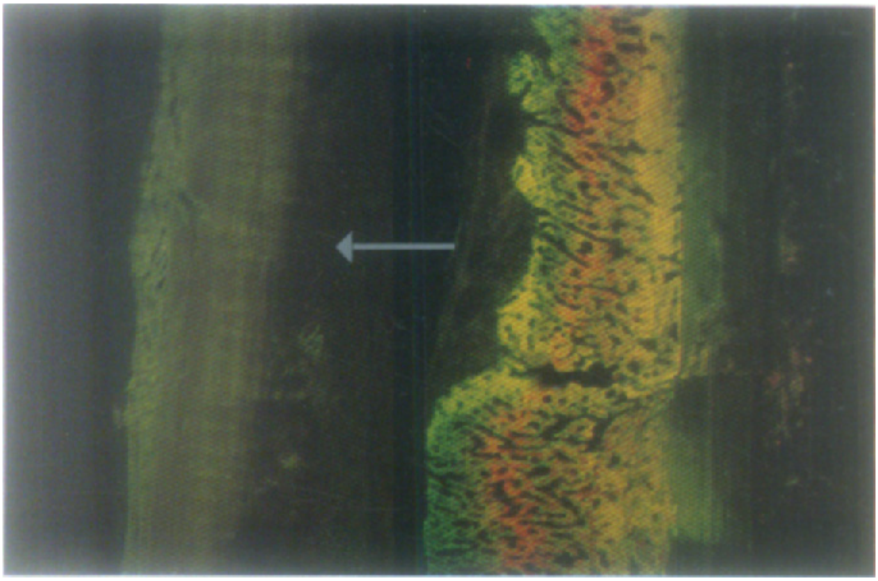


FIG. 34. - Group S (left). Fluorescence preparation 4 weeks after nailing. The enormous peripheral reaction in group NS (right) attains almost 8 times the size of that observed in group S (L.C. 16-22-28). The arrow indicates the osteotomy line.

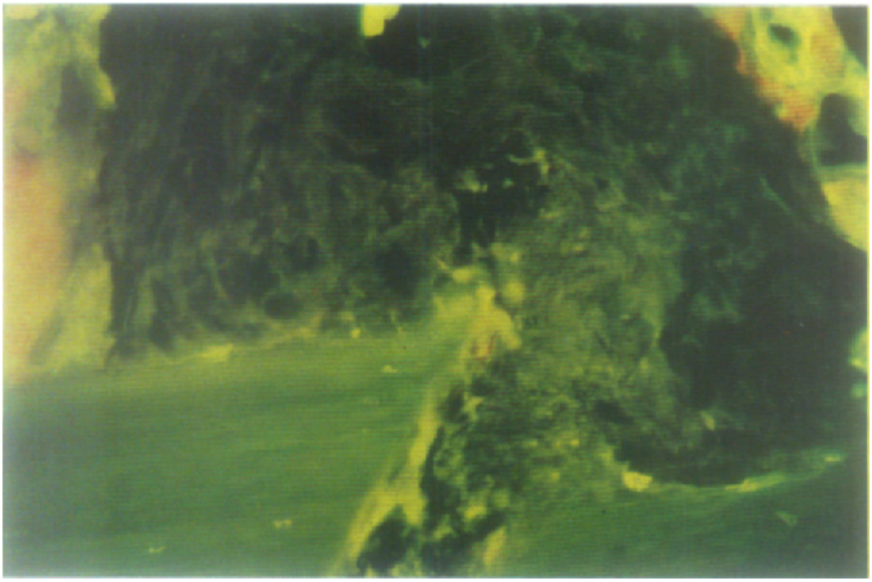


FIG. 35. - Group NS. Fluorescence preparation 4 weeks after nailing (L.C. 16-22-28). At the fracture line the periosteal bone formation is interrupted by vascular granulation tissue with wide resorption areas. Note the large vessels.

This bone consisted of long spicular trabeculae. Close to the fracture gap these trabeculae were orientated towards the gap, but further away along the diaphysis the orientation was perpendicular to the cortex as if very strong bone induction was taking place.

FIG. 36. - Group NS. Fluorescence preparation 6 weeks after nailing (L.C. 26-34-42). Bridging external callus, no activity in the fracture ends.

The periosteal reaction gave newly formed woven bone, which moved like a wave towards the osteotomy level with increasing observation time. In between the « waves » from each side, fibrous tissue, large vessels (Fig. 35) and sometimes cartilage cells were seen. This observation could, of course, be interpreted as a demonstration of instability, but very often, in other parts of the same tibia, periosteal

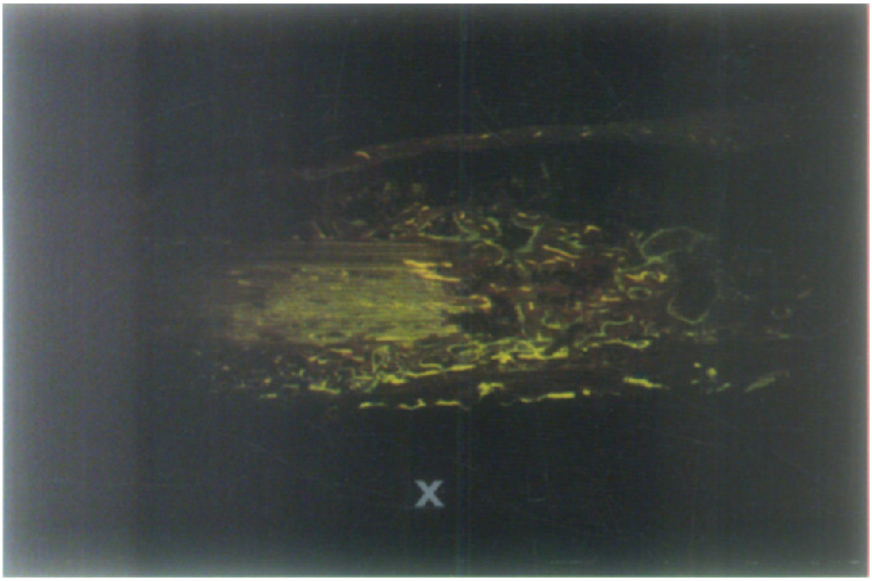


FIG. 37. - Group NS. Fluorescence preparation 13 weeks after nailing (L.C. 47-69-91). Peripheral bridging corticalization. Rebuilding and sequestration of old cortex. At the bottom the site of the nail is seen.

callus could be seen to bridge the osteotomy line (Fig. 36). In the following weeks, beginning from the end of the 6th, the newly formed periosteal bone underwent final maturation. Outside the osteotomy gap, this process followed the same pattern and stages as in group S. The bone maturation and formation of cystic resorption cavities showed only quantitative differences (Fig. 37).

Intramedullary reaction

When reaming, owing to the irregular shape of the medullary cavity, only parts of the innermost cortical layers will be removed (Fig. 38). The *a* zones (see figure) of the medullary cavity are not totally removed by the reamer, but obviously the vessels there must be severely damaged. The nail itself usually fits very well in the distal part of the canal, but will be free from contact with the cortex at several points in the upper part of the diaphysis (Fig. 38).

The revascularization of the medullary cavity and of the inner part of the cortex usually follows three pathways:

1. from the undisturbed upper and lower metaphysis along the *a* zones.

2. directly through the cortex, mainly observed in the upper part of the diaphysis,
3. through the fracture gap where such exists.

Group S

The appearance of vessels in the medullary cavity, growing through the gap, was already observed after the first week (Fig. 39*a* and *b*). A network of vessels in the *a* zones, partly coming from the upper

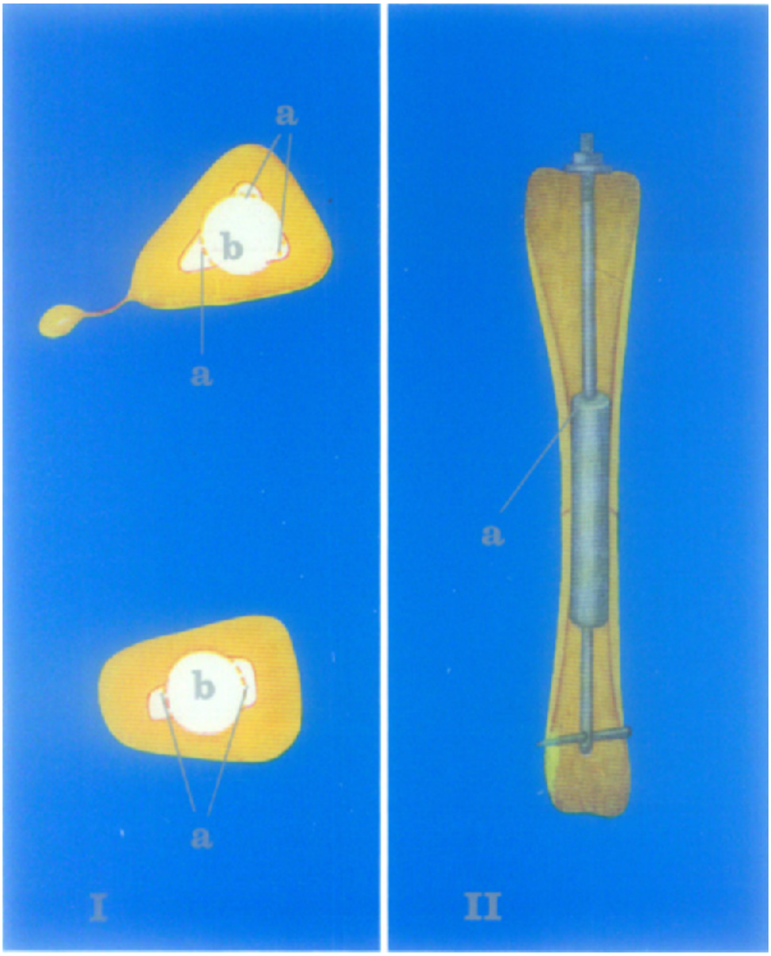


FIG. 38. - Schematic diagram illustrating: I) reamed areas of inner cortex (*b*) and non-reamed parts of the medullary cavity (*a*); II) the fitting of the nail and the free zones where the medullary circulation has free space.

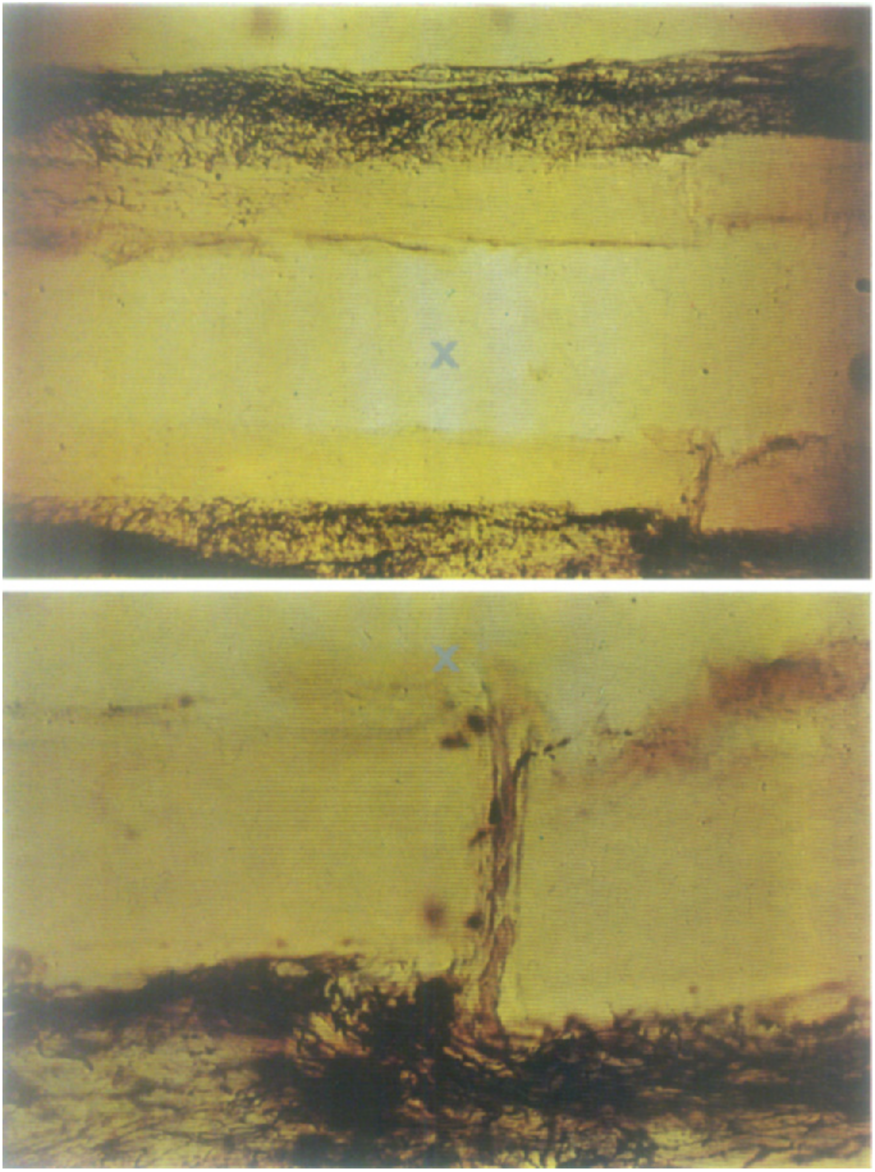


FIG. 39. - Group S. Spalteholz preparation 2 weeks after nailing. *a*) The extent of the avascularity is well demonstrated. Abundant peripheral vascular reaction. Single blood-vessel branches are passing into the osteotomy gap (bottom right). From the proximal fragment the vascular front is progressing together with intermedullary vessels (top left). *b*) Enlargement of the former pictures. (Lower osteotomy line.)

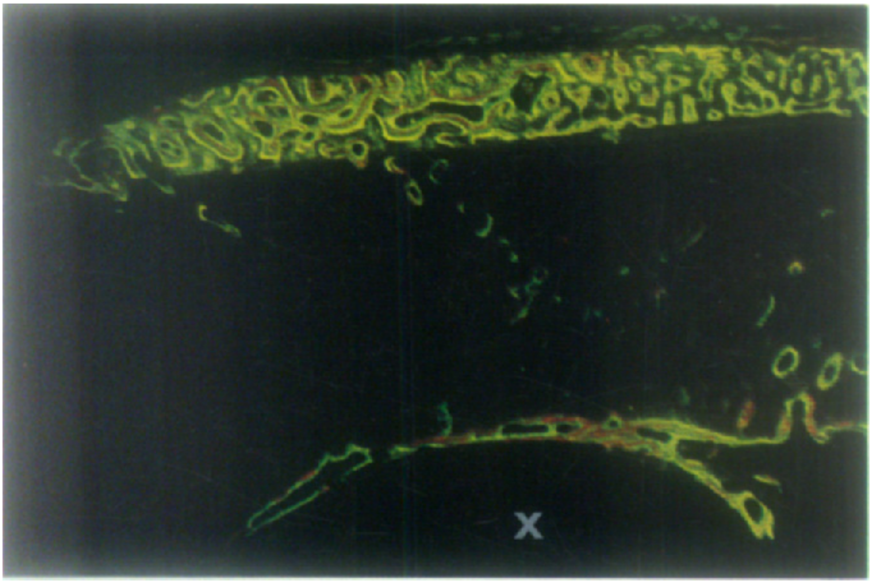


FIG. 40. - Group S. Transverse section. Fluorescence preparation 4 weeks after nailing (L.C. 16-22-28). Newly formed bone enclosing the nail is labelled with yellow (zone *a*), red and green (zone *b*). Note the resorption of peripheral ridges.

FIG. 41. - Group S. Transverse section. Fluorescence preparation 8 weeks after nailing (L.C. 36-46-56). Centrally a large vessel with a lacunar appearance is traversing the cortex and divides into two branches embracing the nail. Intense remodelling in the outer part of the cortex.

end, was seen after the third week. At the same time, single vessels appeared in the *b* zones between the reamed cortex and the nail.

From the third week onwards newly formed bone was seen in the *a* zones immediately adjacent to the nail. The progression of bone formation in the section shown in Fig. 40 can easily be timed. Common also was the observation of vessels directly crossing the cortex and growing almost as far as the nail where they sometimes divided in the form of a T, which embraced the nail (Fig. 41). The further remodelling of the cortex proceeded in a typical manner, consisting of erosion of the inner cortical layer with simultaneous deposition of lamellar bone around the nail (Fig. 42).

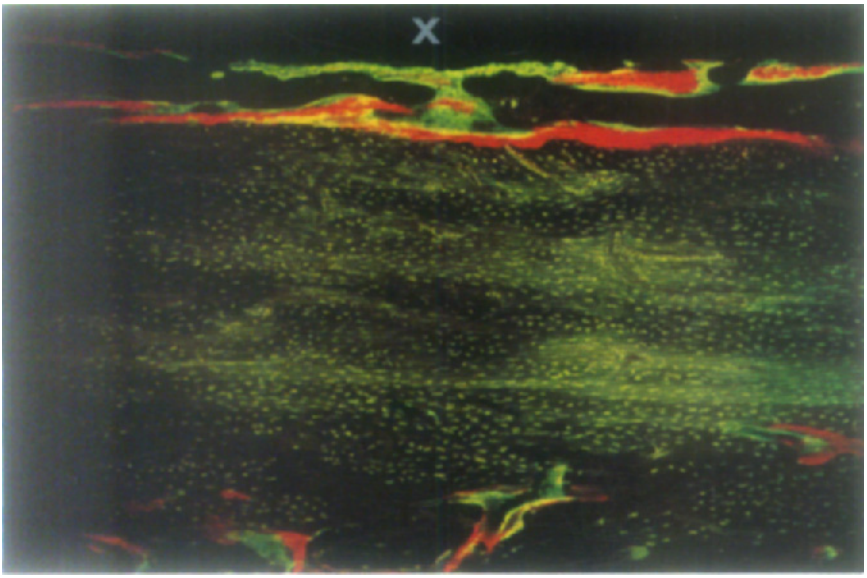


FIG. 42. - Group S. Fluorescence preparation 4 weeks after nailing (L.C. 16-22-28). Remodelling of the inner cortex with simultaneous erosion and deposition of bone lamellae along the nail. Note the rebuilding in the outer cortex (bottom).

The process of erosion of the inner part of the cortex resulted in the confluence of many different cavities surrounding the newly formed bone around the nail (Fig. 43). These cavities contained blood vessels and new bone marrow with marrow cells and fat cells. The vessels, often as large as vascular lacunae, frequently seemed to be in communication with the metaphyseal vascular system, which, after the

4th week, usually took a more active part in the supply of the inner cortex with blood vessels (Fig. 44). In still later stages the new bone around and close to the nail became thicker, and also acquired a more mature appearance (Fig. 45).

Group NS

The intramedullary reaction in this group was usually extremely delayed, except in some rare cases, where the intracortical circulation had not been so severely disturbed (compare zone *a* in Fig. 38 I).

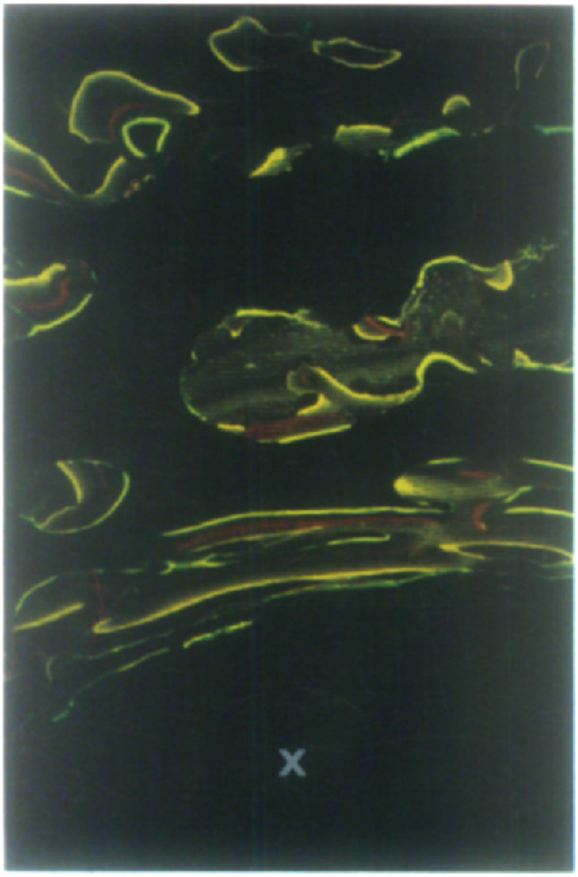


FIG. 43. - Group S. Transverse section. Fluorescence preparation 10 weeks after nailing (L.C. 46-58-70). Maturation of the inner cortex with confluence of erosion cavities. Lamellar bone around the nail.

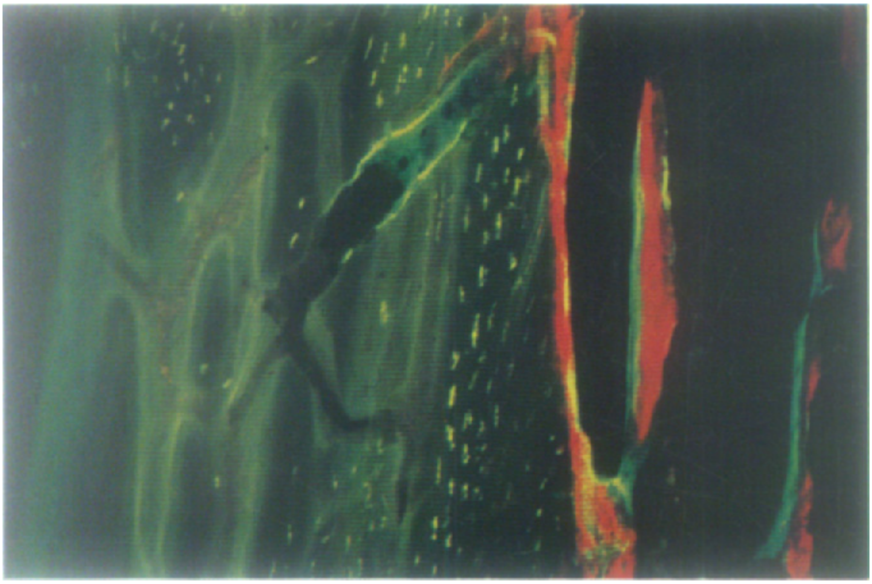


FIG. 44. - Group S. Fluorescence preparation 4 weeks after nailing (L.C. 16-22-28). Revascularization of the inner cortex from vessels between the nail and cortical wall.

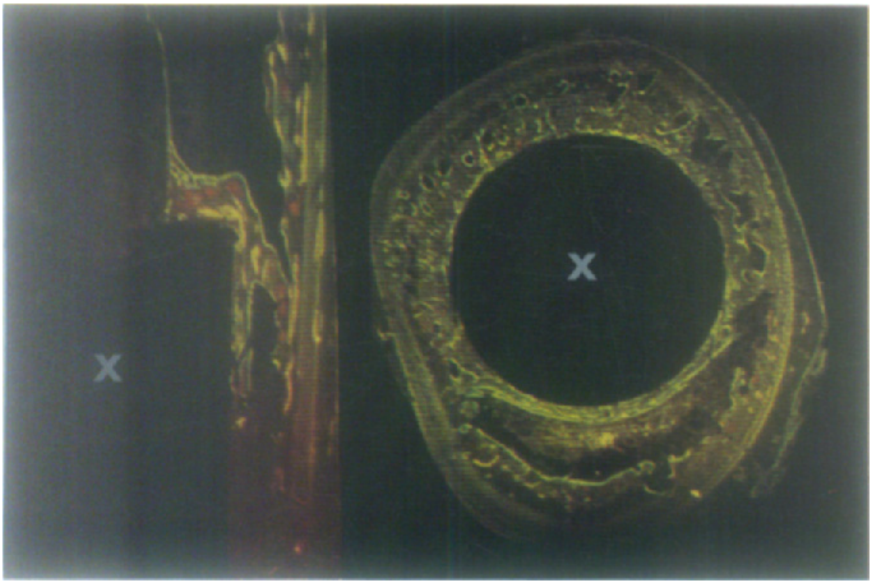


FIG. 45 A. - Group S. Fluorescence preparation 13 weeks after nailing (L.C. 47-69-91). Locking of the nail. Left: longitudinal section shows the upper part of the cast which consists of matured bone well attached to the cortical wall by large beams. Right: distal transverse section demonstrates the stability of the nail. Note the spongy appearance of the middle cortex.

The nail and the bone formation

Group S

Very soon after the vessels reached the nail, usually in the 3rd or 4th week, it became surrounded by newly formed bone (Figs. 40, 42 and 44) which increased successively in amount and maturation (Fig. 43). The bone formed a cast, so to speak, which embraced all three parts of the nail (Fig. 45 A and B). This bone cast around the nail can be regarded as an expression of the total stability of the fixation system.

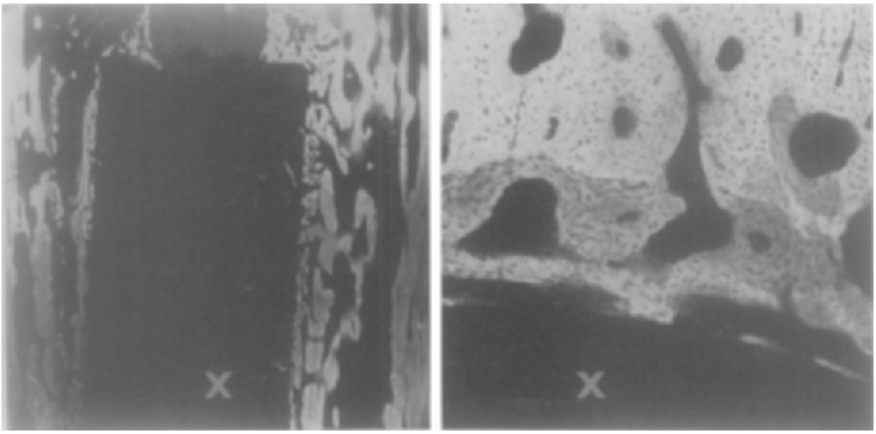


FIG. 45 B. - Corresponding preparation investigated with microradiography. Note the well adapted bone cast of the nail.

Group NS

Up to the 10th week no new bone was usually formed around the nail in this group. In sections examined after the 13th week, incomplete bone casts with a considerable amount of fibrous tissue between the bone and the nail were found. This finding can probably be regarded as a sign of instability.

Osteotomy line

The intramedullary nail, because of its central position, should be the ideal device for achieving equal compression all along the circumference of the contact surfaces of the osteotomy. This condition was not always obtained in our experiments. This was partly due to the slightly curved shape of the rabbit tibia in the longitudinal axis, while the nail was purely cylindrical and was unable to bend in its central part. The curved osteotomy itself cannot always be ideal for good apposition in spite of the fact that it prevents rotation. For these reasons we usually observed in the same animal an osteotomy which was well apposed and had complete contact on the one side of the tibia, but with a gap on the other side.

Group S

The first signs of healing of the osteotomy line started with vascularization. Vessels could appear in the gap as early as in the first week (Fig. 46). When the bone contact is absolute, vascular invasion from the periosteal side is very difficult. In these areas an ingrowth of

FIG. 46. - Group S. Fluorescence preparation one week after nailing (L.C. 1-4-7). In the well adapted osteotomy line a tiny vessel is proceeding.

vessels with simultaneous bone resorption was not observed before the 3rd week. This resorption was almost immediately followed by formation of lamellar bone in the form of primary osteones. The resorption area was U-shaped with formations resembling cutter heads, occurring on both sides of the line, which was often respected as if resorption of the fracture surfaces was more difficult (Fig. 47). The

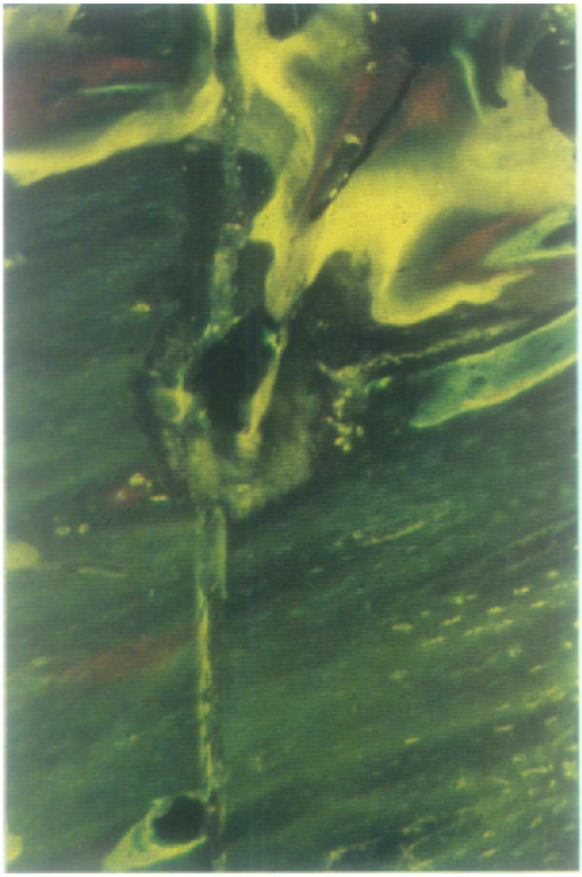


FIG. 47. - Group S. Fluorescence preparation 6 weeks after nailing (L.C. 26-34-42). *U*-shaped area of resorption and deposition of the cutter head type.

osteotomy line, filled out in this way by bone, was later crossed by secondary osteones in the 5th to 6th week.

The U-shaped bone remodelling with resorption and bone formation in the gap eventually connected the two fracture ends. This

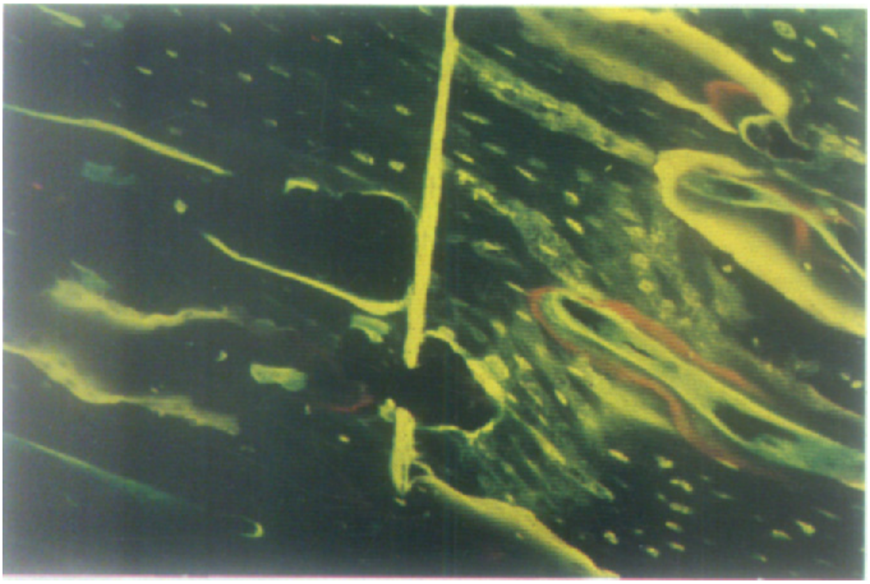


FIG. 48. - Group S. Fluorescence preparation 6 weeks after nailing (L.C. 26-34-42). Secondary osteones are approaching the osteotomy line, and cutter heads stop at the line to produce an « elephant foot » formation.

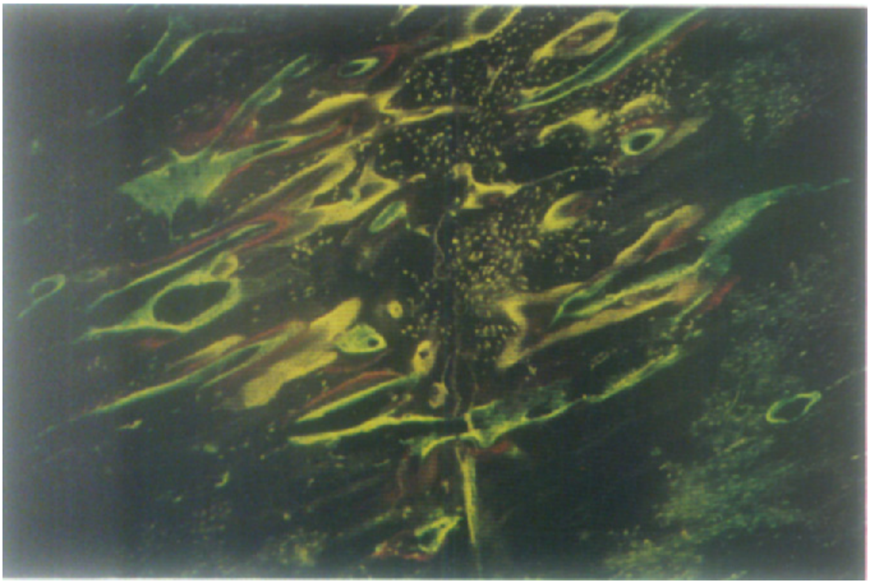


FIG. 49. - Group S. Fluorescence preparation 6 weeks after nailing (L.C. 26-34-42). The healing is almost completed in the outer layer of cortex. The innermost part, where the last osteone has passed through, is still undergoing remodelling.

process came to a stop in its progression along the osteotomy line, after which the newly formed bone underwent maturation. Parts of the closely adapted osteotomy line remained unchanged until it became rebuilt by traversing secondary osteones. Termination of the revascularization process was a very frequent finding and we cannot give any acceptable explanation for it.

The secondary osteones usually appeared earlier in the upper fragment than in the lower. A frequent observation was termination of the excavation by the cutter heads for the secondary osteones at the osteotomy line, where they widened to form the shape of an elephant's foot (Fig. 48).

This finding suggests that the osteone head was searching for a canal in the opposite fragment for its further growth on the other side. This pattern fits well with the common observation that a new secondary osteone usually grows along the old devitalized canals. The crossing of osteones from the distal fragment was observed later in the healing process, after the 8th to 10th week.

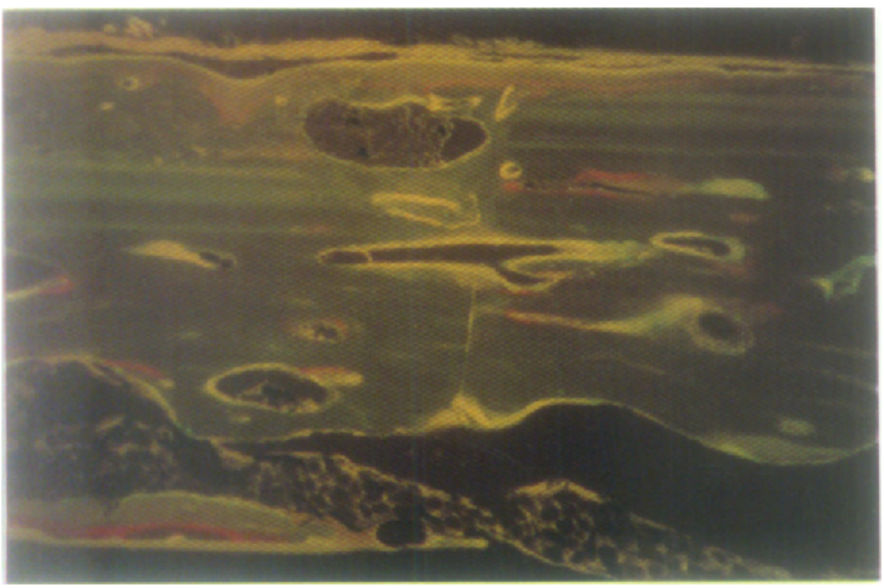


FIG. 50. - Group S. Fluorescence preparation 16 weeks after nailing (L.C. 52-82-112). Osteotomy line still visible. A large secondary osteone crosses the line in the centre of the cortex. Periosteal lamellar bone deposition is going on since at least the time of the red labelling-day 82. Bottom left: part of the lamellar bone cast surrounding the nail.

After the 10th week most of the osteotomy line was filled with new transversely formed bone, and many longitudinal osteones crossed the osteotomy line, including that part where there was close contact. In this way the remodelling of the osteotomy line would become completed, even if some small parts of it remained unchanged for a very long time (Fig. 49 and 50).

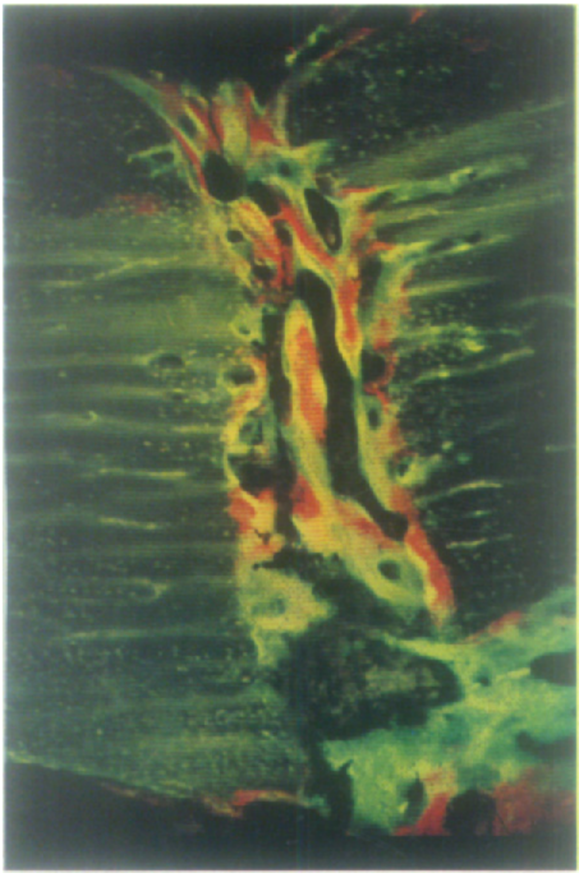


FIG. 51. - Group S. Fluorescence preparation 3 weeks after nailing (L.C. 10-15-21). Wide osteotomy gap early invaded by vessels. Yellow labelled bone (10th day) is seen at the entrance of the gap. Lamellar bone is deposited during the red through green period. Note the retrograde vascularization of the cortical ends.

The wide gap was quickly invaded by new vessels coming from the network produced by the peripheral vascular reaction. Primarily

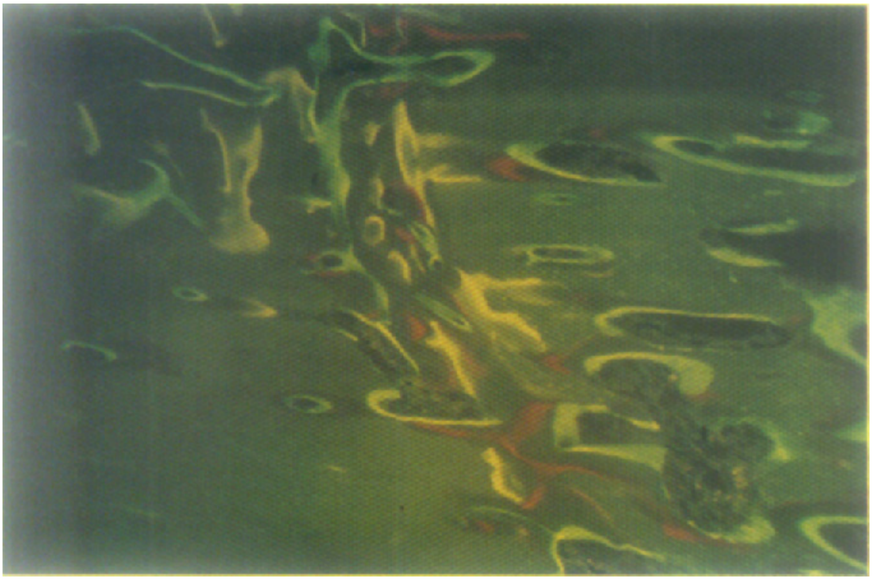


FIG. 52. - Group S. Fluorescence preparation 10 weeks after nailing (L.C. 46-58-70). The longitudinal remodelling of the transversally deposited bone in the gap.

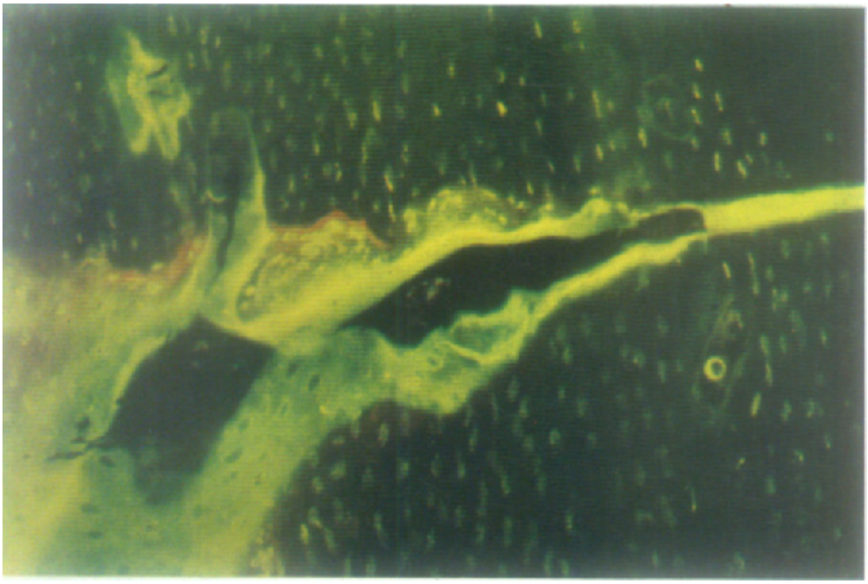


FIG. 53. - Group S. Fluorescence preparation 10 weeks after nailing (L.C. 46-58-70). Triangular shaped area of resorption and deposition. This process is usually not delayed.

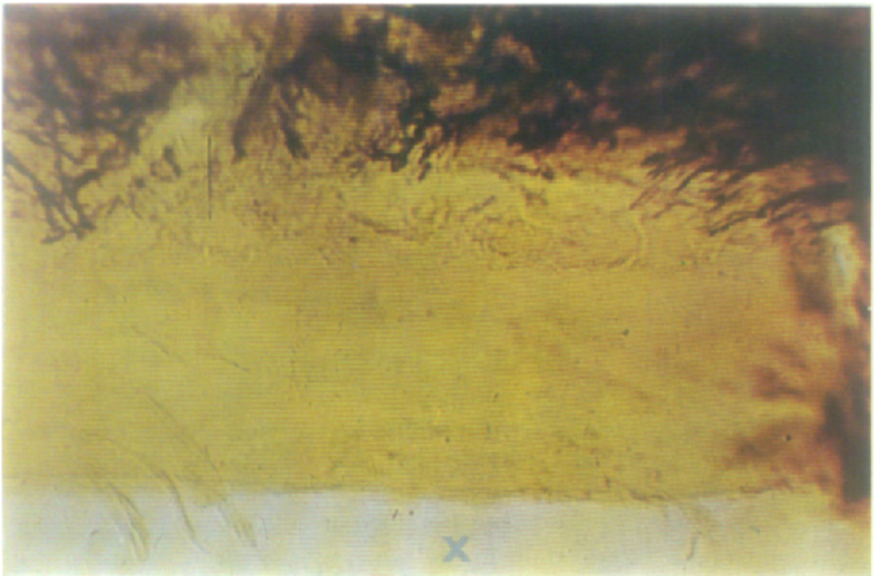


FIG. 54. - Group NS. Spalteholz preparation 2 weeks after nailing. Total avascularity of the cortex even far away from the osteotomy line on the right.

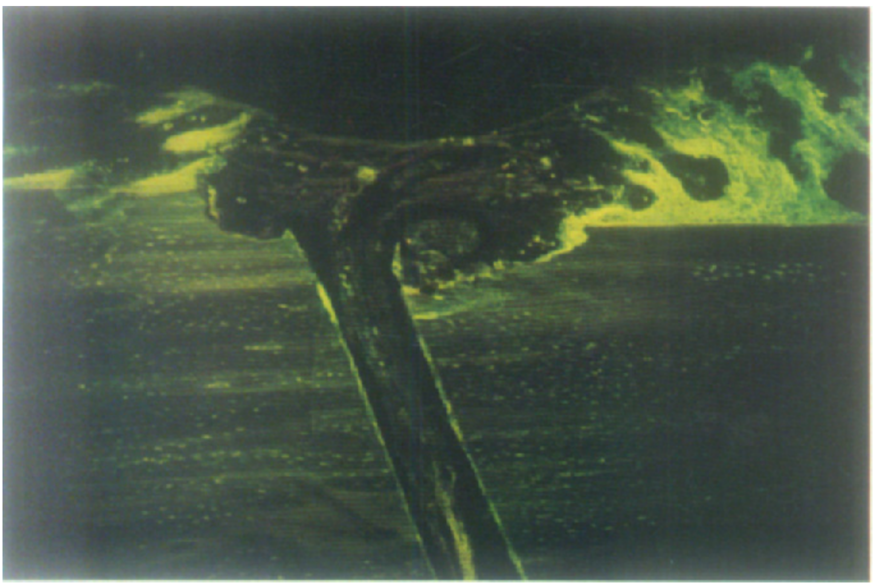


FIG. 55. - Group NS. Fluorescence preparation 2 weeks after nailing (L.C. 6-10-14). The peripheral reaction is delayed, marked with only green labelling. Resorption scalloping in both fracture ends. No bone in the gap.

woven bone was formed around these vessels. This bone was later condensed by the formation of primary osteones and sometimes also by secondary osteones. These transformed the newly formed bone into mature lamellar bone disposed transversally along the gap, usually between the 3rd and 6th weeks (Fig. 51).

The bone was often firmly fixed to the borders of the gap, which was often found to be eroded by osteoclastic resorption arches (Fig. 51).

After the 3rd to 4th week, vessels from the gap sometimes, though not often, found their way into the cortical ends, forming a typical pattern, which is shown in Fig. 51. Here, as well as in the well adapted osteotomy line, secondary osteones crossed the gap after the 6th week, remodelling the bone already formed and restoring the longitudinal architecture of the diaphyseal bone (Fig. 52).

In some cases a wedge-shaped defect was found at the outer part of the osteotomy line, probably caused by the sawing and not an effect of resorption. This defect was filled at an early stage with woven bone, which was later rebuilt in the same way as the bone in the wide gap (Fig. 53).

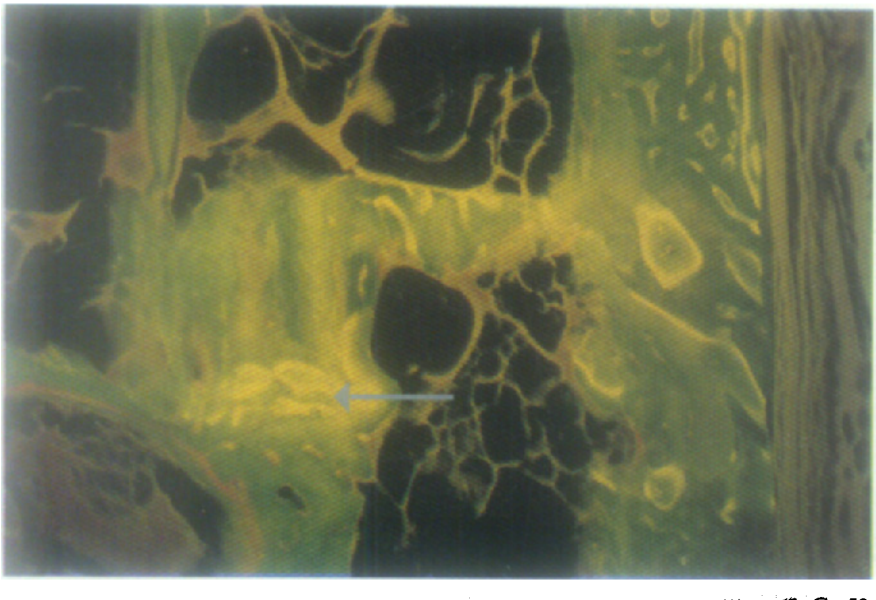


FIG. 56. - Group NS. Fluorescent preparation 16 weeks after nailing (L.C. 52-82-112). The cortical ends have been largely resorbed and the old bone is replaced by large cortical cavities. There is, however, some interfragmentally formed bone visible at the level of the arrow and the cortical end contact is defective. The periosteally formed bone is condensed to a strong reliable fragment uniting bridge (right).

Group NS

The most impressive finding was the lack of vessels and bone in the gap. In Spalteholz preparations examined after the 2nd and also the 4th week, there was an almost total absence of vessels in the cortical ends (Fig. 54).

This is remarkable in comparison with the rapid revascularization observed in group S. Even after the 6th week, when some bone would appear in the osteotomy line, the osseous communication between the fragments consisted mainly of a bridging periosteal cuff.

The cortical ends always remained totally « cold » and avascular without any signs of vessels entering the cortex (Fig. 55), and very seldom cutter heads were seen there even in the 10th week. The characteristic secondary osteones so often observed during this time in group S seemed to have been replaced by the formation of large resorption intracortical cavities. At this time—the 10th week—interfragmental new bone connected the ends of the necrotic cortical bone in some cases (Figs. 56 and 37).

DISCUSSION

Nailing has for many years been a well accepted and valuable method in the treatment of some diaphyseal fractures. Improvements of the technique, however, have been based more on clinical experience than on experimental studies.

Reaming of the medullary cavity with the use of a stronger nail has increased the number of fractures suitable for this treatment. This method has greatly improved the stability and has made immediate weight bearing possible. These are very important factors in the treatment of diaphyseal fractures. Opponents of the method often argue that this mode of treatment causes extensive damage to the circulation of the bone and, as a consequence, increases the risk of complications such as infections and delayed union. They also point out that the method may increase the swelling of the leg and cause circulatory disturbances (Nylander and Semb 1970). The opponents therefore consider that the advantages of the method do not compensate for its disadvantages.

On nailing, and especially on reaming, the medullary vessels in the diaphyseal part of the bone are destroyed. This, together with the periosteal damage caused by a fracture or by an experimental osteotomy, can result in some damage to the cortical circulation.

Previous experiments on rabbits have shown that reaming in the medullary cavity often produces a high intramedullary pressure that forces bone marrow into the intracortical canals, where it may obstruct a large part of the circulation (Danckwardt-Lillieström 1969*c*).

If, however, the reaming is performed after previous evacuation of the marrow contents and during suction of the medullary cavity, the cortical avascularity can be reduced to a very great extent (Danckwardt-Lillieström et al. 1970).

With the present experimental work we have tried to evaluate in what way an osteotomy, firmly stabilized with a compression nail, will heal in the presence of different degrees of cortical damage provoked by the reaming.

The « dome-shaped » osteotomy just below the level of the tibio-

-fibular synostosis, stabilized by a compression nail, has proved to be a suitable model.

The aim of the compression nail is to obtain such good stability that the vascular proliferation in the osteotomy area will not be mechanically disturbed. The compression itself certainly does not induce bone formation, but only maintains the stability, especially by preventing rotation. The compression forces sometimes resulted in slight deformation of the osteotomy ends, but in our opinion the deformity does not produce any disturbance of the cortical canals outside the deformed area.

In group S, since the fatty marrow had been evacuated previously, the impairment of the cortical circulation in the middle part of the diaphysis was due mainly to disruption of vascular communications between the marrow and the cortex. Another reason for the impaired cortical circulation in group NS was the subperiosteal medullo hematoma (Zucman et al. 1968, Danckwardt-Lillieström 1969*c*). This separates the periosteum and disrupts the vascular communications between the periosteum and cortex, which result in further damage to the cortical bone in this area. This medullo hematoma may have a similar effect to that of autologous bone marrow transplantation as described by Burwell (1966).

In our two main experimental groups, group S and group NS, a definite difference in pattern was observed throughout, not only as regards the cortical vascular damage, but also in the general and local clinical appearance, radiological findings and the microscopical healing pattern.

The operative procedure in itself causes stress in the organism as a whole, as has been pointed out by many authors. In spite of the fact that these rabbits were still in the age of growth, they stopped growing for a period of about 20 days. This was observed in both groups. There were, however, some differences between animals undergoing the more crude operation—the non-suction group—and those in which the operation was more careful—the suction group. The former animals appeared to be more affected generally, with, on the whole, a slower weight increase, perhaps due to a larger degree of local trauma and also possibly due to an effect of the distribution into the organism of marrow particles, mobilized by the reaming in this group.

The death rate from fat emboli in the non-suction group was 11%, and a further 10% showed clear signs of the fat embolism syndrome but survived.

In earlier experiments (Olerud et al. 1969) it was found that blood samples from the femoral vein during reaming contained numerous marrow particles.

The soft tissue reaction around the osteotomy in group S was small and of short duration in comparison with group NS, where it was sometimes very extensive and persisted for a long period.

The local clinical findings at the different observation times in the different groups corresponded with the roentgenological and microscopical patterns. The small degree of periosteal bone formation in group S was very similar to the reaction observed in experiments with intermediate avascular fragments stabilized by a compression plate in dogs (Olerud & Danckwardt-Lillieström 1970). The bone was formed almost exclusively close to the osteotomy line, and the first formed woven bone very quickly rebuilt to lamellar bone. In this group we were unable to confirm the generally accepted profuse periosteal bone formation after medullary nailing described from experimental findings by Trueta and Cavadias (1955), Andersson (1965), Richany et al. (1965), Rhinelander et al. (1967) and many others and from clinical observations by Küntscher (1962) and Böhler (1949).

In group NS where the aim was to obtain a high intramedullary pressure during reaming, the considerable soft tissue swelling corresponded to a large amount of callus all along the diaphysis. Such a periosteal reaction was found in some animals by Danckwardt-Lillieström (1969*c*) on reaming the medullary cavity of the rabbit tibia without fracture. This supports the opinion that these periosteal reactions do not depend upon instability. In spite of the considerable peripheral bone formation, clearly visible roentgenologically, the new bone did not always bridge the osteotomy line all around the bone. Some parts of the line were, however, often firmly bridged. This proves that the absence of bridging in other parts is not due to lack of stability.

Our technique with the « dome-shaped » osteotomy fixed with the compression nail assured us of complete stability of the osteotomy in both groups. Stability is considered by many authors (Yamagishi et al. 1955, Friedenberg 1952, Rhinelander et al. 1967, Küntscher 1962) to be a factor which diminishes peripheral bone formation. In our study, however, although good stability was achieved in almost all animals, the large peripheral reaction was only found in group NS. We consider, therefore, that the peripheral bone formation depends, at least under our conditions, much more on subperiosteal marrow deposition, elimination of the marrow circulation and cortical bone necrosis than on instability, though this can be a contributory factor.

The often extensive periosteal bone formation in the Bündelnagelung method (Hackethal 1961) may fit well with this opinion, since a large amount of the marrow content will be forced out from the medullary cavity by the steel pins.

The revascularization of the cortical bone which starts at an early stage from all vascularized areas of the surrounding soft tissue, the periosteum, cortex and marrow cavity, occurred in different ways in the two groups. In group S it followed two lines, firstly by connection with preexisting vessels, in the same way as described by Birch and Brånemark (1969) in revascularization of full thickness skin grafts and by Olerud and Danckwardt-Lillieström (1970) in experiments with avascular cortical fragments, and secondly by the cutter head procedure. In this respect the periosteum plays the largest role in furnishing the blood supply through the cortex to the vascular front. The original centrifugal flow in the cortex furnished by the nutrient artery will be replaced by a centripetal flow from the periosteal vessels. Such a conversion of blood flow has been described by many authors (Brookes 1960, Rhinelander and Bargary 1962, Cavadias and Trueta 1965, Ladanyi et al. 1965) from studies with different experimental models. By vessels perforating the cortex and via vessels passing through the fracture line and by a contribution from the metaphyseal systems, the endosteal circulation will be partly restored.

Revascularization of the large avascular areas of cortex in group NS seemed to be very difficult. Central to the sparsely vascularized outer part of the cortex, cystic cavities were formed which later enlarged and became confluent. The cavities were furnished from vessels increasing in size through the outer cortex. The cortex central to the cavities was not invaded by vessels, but only eroded from the surface. This may have been due to blockage of the bone canals by fat. The decomposed fat may act as a toxic factor and prevent normal revascularization. After some time parts of the inner cortex became sequestrated and at least partly resolved, and this can be seen in the X-ray pictures. The cortical damage in this group showed wide interindividual variations and as a consequence of the conditions described above there were important quantitative differences. The endosteal revascularization also exhibited great variety in timing and intensity.

The osteotomy ends in both groups, S and NS, were primarily avascular. In spite of this, definite differences were seen between the two groups in the revascularization and bone formation at the fracture line. In group S vessels already appeared in the first week, and were followed almost immediately by bone formation, so that the gap in the X-ray pictures had almost disappeared by the 4th to 5th week. A period of 4 to 6 weeks is considered normal for a rabbit tibia to heal (Varma and Metha 1967). In group NS, however, the osteotomy line remained clearly visible and with little reaction even up to the 13th and even the 16th week. The consolidation in these cases depends almost solely upon the enormous periosteal bone formation, and in spite of this bone formation a reliable union between the osteotomy ends will seldom take place. Real bone union never seems to occur between the fracture ends when the intracortical circulation is blocked by fat emboli. In group S there was also vascular invasion from the gap into the osteotomy ends. Also this phenomenon was never seen in group NS. This indicates that there must be some factor in the cortex, probably the fat in the intracortical canals, which, mechanically or chemically, may prevent the invasion of vessels. Supporting the chemical influence is the fact that vessels in group NS would sometimes not even grow into the fracture gap.

Depending upon the size of the osteotomy gap, woven bone or lamellar bone is formed. In later stages, i.e. the 6th to 8th week, the line will be crossed by secondary osteones. Small areas in the region of close contact will, however, still remain unrebuilt after a very long time—up to the 16th week. The reason for this might be that the mechanically very stable nail will eliminate space polarizing factors as a stimulus for total cortical remodelling (Frost 1963, Schènck 1965).

In group S the nail was very soon surrounded by newly formed bone, and later it was « locked » even more closely by thicker mature lamellar bone. At the same time the endosteal part of the original cortex was extensively resorbed but replaced by stable beams which connected the bone cast around the nail with the original cortex, and the nail would never loosen. The nail will in this way also give « stress protection » to the bone, which can explain the spongialization and delay in final remodelling of the cortex, which was very slow in the later stages.

In group NS, where the bone healing was extremely retarded, the anchoring of the nail was very poor. This was certainly due to the impaired vascular situation. The nail had to function as a stabilizing factor for a longer period of time because of the delay in consolidation.

The resorption around the nail will win over the bone formation, with instability as a result. The pseudarthrosis in our rabbits may have been due to this reason. Probably in some cases the cause of delayed healing and pseudarthrosis occurring in clinical practice (L. Böhler 1953, Bürkle de la Camp 1958) can be referred to these factors.

CONCLUSIONS

This experimental work aimed at answering some fundamental questions in the treatment of fractures with reaming and nailing. Though this type of surgery has many aspects, and many problems still remain untouched, we believe that the questions we posed in the introduction can be given some answers:

To the cortical damage, produced by reaming of the medullary cavity the osteotomy adds total avascularity of the osteotomy ends. The nail itself does not seem to produce any further damage to the cortical circulation.

When the avascularity is due to severance of the vascular communication the revascularization process is rapid and occurs by connection with preexisting intracortical vessels or by cutter head formation. The latter process is more or less complete and takes place without any major cyst formation in the cortex. If the avascularity is due to fat emboli in the intracortical canals, the revascularization is very slow and incomplete. Large cystic cavities are formed, which become confluent and often sequestrate parts of the inner layer of the cortex.

With minor cortical damage under stable conditions, limited periosteal bone formation almost invisible on X-ray pictures is seen. With a larger extent of cortical damage, even under stable conditions, considerable periosteal bone formation creates a new cortex.

Under stable conditions and with minor cortical damage, the repair is characterized by immediate bone formation in the osteotomy gap (if such exists), followed by remodelling of the cortex and fracture area by secondary longitudinal osteones. The nail itself, fully fitting the fracture region in the medullary cavity, does not in any way impair the bone formation and healing of the osteotomy because of the good vascularity supplied in the early stages mainly from the periosteal vascular system.

With extensive cortical damage due to marrow emboli, the healing of the osteotomy line is very slow and incomplete or may fail owing to impaired revascularization of the osteotomy ends and the pronounced resorption in this region. If consolidation of the fracture occurs, this will rely on the condensed periosteal bone which acts as a stabilizing cuff around the diaphysis at the osteotomy level.

In the former case, with less cortical damage, the nail will be enclosed firmly, at the same time as bone is laid down in the osteotomy gap. Under the second condition, when large cortical damage is present this enclosing process is greatly delayed. Resorption forces are more pronounced and there is a serious risk that the nail will became loose before the circumferential repair is strong enough to maintain the stability. Instability may then often result in pseudarthrosis.

BIBLIOGRAPHY

ANDERSON L. D. - GILMAR W. S. J. - TOOMS R. E. (1962): *Experimental fractures treated with loose and tight fitting medullary nails.* Surgical Forum, *13*, 455.

ANDERSON L. D. (1965): *Compression plate fixation and the effect of different types of internal fixation on fracture healing.* J. Bone Jt. Surg., *47/A*, 191.

BACKER-GRØNDAHL N. B. (1911): *Untersuchungen über Fettembolie.* Deutsch Z. Chir., *111*, 56.

BAGBY G. W. - JANES J. M. (1958): *The effect of compression on the rate of fracture healing using a special plate.* Am. J. Surg., *95*, 761.

BERGENTZ S. E. (1961): *Studies on the genesis of posttraumatic fat embolis.* Acta Chir. Scand. Suppl. 282.

BIRCH J. - BRÅNEMARK P.-I. (1969): *The vascularization of a free full thickness skin graft. I. A Vital Microscopic Study.* Scand. J. Plast Reconstr. Surg., *3*, 1-10.

BÖHLER J. (1968): *Closed intramedullary nailing of the femur.* Clin. Orthop., *60*, 51.

BÖHLER L. (1953): *Unterschenkelschaftbrüche.* Arch. Klin. Chir., *276*, 192.

BÖHLER L. - BÖHLER J. (1949): *Küntscher's medullary nailing.* J. Bone Jt. Surg., *31/A*, 295.

BROOKES M. (1960): *The vascular reaction of tubular bone to ischaemia in peripheral occlusive vascular disease.* J. Bone Jt. Surg., *42/A*, 110.

BROOKES M. - HARRISON R. G. (1957): *The vascularization of the rabbit femur and tibiofibula.* J. Anat., *91*, 61.

BÜRKLE DE LA CAMP H. (1958): *Fehler und gefahren der alloplastik in der knochen und gelenkchirurgie.* Arch. Klin. Chir., *289*, 463.

BURWELL R. G. (1966): *Studies in the transplantation of bone.* J. Bone Jt. Surg., *48/B*, 532-566.

CAVADIAS A. X. - TRUETA J. (1965): *An experimental study of the vascular contribution to the callus of fracture.* Surg. Gyn. Obst., *120*, 731.

DANCKWARDT-LILLIESTRÖM G. (1967): *Periostal reaktion vid märgborrning å kanin.* Nord. Med., *77*, 59.

DANCKWARDT-LILLIESTRÖM G. (1969*a*): *Fettembolier till rörbenets cortex.* Nord. Med., *81*, 479.

DANCKWARDT-LILLIESTRÖM G. (1969*b*): *Marrow embolism as a cause of circulation block after surgery to the medullary cavity.* Europ. Surg. Res., *1/3*, 174.

DANCKWARDT-LILLIESTRÖM G. (1969*c*): *Reaming of the Medullary Cavity and Its Effect on Diaphyseal Bone.* Acta Orthop. Scand. Suppl., 128.

DANCKWARDT-LILLIESTRÖM G. - LORENZI G. L. - OLERUD S. (1970): *Intracortical circulation after intramedullary reaming with reduction of pressure in the medullary cavity.* J. Bone Jt. Surg. (in press.)

DANIS R. (1949): *Théorie et pratique de l'ostéosynthèse.* Masson et Cie ed., Parigi.

DE MARNEFFE R. (1951): *Recherches morphologiques et expérimentales sur la vascularization osseuse.* Acta Chir. Belg., *50*, 469/568/681.

DE MARNEFFE R. (1953): *Les connaissances actuelles de la vascularization des os et leur incidence sur la pathologie de ce tissu.* Rev. rheum. et maladies ostéo-artic., *20*, 113.

FITZGERALD F. P. (1966): *A new intramedullary nail for nonunion.* Intern. Surgery, *45*, 414.

FRIEDEBERG Z. B. - FRENCH G. (1952): *The effects of known compression forces on fracture healing.* Surg. Gyn. Obst., *94*, 743.

FROST H. M. (1963): *Bone remodelling dynamics.* C. Thomas ed., Springfield.

GEISER M. (1963): *Beitrage zur biologie der Knochenbrücheilung.* F. Enke Ed., Stuttgart.

GÖTHMAN L. (1960*a*): *The arterial pattern of the rabbit's tibia after the application of an intramedullary nail.* Acta Chir. Scand., *120*, 211.

GÖTHMAN L. (1960*b*): *Arterial changes in experimental fractures of the rabbit's tibia treated with intradullary nailing. A Microangiographic study.* Acta Chir. Scand., *120*, 289.

GÖTHMAN L. (1961): *Vascular reactions in experimental fractures.* Acta Chir. Scand. Suppl., 284.

GRANT R. T. - REEVE E. B. (1951): *Observations on the General Effects of Injury in Man.* Medical Research Council. Special Report Series 277. His Majesty's Stationary Office, London.

GRIESSMANN, R. (1944): *Vergleichende Untersuchungen über den Ablauf den Knochenbruchheilung.* Arch. klin. Chir., *205*, 3.

GUSTILO B. R. - NELSON G. E. - HAMEL A. - MOE J. H. (1964): *The effect of intramedullary nailing on the blood supply of the diaphysis of long bones in mature dogs.* J. Bone Jt. Surg., *46/A*, 1362.

HACKETHAL K. H. (1961): *Die Bündel-Nagelung. Experimentelle und Klinische Studie über eine neuartige Methode der Markraum-Schienung langer Röhrenknochen.* Leitfaden der Technik, Springer-Verlag.

HEY GROVES E. W. (1918): *Ununited fractures with special reference to gunshot injuries and the use of bone grafting.* Brit. Jour. Surg., *6*, 203.

JOHNSON L. C. (1966): *The kinetics of skeletal remodelling.* In: « *Structural organisation of the skeleton* ». D. Begsma Ed., New York.

KAESSMANN H. J. (1966): *Stabile Osteosynthese durch den Kompression snagel.* Chirurg., *37*, 272.

KAESSMANN H. J. - WEBER H. G. (1969): *Der Kompressionsnagel, eine modifikation des marknagels nach Küntscher.* Brun's Beiträge zur Klin. Chir., *217*, 315.

KERSTELL J. (1969): *Studies on the pathogenesis of post-traumatic fat embolism.* Acta Med. Scand. Suppl., *499*, 1969.

KOEKEMBERG L. J. (1963): *Vascularisation in the healing of fractures.* Chirurgische Universiteits Kliniek, Ed., Amsterdam.

KÜNTSCHER G. (1940*a*): *Ein neues frakturheilverfahre.* Klin. Wschr., *19*, 335.

KÜNTSCHER G. (1940*b*) *Die marknagelung von Knochenbrüchen.* Klinischer Teil, Klin. Wschr., *19*, 833.

KÜNTSCHER G. (1941): *Callus ohne knochenbrüch.* Ztbl. für Chirurg., *68*, 857.

KÜNTSCHER G. (1950): *Die Marknagelun.* Saenger Edit., Berlin.

KÜNTSCHER G. (1958): *The Küntscher method of intramedullary nailing.* J. Bone Jt. Surg., *40/A*, 17.

KÜNTSCHER G. (1962): *Praxis der Marknagelung.* Friedrich-Karl Schattauer-Verlag, Stuttgart.

LADANYL J. - FÖLDES I. - TASNADY L. (1965): *Blood supply of the callus after intramedullary nailing.* Acta Chir. Hung., *6*, 365.

LAMBOTTE A. (1913): *Chirurgie Opératoire des fractures.* Masson Ed., Parigi.

LANDELIUS E. (1951): *Intramedullary Pinning with Kirschner Wires.* Acta Chir. Scand., *101*, 203.

LANGE M. (1954): *Il trattamento chirurgico e la osteosintesi metallica nelle fratture.* Arch. Putti, *5*, 45.

LECHNER F. - SCHUSTER J. (1963): *Sur le traitment dirigé de l'embolie graisseuse par le phospholipides « essentiels » (substance EPL).* Chir. Praxis, *7*, 13.

LEHMAN E. P. - MCNATTIN R. F. (1928): *Fat embolism; incidence at postmortem.* AMA Arch. Surg., *17*, 179.

MAATZ R. (1951): *Die wundmechanik in der federosteosynthese.* Ztschr. Orthop., *80*, 643.

MITAL M. - COHEN J. (1966): *Repair of experimental bony intramedullary injuries varying in degree.* Surgical Forum., *17*, 451.

MÖRL F. K. (1967): *Embolia grassosa ed inibitori delle proteasi.* Die Med. Welt., *35*, 9.

NYLANDER G. - SEMB H. (1970): *The veins of the lower leg after tibial fractures.* Surg. Gyn. & Obstr. (in press).

OLERUD S. - DANCKWARDT-LILLIESTRÖM G. (1968): *Fracture healing in compression osteosynthesis in the dog.* J. Bone Jt. Surg., *50/B*, 844.

OLERUD S. - DANCKWARDT-LILLIESTRÖM G. (1970): *Fracture healing in compression osteosynthesis. An experimental study in dogs with an avascular, diaphyseal, intermediate fragment.* Congress band 1970. SICOT.

OLERUD S. - DANCKWARDT-LILLIESTRÖM G. - LORENZI G. L. (1969): *Do medullary components appear in the femoral vein during the reaming of the tibia?* Europ. Surg. Res., *1/3*, 243.

OLERUD S. - LORENZI G. L. (1969): *Triple fluorochrome labelling of the bone.* Europ. Surg. Res., *1/3*, 177.

OLERUD S. - LORENZI G. L. (1970): *Triple fluorochrome labelling in bone formation and bone resorption.* J. Bone Jt. Surg. *52/A*, 274.

PALMER J. (1951): *On the complications and technical problems of medullary nailing.* Acta Chir. Scand., *101*, 484.

PELTIER L. F. (1956): *Fat embolism. The prophylactic value of tourniquet.* J. Bone Jt. Surg., *38/A*, 835.

PELTIER L. F. (1956): *Fat embolism. III. The toxic properties of neutral fat and free fatty acids.* Surgery, *40*, 665.

PETROKOV V. (1962): Bruns Beitr. klin. Chir., *205*, 265.

RHINELANDER F. W. (1968): *The normal microcirculation of diaphyseal cortex and its response to fracture.* J. Bone Jt. Surg., *50/A*, 784.

RHINELANDER F. W. - BARGARY R. A. (1962): *Microangiography in bone healing. I: undisplaced closed fractures.* J. Bone Jt. Surg., *44/A*, 1273.

RHINELANDER F. W. - GRACILLE R. - PHILLIP R. - STEEL W. (1967): *Micrangio-*

graphy in bone healing. III: Osteotomies with internal fixation. J. Bone Jt. Surg., *49/A*, 1006.

RICHANY S. F. - SPINZ H. - KRANER K. - ASHBY J. - MERRIL J. G. (1965): *The role of the diaphyseal medulla in the repair and regeneration of the femoral shaft in the adult cat.* J. Bone Jt. Surg., *47/A*, 1565.

ROKKANEN P. - SLÄTIS P. - VONKKE E. (1969): *Closed or open intramedullary nailing of femoral shaft fractures.* J. Bone Jt. Surg., *51/B*, 313.

RUSH L. V. - RUSH H. L. (1937): *A reconstruction operation for comminuted fracture of the upper third of the ulna.* Amer. J. Surg., *38*, 332.

RUSH L. V. - RUSH H. L. (1949): *Evaluation of Medullary Fixation of Fractures by the Longitudinal Pin.* American J. of Surg., *3*, 324.

SALDEEN T. (1969): *Intravascular coagulation in the lungs in experimental fat embolism.* Acta Chir. Scand., *135*, 653-662.

SCHENK R. (1965): *Primary healing of fractures.* The Roche Courier, *18*, 23.

SCHENK R. - WILLENEGGER H. (1963): *Zum histologischem bild der sogenannten primärheilung der knochenkompakta nach experimentellen Osteotomien am Hund.* Experientia, *20*, 593.

SCHENK R. (1965): *Fluoreszenmikroskopische untersuchungen zur heilung von Schaftfrakturen nach stabiler Osteosynthese am Hund.* Proc. 2nd Europ. Symp. on Calc. Tissues, pag. 125.

SCHENK R. - WILLENEGGER H. (1967): *Morphological findings in primary fracture healing.* Symp. Biol. Hung., *7*, 75.

SCHNEIDER H. W. (1968): *Use of the 4-flanged self-cutting intramedullary nail for fixation of femoral fractures.* Clin. Orthop., *60*, 29.

SILANI C. - AMANTE S. (1949): *Ricerche sperimentali sul trattamento delle fratture secondo Küntscher.* Arch. Ortop., *62*, 165.

SPALTEHOLZ W. (1911): *A method for clearing of human and animal specimens.* Verlag von S. Hirzel ed., Leipzig.

TRUETA J. - CAVADIAS A. X. (1955): *Vascular changes caused by Küntscher type of nailing.* J. Bone Jt. Surg., *37/B*, 492.

TRUETA J. - CAVADIAS A. X. (1964): *A study of blood supply of the long bone.* Surg. Gyn. Obst., *118/3*, 485.

UFFREDUZZI O. (1942): *Fissazione dei monconi di frattura con chiodi midollari lunghi e sottili.* Giorn. Accad. Med., Torino, pag. 7.

VARMA B. P. - METHA S. H. (1967): *Fracture healing with intramedullary nail fixation of the long bones. An experimental study.* Acta Orthop. Scand., *38*, 419.

WEHNER W. (1968): *Die Fettembolic VEB.* Verlag Volk und Gesundheit, Berlin.

VESELEY D. G. (1968): *Technic for use of the single and the double split diamont nail for fractures of the femur.* Clin. Orthop., *60*, 95.

VINDITTI D. - BENINI M. (1962): *Proposta di un chiodo endomidollare a pressione o coartante.* Min. Ort., *13*, 368.

YAMAGISHI M. - YOSHIMURA Y. (1955): *The biomechanics of fracture healing.* J. Bone Jt. Surg., *37/A*, 1035.

ZUCMAN J. - MAURER P. - BERBESSON C. - BARBOT J. (1968): *Etude expérimentale de l'action ostéogenique des greffes de périoste, des greffes de moelle osseuse et de l'alesage centro-médullaire.* Revue de Chir. Orthop., *54*, 15.