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Secondary Internal Fixation

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SECONDARY INTERNAL FIXATION

Experimental studies on revascularization and healing in osteotomized rabbit tibias

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Osteotomies of rabbit tibias were immobilized by:

I Primary plating and secondary intramedullary nailing after reaming, and by

II Primary intramedullary nailing after reaming and secondary plate fixation.

In neither of this operation sequences, did the second operation lead to significant increased cortical avascularity. Quite the opposite was true: after the secondary operation there was generally a rapid revascularization.

During the time of this investigation, there was no evidence that the secondary operation increased the risk for infection.

Unstable primary plate fixation led generally to a tendency to delayed revascularization and union. After stable secondary fixation by means of an intramedullary nail, rapid fracture consolidation was, however, obtained through both periosteal bone formation and direct intracortical bone formation. The cortex and the osteotomy were thus remodelled by simultaneous resorption and new formation of bone, which gradually led to a certain cancellous transformation of the cortex.

Primary reaming and intramedullary nailing also yielded a consolidation of the osteotomy by both periosteal callus formation and direct intracortical bone formation. As in the first study, the remodelling of the cortex and the osteotomy resulted in advanced changes in the structure of the cortex.

When a stable intramedullary nail is used as a secondary method of fixation, satisfactory protection against a new fracture can be obtained. Refractures and new fractures can otherwise happen quite easily in cases of extensive cancellous transformation. On the other hand, secondary fixation by plate after primary intramedullary nailing seems to be less suitable. The plate and the relatively moderate periosteal callus formation can probably not neutralize a possible cancellous transformation in the fracture area in the same way as a stable intramedullary nail. Consequently, in clinical practice it is more safe to change a plate for a medullary nail than to perform the operations in the reverse order.

During recent years, there have been several clinical studies concerning secondary internal fixation of tibial fractures, that is to say repeated "osteosynthesis", after primary internal fixation (Rehn 1968, Spier 1969, Volk 1967, Zimmermann 1967, Sander and Staude 1968, Olerud & Karlström 1972, Probst 1973). The reason for the secondary operation is usually delayed union, although the secondary measure was already primarily planned in isolated instances (Müller, Allgöwer & Willenegger 1969, Olerud & Karlström 1972).

Secondary reaming and intramedullary nailing after a previous internal fixation, plating, for example, is now a relatively well

accepted method especially for the treatment of disturbed healing in shaft fractures of the femur and tibia (Küntscher 1962, Müller et al. 1965, 1969, Olerud & Karlström 1972, Probst 1973 and 1974).

The reversed procedure – primary reaming and intramedullary nailing with later secondary plating still seems to be an unusual procedure (Volk 1967, Probst 1973).

In previous experimental studies, revascularization and bone healing after internal fixation have been studied only after one procedure (Trueta & Cavadias 1955, Göthman 1960, 1961, 1962 a, b, c, Rhinelander et al. 1967, Willenegger et al. 1962, Schenck & Willenegger 1963, 1964, Schenck 1965, Andersson 1965, Emery & Murakami 1967, Zuchman et al. 1968, Milner & Rhinelander 1968, Olerud & Danckwardt-Lilliestrom 1968, 1971, Danckwardt-Lilliestrom et al. 1970, Schweiberer et al. 1970, 1973, 1974, Elsasser et al. 1975, Hutschenreuter et al. 1969, Perren et al. 1969, Rahn et al. 1971, Slätis 1977).

This study proposes primarily to answer the following questions:

1. How is the microcirculation and healing of the bone affected by a secondary intramedullary nailing after a primary plate fixation?
2. Of what significance for further healing is the stability attained by intramedullary nailing after reaming during the second operation?
3. Does the secondary intramedullary nailing cause such vascular damage that the risks of infection and delayed union are increased?
4. How are healing conditions affected by a reversed procedure, that is, reaming and intramedullary nailing followed by secondary plate fixation?

MATERIAL AND METHODS

MATERIAL

The investigation was carried out on 57 male and non-pregnant female albino rabbits, 7–8 months old, and weighing 2.4 to 3.7 kg, with a mean weight of 2.9 kg. Because of technical failures and one infection 14 animals were excluded from the material (see Complications). The results are therefore based on 43 observations.

After tibial osteotomy two studies were made:

I Primary plate fixation and secondary intramedullary nailing after reaming of the medullary cavity.

II Primary reaming, medullary nailing and secondary plating.

In the first series, which comprised 34 animals, the periods of plate fixation were three and six weeks. The animals were then sacrificed after two days (control group) and after three, six and nine weeks (see Figure 1, p. 19, where designations of the groups are given).

In the second series, which amounted to nine animals, the secondary operation was performed after three and six weeks. All the animals were then observed for six weeks before they were sacrificed. These two groups were called 3n + 6p and 6n + 6p respectively.

METHODS

In the first series the following operative procedures were used.

Operation 1: After weighing, the rabbits were anaesthetized with Nembutal (approx. 30 mg per kg body weight), which was injected into an aural vein. The needle was left in place for further maintenance doses during surgery. The animal was then placed on a special splint which fixed the left leg in 60° flexion in the hip and knee joint (Danckwardt-Lilliestrom 1969, Danckwardt-Lilliestrom et al. 1970). The fur on the left leg was cut away and the skin disinfected with antiseptic alcohol solution. The middle third of the tibia was then exposed with a straight anterior incision through skin and fascia. The place for the osteotomy was then marked on the tibia 1/2 cm distal to the tibio-fibular junction. A four-hole, small DC-plate (36 × 7 mm) of titanium (Perren et al. 1969, Allgöwer et al. 1973) was then placed on the medial tibial facet. The middle of the plate was placed over the spot for the planned osteotomy. The plate was fixed with four 2.7 mm cortical screws in prethreaded screw holes. After being assured that the position of the plate was satisfactory and that the screws had a good grip in both the lateral and the medial cortex, the plate and screws were removed. A dome shaped osteotomy was then made with a goldsmith's saw (blade thickness 200 μ). The convexity of the dome faced upward. The ends of the osteotomy were then reduced to the best possible position.

The plate was replaced and by tightening the screws compression in the osteotomy was attained. By prebending the plate to some degree, an attempt was made to attain the best possible compression in the osteotomy on the lateral side as well (Müller et al. 1969, Allgöwer et al. 1973) (Figure 2a). Fascia and skin were sutured with silk or nylon and the wound was covered with plastic spray (Nobecutan®). Radiograms with frontal and lateral projections were taken post-operatively.

Operation 2: Anaesthesia and other preparations were carried out as in operation 1; in addition radiograms of the left leg were taken. The left tibia was exposed with a slightly curved incision from the upper part of the knee joint down to the distal part of the tibia. With a 0.5 mm drill a hole was made in the anterior corticalis of the distal tibia. A plastic catheter with an inner diameter of 0.4 mm was placed into the marrow cavity through this hole.

The catheter was pushed under suction as far as possible into the marrow cavity. As much marrow as possible was removed by suction; it was, however, impossible to go past the screws. The patellar tendon was then divided longitudinally and the precondylar space of the upper tibia epiphysis exposed. An awl was then inserted through the metaphysis and into the marrow cavity. Reaming was then done with dental ball reamers (1.3–3.7 mm in diameter). The ball shaped reamers were mounted on a steelspring shaft 0.3 mm smaller in diameter than the reamer (Danckwardt-Lilliestrom 1969). The reamers were driven by an electrical motor with a speed of 300 r.p.m. While reaming with the first reamer, one screw at a time was removed, starting at the top and going down, so that the stability in the osteotomy could be maintained as long as possible. After all the screws had been removed, reamers of increasing diameter were used until it could be felt that they reached the cortical bone both below and above the osteotomy. During the entire reaming procedure, the proximal hole in the tibia was continually flooded with physiological saline solution, at the same time as a suction catheter was placed in the distal hole. A compression nail (Figure 2c,d) of the type previously used by Danckwardt-Lilliestrom et al. (1970) was then driven into the medullary cavity and fixed with a pin through the existing hole distally. The pin was drilled into the posterior cortex to secure reliable fixation. A washer was placed on the upper threaded part of the nail after which a nut was screwed on. By tightening this nut compression and thereby stability of the osteotomy was attained (Figure 2c,d). The patellar ligament, the fascia and the skin were sutured with silk or nylon. The wound was covered with plastic spray. After the operation was completed, new radiograms were taken.

In the second series the same operations were performed but in reverse order.

Neither after the first nor the second operation was plaster applied. Prophylactic antiobiotic treatment was not used either.

Recording methods: Radiograms with "Cristallite" Kodak X-ray film, including both frontal and lateral projections of the left leg were taken after the first operation, before and after the second operation, as well as at the end of each observation period.

All animals were labelled with fluorochrome substances (Milch et al. 1958, Olerud & Lorenzi 1969, 1970) during the observation period. (N, N'di) carbomethyl, aminomethyl fluorescences (DCAF), hematoporphyrine and oxy-tetracycline were used.

DCAF-solution (2 g DCAF in 100 ml 2 per cent sodium bicarbonate solution) was injected intravenously, at 20 mg per kg body weight.

The hematoporphyrine solution (3 g hematoporphyrine hydrochloride in 100 ml of a solution containing 2 per cent sodium bicarbonate and 10 per cent alcohol) was administered intravenously, 300 mg per kg body weight.

Oxy-tetracycline (Oxy-Dumocyclin® Dumex, 33 mg/ml) was injected intramuscularly, 50 mg per kg body weight.

The labelling codes (LC) are given in Tables 1 and 2.

At the end of each observation period, the animals were anaesthetized as previously described. New radiograms were taken, except in the control groups. 2 ml Heparin (5000 U/ml) was administered intravenously. The aorta was exposed by way of laparatomy incision and cannulated in the distal direction with a 1.5 mm plastic catheter. Through this catheter an infusion was then started with 200 ml Pelikan India Ink (Günter Wagner) in 800 ml physiological saline solution. The infusion pressure was c:a 130 cm H_2O. The animals usually died after 200–300 ml had been infused. The rate of infusion decreased gradually and after infusion of 800–1000 ml the infusion was discontinued.

Both legs were then removed and immediately deep-frozen. After a few days, the major part of the soft tissues was removed. The proximal and distal epiphysis of the tibia was sawn off after which the nail or the plate could be removed. The specimens were freeze dried until a constant weight was attained (usually after 3 days); they were then treated in two different ways for histological examination:

Table 1. Labelling code (L.C.) giving the time for labelling with the fluorochrome substances in series I

Group	Labelling day after operation 1			
	DCAF I	Hematoporphyrine	Oxy-tetracycline	DCAF II
3 wc	9	14	21	—
6 wc	25	33	42	—
3p + 3n	21	30	35	40
3p + 6n	21	45	54	61
3p + 9n	21	60	71	82
6p + 3n	42	50	55	61
6p + 6n	42	68	76	82
6p + 9n	42	82	94	103

Table 2. Labelling code (L.C.) giving the time for labelling with the fluorochrome substances in series II

Group	DCAF I	Hematopor-phyrine	Oxy-tetra-cycline I	DCAF II	Oxy-tetra-cycline II
3n + 6p	21	45	53	61	—
6n + 6p	42	66	74	82 (3 animals)	82 (3 animals)

1. Fixation in formaldehyde and decalcification with nitric acid. After paraffin embedding the specimens were cut transversally and longitudinally into 0.5 mm thick sections which were prepared by the Spalteholz (1911) process for observation in a three dimensional microscope.
2. Methacrylate embedding. The specimens were sawn into 0.5 mm thick longitudinal and transverse sections. These sections were then ground down to a thickness of 20–60 μ for observation in a fluorescent light microscope (Olerud & Lorenzi 1969).

RESULTS

COMPLICATIONS

None of the animals died while under anaesthesia or during the observation periods. All of the animals were unaffected by both operations. There were no signs of fat emboli in any of the animals.

Because of local complications, 14 animals were excluded from the study (1 massive local infection after the first operation, 9 fractures during or after the first operation, and 3 fractures during or after the second operation).

Macroscopic observations during and after the operations

Series I: After the first operation good stability was maintained through plate fixation in 32 animals. In 2 cases the stability was dubious, but sufficient for the animals to be included in the material (one in 6p + 3n and one in 6p + 6n). In both of these cases there was macroscopic stability in the osteotomy at the second operation when at least a certain consolidation had occurred in 26 animals, while 8 animals had a completely unstable osteotomy.

After reaming and intramedullary nailing were completed, stable fixation of the osteotomy was attained in all cases.

At the end of the observation periods, when the tibia was removed, all the osteotomies were macroscopically healed, some with a massive periosteal callus.

Series II: At the first operation, good stability was obtained by reaming and intramedullary nailing. In only one case could some instability be found when the second operation was undertaken.

At operation number 2, the osteotomy was macroscopically consolidated in all cases, and plate fixation could be carried out without difficulty.

RADIOLOGICAL FINDINGS

Series I: The observation period for plate fixation was, as previously described, three weeks for 17 animals and six weeks for 17 animals. The plate fixation was considered stable if the position of the osteotomy was unchanged radiologically at the end of these observation periods and if no so called irritation callus was seen.

In 9 cases of the three week group and in 10 cases of the six week group the fixation was stable. In these *stable* plate fixations the osteotomy was radiologically open in all of the three-week animals, whereas it was obliterated in all of the six-week animals.

In the 8 *unstable* three-week plate fixations, the osteotomy was open at the time of the second operation in all cases. In 3 of the cases there were also signs of delayed union with a tendency to pseudarthrosis (Figure 3a).

In the 7 unstable plate fixations in the six-week group the osteotomy gap was radiologically "erased" in 4 cases and still visible in 3 cases. Two of the latter animals showed signs of delayed union.

During the observation times for plate fixation, no visible periosteal reaction at the osteotomy could be shown radiologically. Bone formation in the osteotomy seemed to be so called primary radiological bone healing (Wieser & Allgöwer 1962). In several cases, however, there was periosteal bone formation around the screws and plate, both in cases of stable and unstable fixation.

In the 5 cases with delayed union and pseudarthrosis a relatively voluminous callus cuff developed over a large part of the diaphysis. At the exact level of the osteotomy, however, there was a 1–2 mm break in the callus cuff (Figure 3a).

After reaming and intramedullary nailing, a good position was generally attained for the nail (Figure 3b).

In those cases where the osteotomy was stable after completed plate fixation, the secondary intramedullary nailing caused a very moderate amount of peripheral bone formation (Figure 2d). If, on the other hand, the plate fixation was unstable, and especially where there were signs of delayed union, the periosteal bone formation increased. When this callus matured, a new layer of bone developed along the greater part of the diaphysis. At the same time, the original cortex of the diaphysis was seen to sequestrate (Figure 5). With longer nail fixation times, an increased porosity of the bone was seen (especially around the osteotomy) as a sign of a reconstructive process.

The osteotomy line, which was always visible after three weeks plate fixation, could usually still be discerned after three more weeks nail fixation. The osteotomy was radiologically healed after six weeks of nail fixation in most cases and after nine weeks in all cases (Figure 4).

After six weeks plate fixation the osteotomy line had disappeared in most cases. In those cases where the osteotomy was still visible at the time of the second operation, it healed quickly after nailing – usually after three weeks and always after six weeks (Figure 2d and Figure 5).

Series II: In the unstable fracture described above, the position in the osteotomy had changed somewhat between operation 1 and 2. In this case the periosteal bone formation was relatively extensive. In all the other cases, the periosteal bone formation was slight or moderate (Figure 6). After three weeks of nail fixation, the osteotomy was always open, whereas it was completely obliterated in one case, and could be seen in 3 cases after six weeks (Figure 20).

At the end of the observation period the osteotomy gap in group 3n + 6p was completely effaced in 2 cases and still visible in 2 cases (Figure 7a). In group 6n + 6p, the osteotomy was completely healed radiologically in all 4 cases after 12 weeks (Figure 7b).

MICROSCOPICAL OBSERVATIONS

Series I: The longitudinal sections were for practical reasons divided into zones (see Figure 8).

Control groups (3wc, 6wc)

Periosteal reaction

The first operation with plate fixation of the osteotomy must always have resulted in a relatively serious destruction of the periosteal circulation. In spite of this, there was extensive periosteal revascularization in both 3wc and 6wc, usually accompanied by general blood vessel dilation. In zone 3 and 2 there was often a certain subperiosteal bone formation with labelling from the first, second and third week. This newly formed bone was generally localized to the lateral side (opposite the plate), and was relatively mature distally and proximally. In the 3wc especially, the bone formation was delayed close to the osteotomy and consisted of trabecular bone (Figure 9). In addition to dilated blood vessels, a number of resorption cavities of moderate size were seen subperiosteally in 3wc. After six weeks these cavities had increased in size. In those cases where complete contact between the osteotomy surfaces did not exist, the trabecular bone in zone 0 continued to grow into the osteotomy gap. After 6 weeks this immature bone had usually been replaced by mature lamellar bone.

Cortical reaction

In group 3wc, which was observed two days after reaming and intramedullary nailing, there was almost total avascularity in the innermost cortical layers next to the osteotomy in zone 0. In zones 1, 2 and 3 the India Ink filled vessels increased in numbers and in the metaphyses, the cortical circulation was practically intact. The peripheral layers of the cortex showed a generally better vascularization than the inner layer.

In zones 2 and 3 the presence of intracortically newly formed bone was very scant at three weeks. A certain tendency towards beginning bone formation was, however, found next to dilated blood vessels and small resorption cavities. After six weeks, however, one could find large resorption cavities and bone formation by both primary and the secondary osteons (so called cutter heads). The resorption zones were larger in zone 0 as well as in the periosteal and endosteal direction. The labelling gave evidence that this first tendency to intracanalicular bone formation in 3wc had to some extent started as early as the second week, but that the major portion had taken place in the third week (Figure 10).

In 6wc the labelling showed how the resorption had started in the third week (or earlier), and that the largest portion of the intracanalicular bone formation had occurred in the fifth and sixth week (Figure 11).

Marrow circulation and endosteal reaction

Since the animals in the control groups only lived two days after the second operation, the intramedullary circulation in the diaphyses was of course practically non existent. Because of the irregularity of the marrow cavity, the entire innermost cortical layer was not reamed off. For that reason, parts of the endosteal reaction as well as the intramedullary circulation could be observed in some specimens. Proximally and distally to the thick part of the nail the intramedullary circulation was restored to a large extent both after three and six weeks.

The osteotomy

In cases of good contact in the osteotomy, the Spalteholz preparations showed how the osteotomy was filled with vessels growing in

from the periosteal vascular reaction. When there was almost complete contact between the osteotomy surfaces, there were few vessels apparent in the gap, and none at all in the central portions. On the other hand there were some vessels from the periosteum as well as intracortical vessels penetrating into the osteotomy giving rise to erosion.

Even in the gap itself, some resorption of the fragment ends could be seen. When the periosteal reaction was extensive, it could be seen how the formation of immature bone continued into the gap (Figure 9). Where there had been good contact between the fragments initially, resorption of fragment ends and isolated transverse osteons in the gap were seen in some of the sections.

After six weeks the osteotomy zone was relatively well vascularized. Trabecular bone was not found in the gap. As a rule it was filled by transverse osteons. Labelling showed that the resorption of the fragment ends occurred mainly in the third to fifth week and that bone formation took place in the fifth and sixth week (Figure 12). Beginning intracanalicular bone formation over the osteotomy was found in several cases with relatively good adaptation. In some of the cases where there was absolute contact between the fragments, the osteotomy was partly devoid of all reaction. In these cases there was often a triangular or U-shaped area in the periphery of the osteotomy which contained blood vessels growing in from the periosteum and the outer layers of cortex. The gap in these areas was being reconstructed by resorption and new bone formation. More centrally, the fragment ends were avascular and there was no reaction in the osteotomy line.

Intramedullary nailing after 3 weeks plate fixation (3p + 3n, 3p + 6n, 3p + 9n)

Periosteal reaction

After three weeks of fixation by nail, the subperiosteal resorption cavities had often increased in size, especially in zone 0. The formation of trabecular bone was often substantial and continuous over the osteotomy (Figure 13). After six weeks, and especially after nine weeks, this immature bone was replaced by more mature well vascularized, lamellar bone, formed between the sixth and 11th week. The greater avascularity in the cortex, the more extensive the periosteal bone formation was (Figure 14).

Cortical reaction

After three as well as after six weeks of nail fixation, the blood vessels in zone 0 and 1 were still relatively sparse in some of the specimens. Nine weeks after nailing, the occurrence of cortical blood vessels was copious even in zone 0 and 1. The degree of revascularization was different in different specimens, but it was always a little more scanty on the plate side. In a few cases extensive necrosis was even found in the cortex of the plate side (Figure 14).

In zone 2 and 3 the occurrence of blood vessels was relatively abundant after three weeks (Figure 15), and after six and nine weeks a large number of wide vessels and even resorption cavities, as well as concurrent intracanalicular bone formation (Figure 16) was seen. After six weeks beginning mature bone formation was seen in the screw holes, which were difficult to find after nine weeks.

Marrow circulation and endosteal reaction

Because of the irregularity of the cross section of the medullary cavity and sometimes because of a dislocation in the osteotomy, it was possible to see that the marrow circulation was already restored 3 weeks after nailing (Figure 15). In addition, there was relatively profuse endosteal bone formation around the nail in some cases. Labelling showed that this bone was formed in the fifth and sixth weeks (Figure 13). The endosteal bone was immature after three weeks, but had after six weeks been replaced by mature lamellar bone to a large extent.

The osteotomy

After three weeks of nail fixation a good revascularization of the 0-zone was at hand. When the fragments had good contact, the resorption of the fragment ends was very slight, and ingrowth of blood vessels with resorption and bone formation had most often taken place from the periosteal vessels. Avascularity was often seen more centrally in the cortex.

After six weeks of nail fixation, there was often an abundance of India ink filled vessels at the osteotomy. There were also isolated secondary osteons which crossed the osteotomy line (Figure 17).

Nine weeks after nailing, the well adapted osteotomies were healing well with a large amount of longitudinal osteons and isolated transverse osteons.

When there was a large gap in the osteotomy, the periosteal reaction continued into the gap after three weeks. There was now newly formed trabecular bone between moderately resorbed osteotomy surfaces.

After six weeks the immature bone was generally replaced by lamellar bone. In most cases there were now larger resorption cavities next to the osteotomy (Figure 18). The appearance of transversally oriented secondary osteons in the osteotomy gap was even more pronounced after nine weeks (Figure 18). Labelling showed that the immature bone in the osteotomy gap was formed between the sixth and the 12th week.

Intramedullary nailing after 6 weeks plate fixation (6p + 3m, 6p + 6n, 6p + 9n)

Periosteal reaction

After six weeks fixation by plate, and after completion of intramedullary nailing, there was often extensive peripheral callus of mature corticalized bone. This bone was labelled with fluorochrome substances from the seventh to the 15th week. This callus cuff had grown gradually during the nail fixation. Primary instability as well as extensive cortical avascularity had resulted in a more abundant periosteal bone formation. Subperiosteally there were large, partially confluent resorption cavities.

Cortical reaction

The cortex in all the zones was well vascularized after six weeks of plate fixation. The Spalteholz-specimens showed that the cortex was supplied by penetrating vessels from both the periosteum and the marrow cavity.

Intracanalicular bone formation – both primary and secondary osteons – were seen to an increasing extent in longer observation periods.

After three weeks, resorption cavities were already common in the whole diaphysis. These cavities tended to increase in size with the longer observation periods. They also increased in size in the same specimen from zone 3 to zone 0; in other words the degree of cancellous transformation increased closer to the osteotomy.

Marrow circulation and endosteal reaction

The intramedullary circulation was restored three weeks after the secondary reaming and intramedullary nailing. The marrow cavity communicated with the periosteal vessels by means of a number of vessels penetrating through the cortex.

Around the nail, there was often a layer of newly formed bone, as was the case in the three-week group.

The osteotomy

Three weeks after intramedullary nailing, the osteotomies were healed on the whole, whether there was contact or a gap. Resorption cavities were common in zone 0, and the degree of reconstruction was variable. With good fragment contact, the osteotomy line was often partially visible after 3 weeks (Figure 19). It was, however, in some parts always transformed by transverse osteons in the gap itself and by secondary longitudinal osteons (Figure 20).

After three to six weeks narrow osteotomy gaps were generally filled by transverse secondary osteons as well as by several longitudinal osteons with heads that crossed over the gap. At the same time, it occurred that transverse vessels in the track had changed course by 90° and grown into the osteotomy ends. Thus there had been a retrograde revascularization of the cortex (Figure 20).

Nine weeks after nailing, the osteotomy was often difficult to see because of the rebuilding of the bone. Large vessels and even large resorption cavities crossed the gap, which was almost completely replaced by mature lamellar bone.

In the larger primary osteotomy gaps, a more obvious resorption of the fragment ends had usually taken place, where upon the gap was successively filled by transverse secondary osteons. The whole 0-zone was in these cases filled by wide vessels and large resorption cavities (Figure 21).

Series II: The same zone classification as described in series I was used in the histological investigation of the longitudinal sections (Figure 8).

Periosteal reaction

The periosteal circulation was completely restored in both groups (3n + 6p and 6n + 6p) by the end of the observation periods. In some of the Spalteholz preparations there was an even greater periosteal vascular bed on the operated left side, compared to the right leg. This was especially often the case for the lateral side. In most cases, it could be observed how the periosteal vessels supplied the outer layers of cortex, and that there was an ingrowth of periosteal vessels into the osteotomy.

The periosteal bone formation was often relatively abundant and even in the early preparations, strikingly mature and corticalized. There was a larger quantity of this periosteally formed bone in the 6n + 6p group. There was, however, no obvious difference in the degree of maturity of the bone (Figure 22). The newly formed bone was, in zone 0–2, more abundant on the lateral side than on the plate side. In zone 3 (around the plate ends), the periosteal bone formation was larger on the plated medial side than on the lateral side. There was always some resorption of the peripheral cortex under the plate.

This was replaced by a thin layer of newly formed relatively mature bone (Figure 23). In one case from each group, the osteotomy showed no reaction in some places, with no evidence of union. In these cases the periosteal reaction was also missing in exactly these places. In other places, the periosteal bone formation corresponded completely to that found in the other cases.

Cortical reaction

The cortex in zone 1–3 was well vascularized in all preparations. In some of the sections, the vascularization was somewhat sparse in zone 0. There was no actual difference in the vascularization of the two groups. On the other hand, the resorption cavities were generally larger in the specimens with the longer observation time than in the 3n + 6p group. It also became evident from the transverse sections that there was an increased incidence of resorption cavities and dilated blood vessels on the operated side.

Large subperiosteal resorption cavities were regularly found in the earlier preparations (Figure 24). In the 6n + 6p group, these large cavities were also usually found, but there were also other resorption zones of similar size more centrally in the cortex. Any certain difference in the degree of so called cancellous transformation of the plate side compared with the lateral side could not be seen in either of the groups.

Intracanalicular bone formation was common in all zones in both groups. Labelling showed that such bone formation occurred during the whole plate fixation time (Figure 23).

Marrow circulation and endosteal reaction

At the first operation, when after reaming, intramedullary nailing of the osteotomy was done, the major portion of the marrow canal in the diaphysis must have been destroyed. Spalteholz preparations showed that the marrow circulation was well restored after only three weeks plate fixation. There were many vessels which penetrated the cortex in all zones from the medullary circulation.

In the earlier group (3n + 3p), a certain new formation of relatively immature endosteal bone could be seen in zones 0, 1 and 2. Even in zone 3, such newly formed bone occurred at times, but to a much smaller extent (Figure 23). In the 6n + 6p group, this immature bone was resorbed and generally replaced by a thin layer of more mature bone.

The osteotomy

In two of the animals (one from each group) there were parts with a reactionless and open osteotomy gap. In both these cases there were also sections of union in the osteotomy.

In both groups union generally occurred by so called gap healing. Thus there was an ingrowth of vessels into the gap from both the periosteal and marrow circulation. Along these vessels, transverse osteons were formed, which were later partly replaced by longitudinal secondary osteons over the osteotomy. Examples of so called retrograde revascularization and bone formation were also seen (Figure 24).

The 6n + 6p group differed from the 3n + 6p group in that the resorption zones were generally larger in the former both in zone 0 and in the osteotomy (Figure 24).

When there was absolute contact between the osteotomy surfaces, the central portions in the 3n + 6p group were devoid of reaction. In these cases resorption had occurred endosteally, but the periosteal resorption was more extensive with a triangular area with vessel ingrowth and new bone formation. With corresponding conditions in the 6n + 6p group, the osteotomy had been completely remodelled by resorption and intracanalicular bone formation. In such areas, the osteotomy line was often hard to identify.

DISCUSSION

Internal fixations with both compression plate and intramedullary nail are now quite well accepted forms of treatment for fractures and non-unions in diaphyseal bone. Both methods do have opponents, however. The reasons for their negative attitude to these methods of treatment are both clinical experience (Richon et al. 1967, Wade 1970, Merle d'Aubigné 1970, Bauer & Hulth 1973) and the results of experimental investigations (Trueta 1974, Trueta & Cavadias 1955, 1964, Gustilo et al. 1964, Rhinelander et al. 1967). Internal fixation always involves vascular damage and the risk of infection; this has often been used as a warning against both plate fixation and intramedullary nailing.

Clinical and experimental results pointing to the fact that plate fixation leads to a weakening of the bone which tends to fracture easily again (Burstein et al. 1972, Diehl & Mittelmeier 1974, Strömberg 1975, Uhtoff & Dubuc 1971, Blaimont 1968, Matter et al. 1974, Richon et al. 1967, Hutzschenreuter et al. 1969, Gördes et al. 1975, Tonino et al. 1976, Slätis 1977), have also been used as arguments against plating.

Against the use of intramedullary nailing, it has been argued that the marrow circulation is destroyed, which can lead to cortical necroses and delayed union (Trueta & Cavadias 1955, 1964, Gustilo 1964, Crock 1967, Rhinelander, 1972). However, Schweiberer et al. (1970, 1973, 1974) have shown that the marrow circulation is rapidly restored if the intramedullary fixation is stable.

During recent years, the method of reaming before intramedullary nailing introduced by Küntscher (1950), has significantly contributed to the improvement

of stability after nailing. Reaming does, however, cause an increase in the intramedullary pressure (Wehner 1968, Wehner et al. 1966, Danckwardt-Lilliestrom 1969). Danckwardt-Lilliestrom also found marrow fat emboli in the cortical blood vessels during reaming which lead to a significant cortical avascularity. This effect can be reduced by the removal of marrow distally by suction during reaming (Danckwardt-Lilliestrom et al 1970a). Danckwardt-Lilliestrom and coworkers (1970b) have also shown that the reaming and nailing of osteotomized rabbit tibias with and without distal suction resulted in obviously different types of healing.

Secondary internal fixation, that is to say renewed operation either after the failure of the primary operation or as a planned secondary procedure in a scheme of treatment, has during recent years been shown to have certain clinical advantages, especially if the primary operation consists of plate fixation and the secondary operation of reaming and intramedullary nailing (Olerud & Karlstrom 1972).

The opposite procedure (primary intramedullary nailing and secondary plate fixation) has hardly been treated in the literature. Some have warned against such a procedure (Probst 1973). It has been claimed that intramedullary nailing (especially after reaming) destroys the intramedullary circulation and secondarily also greater or smaller parts of the cortical circulation. This would provide poor conditions for union after secondary plate fixation which in itself also causes a certain amount of periosteal vascular damage (Henkel 1974). Rehn (1968) has used stable plate fixation after insufficient intramedullary nailing. He recommends waiting 6–12 weeks between nail extraction and plate fixation ("tertiary internal fixation").

Both plate fixation and intramedullary nailing lead to blood vessel damage – periosteal damage and damage primarily to the medullary and cortical circulation respectively (Trueta 1974, Rhinelander 1974). In clinical practice, however, good results after secondary internal fixation with an intramedullary nail have often been reported (Küntscher 1962, Karlström & Olerud 1972, Probst 1973, Christensen 1973, 1976). The purpose of this study is thus to experimentally investigate revascularization and healing after two internal fixations which both lead to damage of the circulation so necessary to healing.

A dome shaped osteotomy just below the tibio-fibular synostosis on the rabbit tibia has previously been shown to be a good test model, especially to study healing after intramedullary nailing (Danckwardt-Lilliestrom et al. 1970). The compression-type intramedullary nail which these authors constructed has also been used in this study.

In some cases of primary plating, good adaptation and stability were attained macroscopically and radiologically at the first operation. In other cases, there was a degree of instability during all or parts of the plate fixation period. After reaming and intramedullary nailing, the osteotomy was stabilized.

At the second operation in series I, release of pressure in the marrow cavity was obtained by employing a distally introduced suction catheter. The effect of this suction was, however, dubious since the catheter could not be inserted past the screws at the beginning of reaming. On the other hand, the holes left by the screws when they were removed one by one, must have contributed to a reduction of the intramedullary pressure.

An imperfect fragment contact, and instability after the first operation resulted in an increased tendency to periosteal bone formation. This periosteal reaction consisted primarily of trabecular bone, which was, however, quickly replaced by mature, lamellar bone. Even when the first operation had resulted in a stable fixation, one could in some cases observe peripheral callus developing, which then increased after the second operation. Both instability and reaming can thus be thought to contribute to the

formation of voluminous peripheral callus after secondary intramedullary nailing (Anderson et al. 1962, Richany et al. 1965, Varma & Mehta 1967, Danckwardt-Lilliestrom et al. 1970, Rhinelander 1972).

The thickness of the periosteal callus also tended to increase in cases of more extensive cortical damage (by the reaming itself, or by avascularity).

In a small number of cases there was remaining avascularity in the cortex after secondary intramedullary nailing. As a rule, however, there was rapid revascularization – partly in the preformed canals and partly through the so called cutter heads. In this respect the significance of the cortical circulation was greatest in the beginning, when normal centrifugal circulation in the tibia was replaced by centripedal blood flow (Brookes 1971, Rhinelander & Baragry 1962, Cavadias & Trueta 1965, Ladanyl et al. 1965). The marrow circulation was quickly restored by vessels growing in through the osteotomy, penetrating the cortex from the metaphyseal circulation. With longer observation times, it could be seen that even the restored marrow circulation contributed to the revascularization of the cortex.

The osteotomy ends which were primarily avascular, were at first revascularized by the ingrowth of vessels from the periosteal vascular system into the gap whenever possible. Alternatively, revascularization occurred by penetrating vessels in the cortex. When there was a gap in the osteotomy, immature bone, quickly replaced by mature lamellated bone, was formed in the early stages after nailing. After three to six weeks of nail fixation, the osteotomy in many cases was crossed by secondary osteons in the shape of cutter heads. This direct intracanalicular bone formation occurred sooner after nailing when the plate fixation time was six weeks than when it was three weeks. Thereupon a lively reconstruction of the cortex began in the osteotomy zone, which was often difficult to see after nine weeks of nail fixation. In some areas, where there was very good contact between the osteotomy surfaces, the osteotomy line persisted unremodelled even after 15 weeks, which was the longest observation time.

Both the plate and the nail give a certain stress protection, which can explain this so called cancellous transformation combined with a delayed remodelling of cortex in the osteotomy zone.

The constant rapid revascularization of the cortex after secondary intramedullary nailing can have its origin in the periosteal reaction with dilation and proliferation of the vessels and thickening of the remaining periosteum. This reaction, which even seems to have included the peripheral layers of cortex after a longer period of plate fixation, may have had a protective effect against vascular damage at the secondary operation.

In the first series of this study, it was shown that cortex was revascularized relatively quickly after primary plate fixation of an osteotomy and a secondary intramedullary nailing. The results in series II indicate that revascularization takes place quickly even when intramedullary nailing is done first and plate fixation as a secondary measure. Revascularization was certainly made more possible by the reduction of intramedullary pressure used during operation 1 (Danckwardt-Lilliestrom et al. 1970).

Vascular damage and necroses did not seem to be the great risk when different types of internal fixation were used in this way. On the contrary, there is a prompt revascularization of both the marrow cavity and the cortical bone after the secondary procedure. On the other hand, it was obvious that the bone was greatly remodelled, especially because of the widening of the Haversian canals and the production of large resorption cavities (so called cancellous transformation). This change in bone structure seems to be of a transitory nature. A normalizing of the cortical architecture seems to take place in time. Recent experimental series with long observation times show that the length of time cancellous transformation remains varies

from species to species (Matter et al. 1974, Strömberg 1976). After plate fixation alone, cancellous transformation is mainly localized to the cortex under the plate, whereas it seems to be more extensive after intramedullary nailing and later plate fixation. Thus several cases were noted in the second series where cancellous transformation was quite as pronounced on the lateral side as on the plated medial side.

Both experimental studies and clinical experience seem to indicate that cancellous transformation is one of the great disadvantages of rigid plate fixation with a not entirely negligible risk of a new fracture (Burstein et al. 1972, Diehl & Mittelmeier 1974, Strömberg 1975, Uhtoff & Dubuc 1971 Blaimont 1968, Gördes et al. 1975, Tonino et al. 1976, Slätis 1977). It seems most likely that primary plate fixation and secondary intramedullary nailing lead to at least the same extent of cancellous transformation. Here the risks for refracture are counteracted by the intramedullary nail which gives a high degree of stability. With primary intramedullary nailing and secondary plate fixation one can suppose that cancellous transformation in the cortex is to some degree neutralized by the periosteal callus cuff, the formation of which is stimulated by reaming and/or intramedullary nailing. Intramedullary nails seem to provide a more reliable fixation than a plate, since the cortex gradually takes over the role of the nail as stabilizer.

CONCLUSIONS

When intramedullary nailing was undertaken as a secondary measure after plate fixation, as was done in this experimental study, the vascular damage of each procedure does not seem to be additive. Instead, the reparative process of the periosteal vascular damage (with hyperemia among other things) after the first operation seems to limit the cortical avascularity after the second operation.

Cortical revascularization in the osteotomy zone occurs mainly through the ingrowth of vessels from the hyperemic periosteum into the osteotomy. In addition there is a certain revascularization of the cortex by longitudinally penetrating vessels. Of least importance was the revascularization of the cortex from the medullary cavity, where the circulation was only partly restored because of the presence of the nail.

If the primary plate fixation was unstable, the revascularization of the cortex, like the healing of the osteotomy, was delayed. This was to some extent compensated by the periosteal reaction, by means of an increase in periosteal bone formation.

Healing of the osteotomy gap (if there is a diastasis) usually occurs by the simultaneous resorption of the fragments and the formation of immature bone, which was relatively quickly replaced by mature lamellar bone with mainly transversally oriented osteons. Remodelling occurs then through secondary longitudinal osteons.

In case of absolute contact in the osteotomy, there was direct healing and remodelling of the cortex by way of longitudinal osteons. This healing can be delayed, especially in the central parts. The reason for this is unknown, but a lack of induction because of a too rigid fixation has been suggested (Olerud and Danckwardt-Lilliestrom 1971).

In delayed union or pseudarthrosis after plate fixation, healing conditions are not impaired by secondary reaming and intramedullary nailing. Quite the contrary: after stabilization with an intramedullary nail, rapid union of the osteotomy was attained. The formation of periosteal callus and the primary and secondary osteons in the osteotomy zone act together towards this end. The secondary intramedullary nailing does not seem to increase the risk of infection either. This could be explained by the hyperemia after the first operation and the thereby limited cortical avascularity.

After primary reaming and intramedullary nailing and secondary plating, a rapid revas-

cularization of the cortex takes place provided that deposition of marrow fat in intracortical canals is counteracted by distal suction reducing the intramedullary pressure. The explanation for this is probably the hyperemia which is a phase in the reparative process and which accounts for the fact that a secondary operation will lead to only a limited cortical avascularity.

Both the periosteal and the endosteal circulation take part in the revascularization of the cortex after a primary intramedullary nailing and a secondary plate fixation. In addition, there is an intracortical revascularization by so called cutter heads and penetration of vessels in preformed canals.

When the primary intramedullary nailing leads to stable fixation of the osteotomy, the periosteal bone formation is moderate. This, however, undoubtedly contributes to the consolidation of the fracture.

Union of the osteotomy in primary intramedullary nailing generally begins with the ingrowth of vessels from the periosteum and later from the marrow cavity as well. Trabecular bone in the form of transverse osteons is formed quite soon. Later, the cortex and the osteotomy is rebuilt by secondary longitudinal osteons. Resorption zones and widened canals in the major part of cortex lead to an extensive cancellous transformation during the actual observation periods.

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Operation 1 = Osteotomy and internal fixation by plate and screws

Operation 2 = Reaming + intramedullary nailing

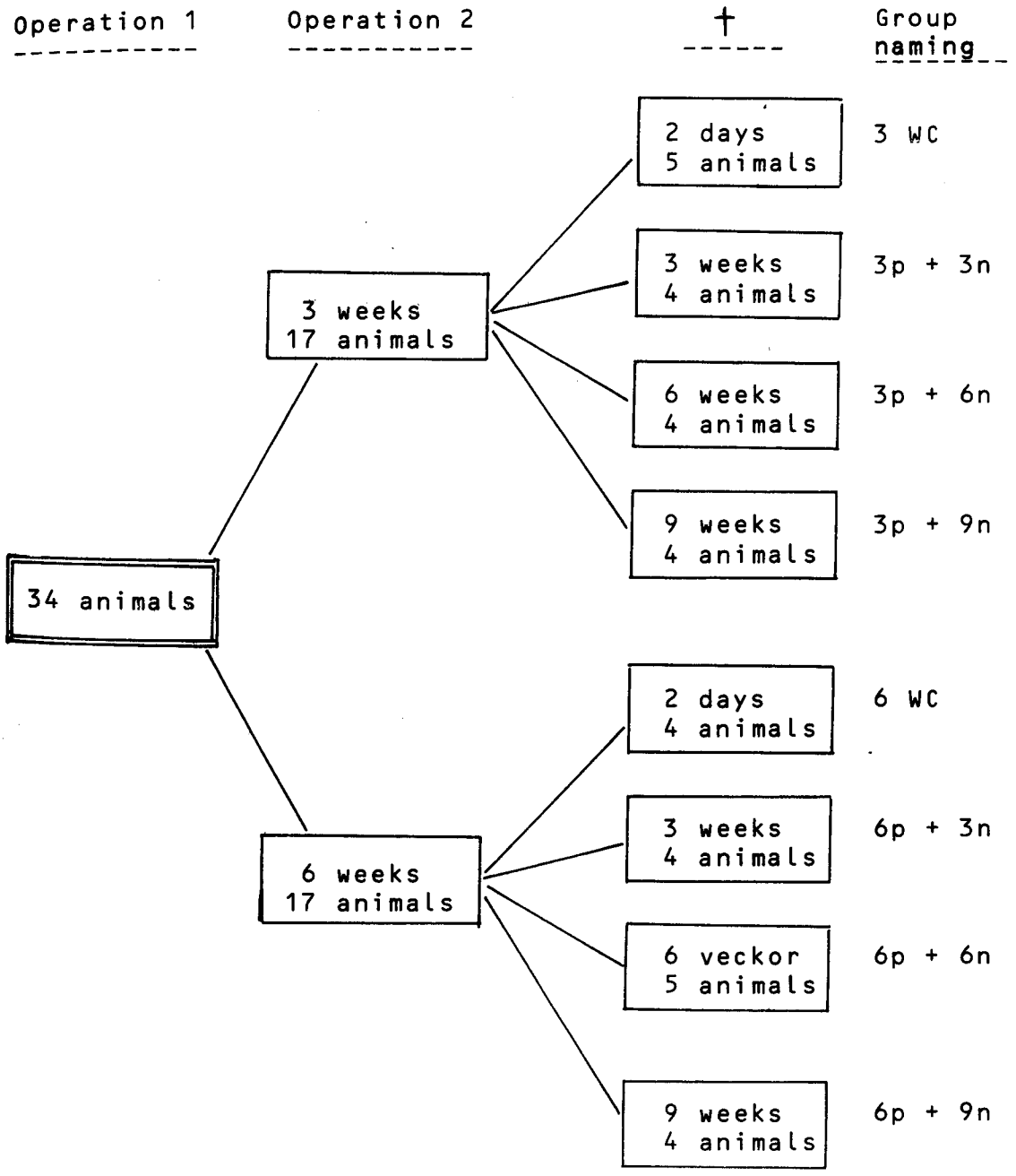
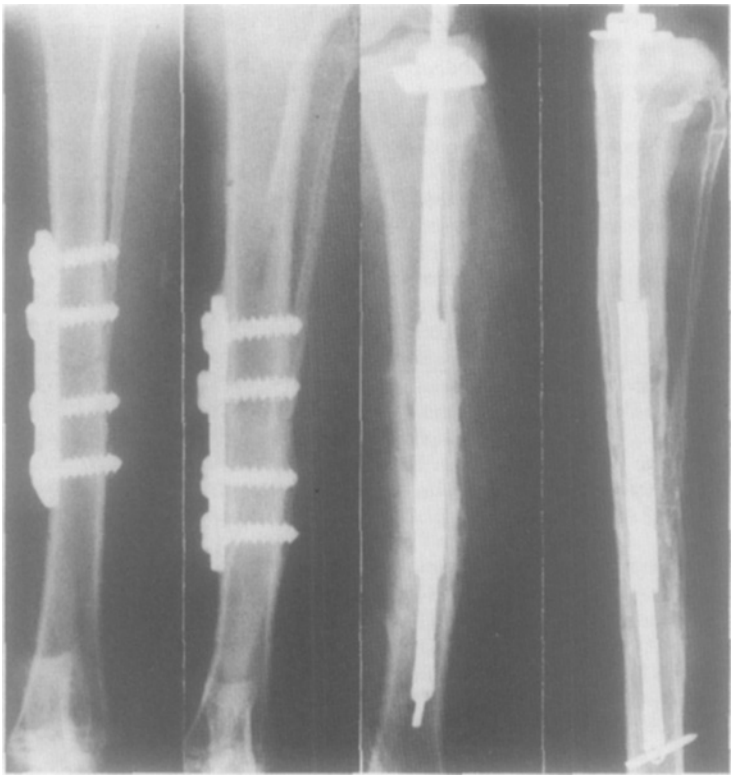


Figure 1. Scheme of operations and observation time.



a b c d

Figure 2. (Animal 49) (a) Plate fixation of a dome-shaped osteotomy. (b) After 6 weeks plate fixation. The osteotomy is healed with insignificant periosteal callus. Some periosteal bone formation can be seen around the screw tips and at the ends of the plate. (c) Postoperative radiograms after reaming and intramedullary nailing. (d) After 9 weeks intramedullary nail fixation the screw holes can still be seen. Moderate peripheral callus. The osteotomy is well healed.*

* The number of the animals is the marking used by the laboratory for each rabbit and does not show the sequence in these special animal series.

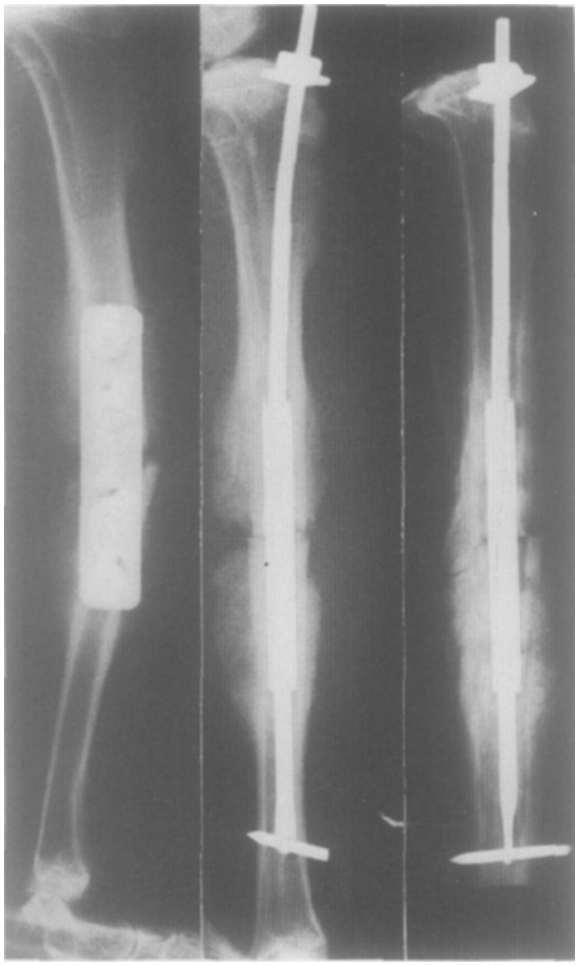
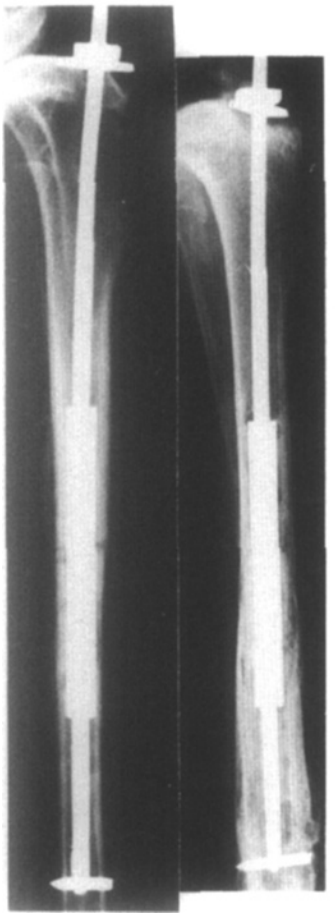


Figure 3. (Animal 92) (a) Radiogram after 3 weeks of unstable plate fixation. Abundant, non-bridging, periosteal callus is seen. A non-union has developed. (b) After 3 weeks unstable plate fixation, reaming and intramedullary nailing has been done (postoperative radiogram). The osteotomy is open and the abundant periosteal callus does not reach the gap. The intramedullary nail provides stable fixation. (c) After 3 weeks nail fixation practically healed osteotomy with bridging callus on the lateral side.



a b

Figure 4. (Animal 48) (a) Postoperative radiogram after reaming and intramedullary nailing carried out after 3 weeks plate fixation. The osteotomy is still visible. (b) After 9 weeks nail fixation the osteotomy is healed.

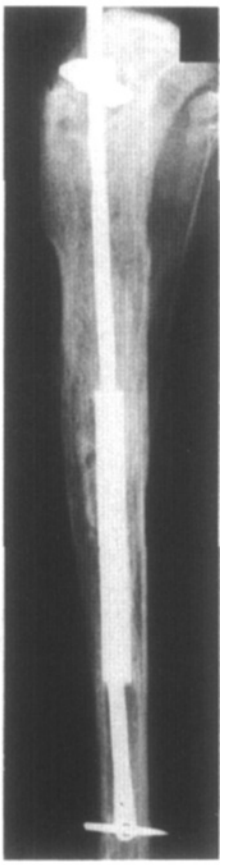
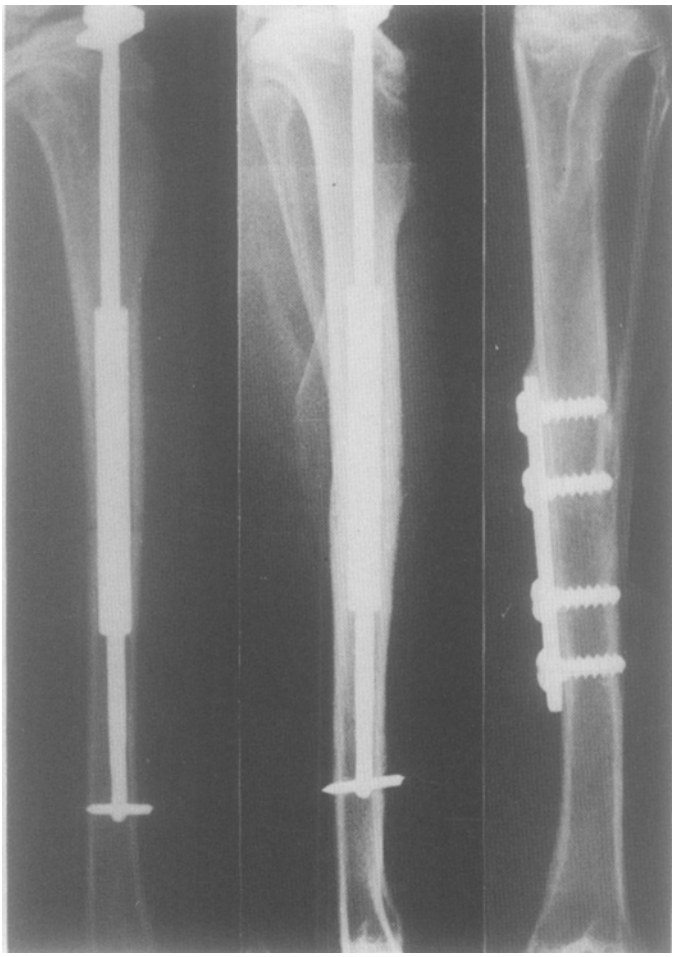
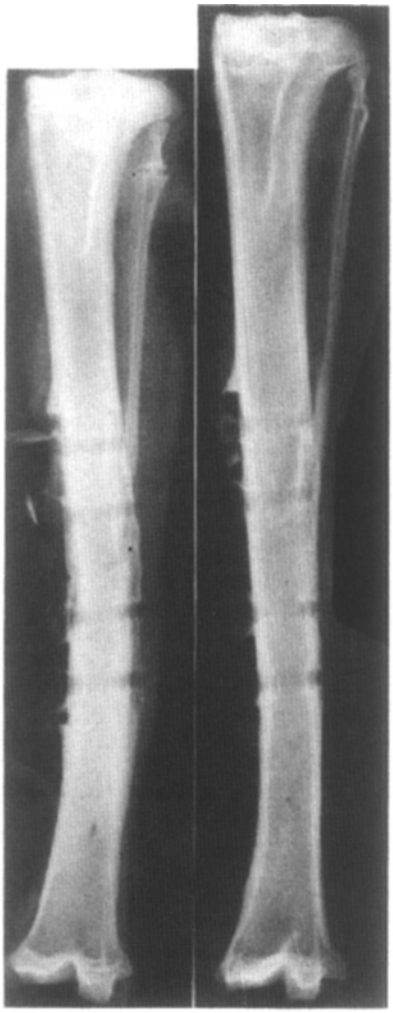


Figure 5. (Animal 47) Radiogram after 6 weeks plate fixation and 9 weeks nail fixation. The plate fixation had been somewhat unstable. A relatively abundant peripheral corticalized callus covers a large part of the diaphysis outside the original cortex which probably had been mainly avascular; this can be seen by a suspect area of avascular bone frontally at the level of the osteotomy. The osteotomy is well united.



a b c

Figure 6. (Animal 315) (6n + 6p) (a) Radiogram after operation 1. (b) Radiogram after 6 weeks, before operation 2. Moderate periosteal callus formation. (c) Radiogram after 6 weeks plate fixation. The periosteal callus formation is very scant in the osteotomy zones. The osteotomy is healed.



a b

Figure 7. (Animal 311) (3n + 6p) (a) Radiogram after 3 weeks nail fixation and 6 weeks plate fixation. Plate and screws removed. The osteotomy is almost completely obliterated, but can still be seen. Moderate periosteal callus. (b) (Animal 315) (6n + 6p) Radiogram after 6 weeks nail fixation and 6 weeks plate fixation. Plate and screws removed. The osteotomy is healed and can no longer be seen.

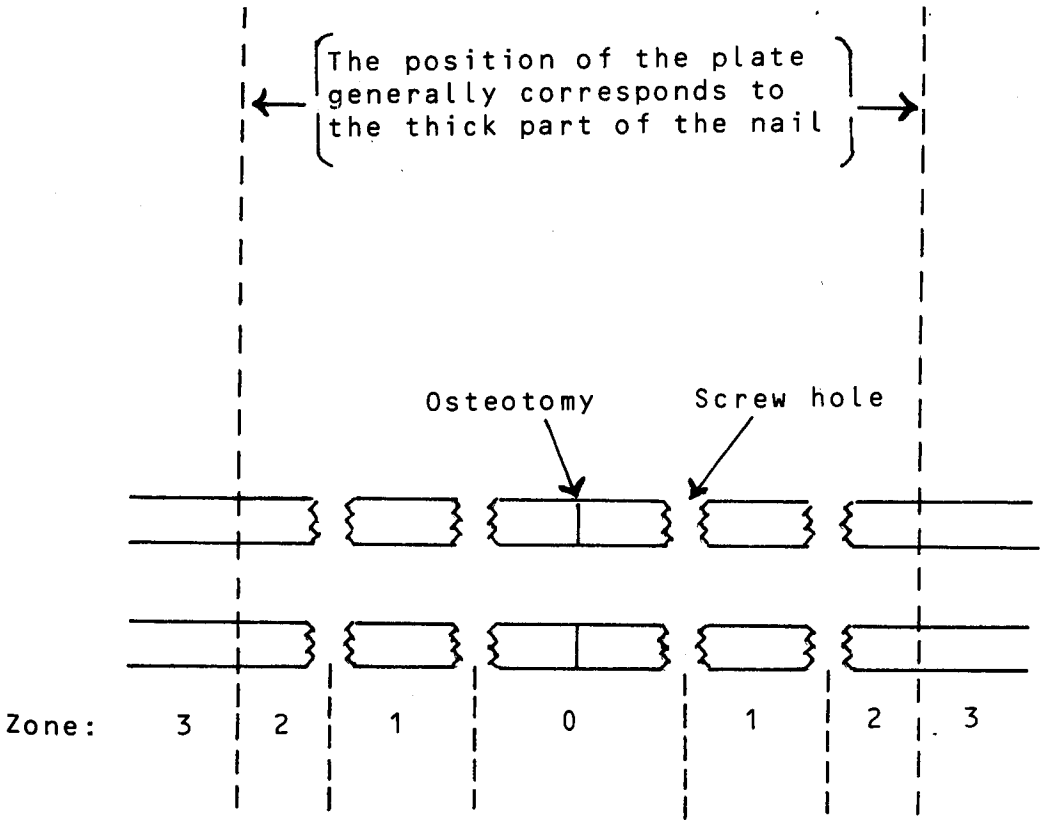


Figure 8. Definition of zones of the longitudinal sections used in the microscopic observations.

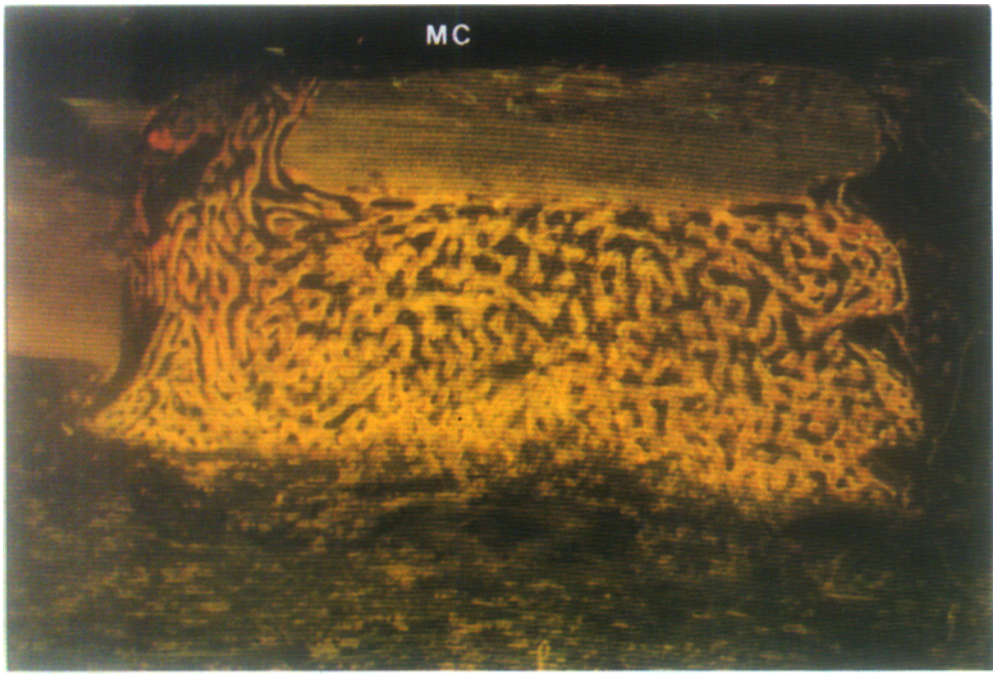


Figure 9. (Animal 44) Fluorescence preparation (3wc) (L.C. 9, 14, 21) of zone 0, the lateral side. Instability of the osteotomy has resulted in abundant periosteal formation of trabecular bone around the screw tips. The immature bone continues into the open osteotomy gap. In the gap itself, a beginning resorption is seen. (M.C. = medullary cavity).

Figure 10 (Animal 84) Fluorescence preparation (3wc) (L.C. 9, 14, 21) from 0-zone, showing resorption zones and a cutter head. Some of the canals are not, however, India ink filled and centrally in the cortex there are no necrotic areas. (X = cutter head).

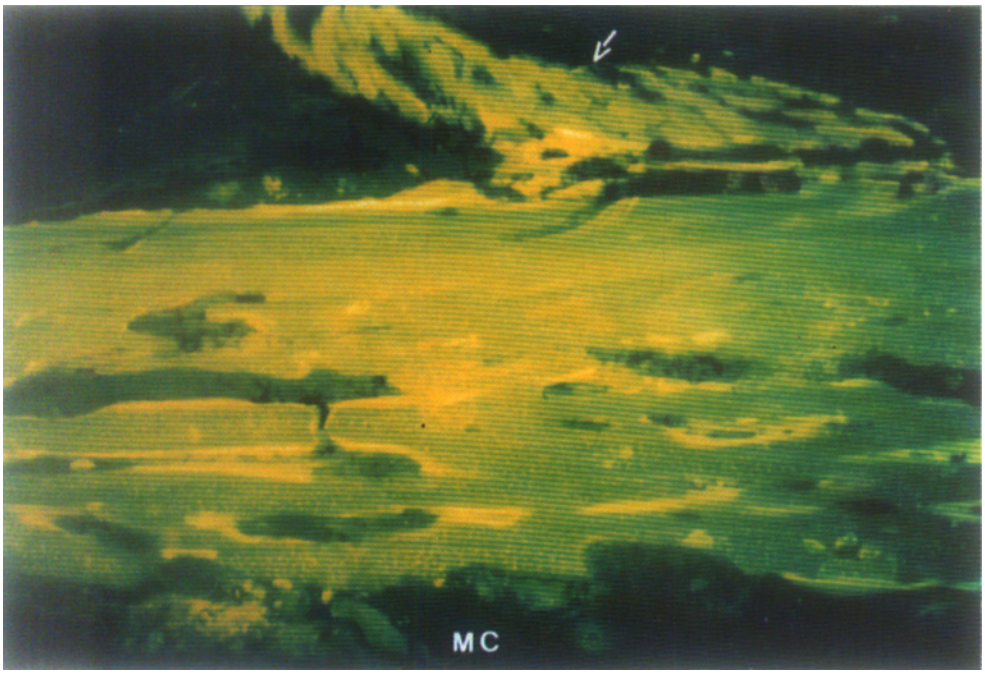
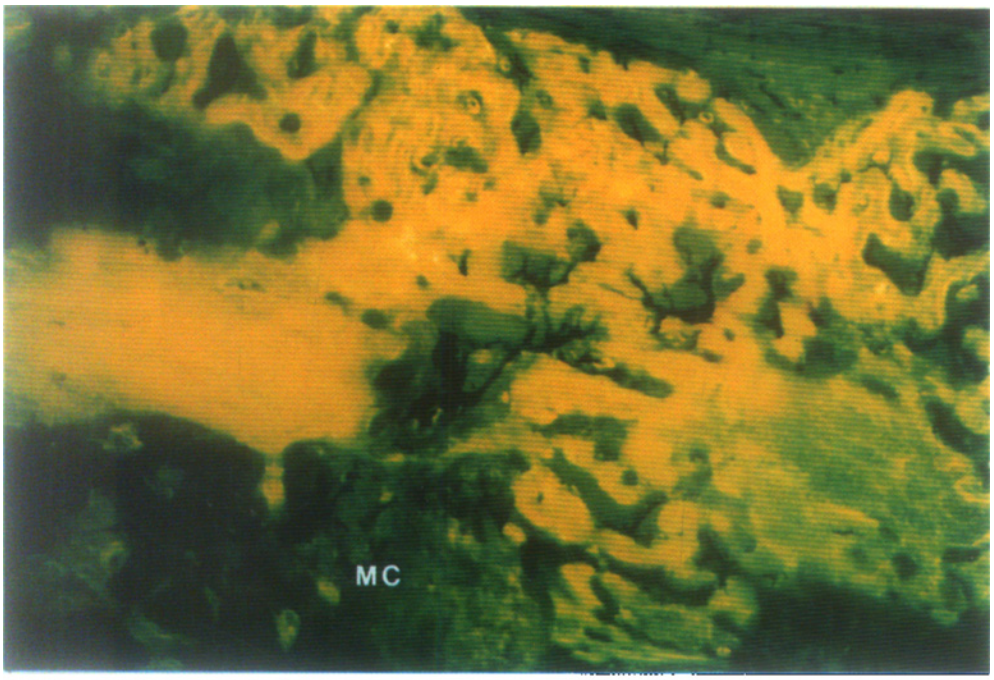
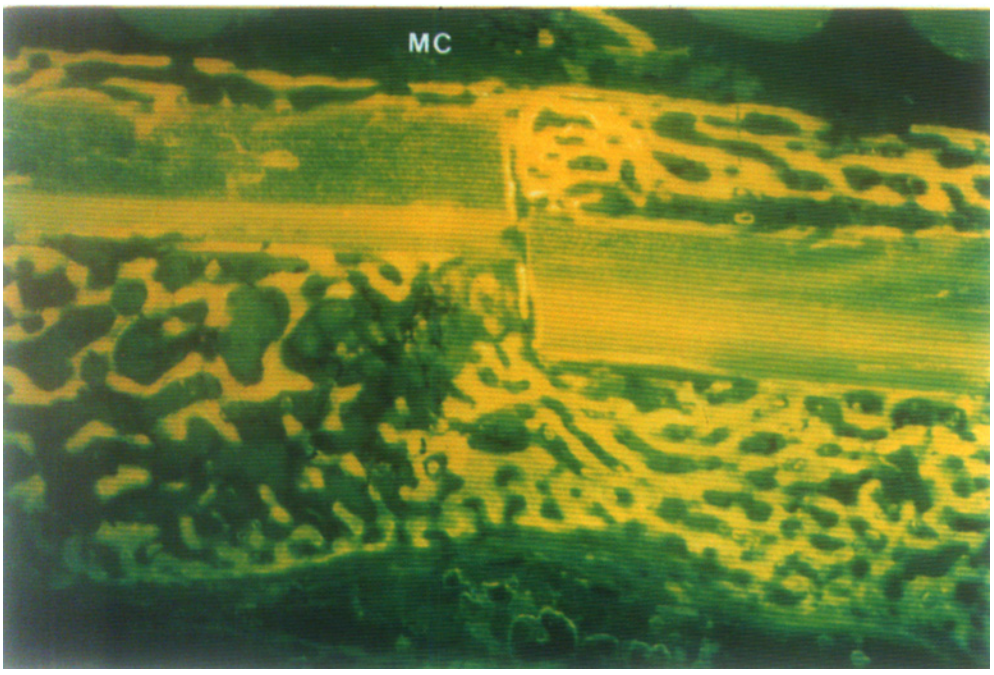


Figure 11. (Animal 140) Fluorescence preparation (6wc) (L.C. 25, 33, 42) from the plate side, zone 2–3. Relatively large resorption cavities with wide vessels. Beginning intracanalicular bone formation and also some mature periosteal bone formation (→). (M.C. = medullary cavity).

Figure 12. (Animal 140) Fluorescence preparation (6wc) (L.C. 25, 33, 42) of the osteotomy when the newly formed bone to a great extent has been remodelled to lamellar bone with osteons mainly oriented transversally.



a



b

Figure 13. (Animal 176) Fluorescence preparation (3p + 3n) (L.C. 21, 30, 35, 40) from zone 0 and the osteotomy gap; (a) the plated medial side, (b) lateral side. In this case the osteotomy was unstable after plate fixation. A certain amount of dislocation in the osteotomy occurred during reaming and intramedullary nailing. Extensive resorption of osteotomy ends on the plate side (resorption increased by instability). Continuous periosteal and endosteal callus in the form of immature trabecular bone on both the plate side and the lateral side. The extensive endosteal and periosteal callus formation has completely neutralized necroses and resorption. (M.C. = medullary cavity).

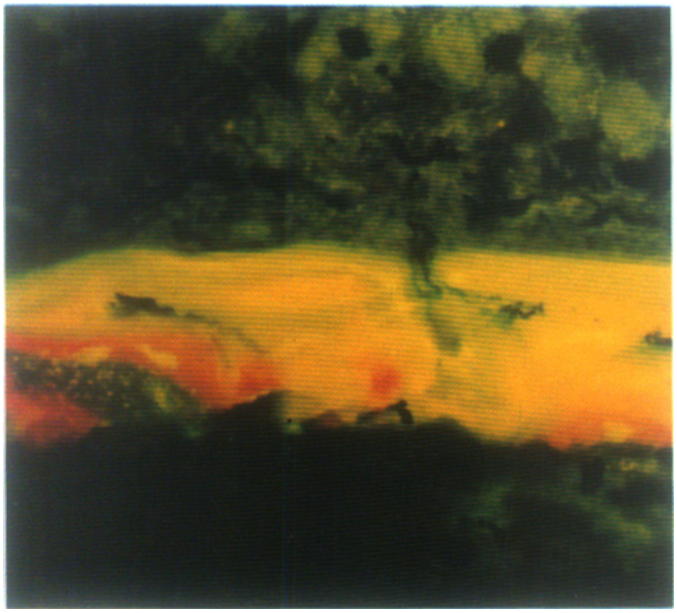
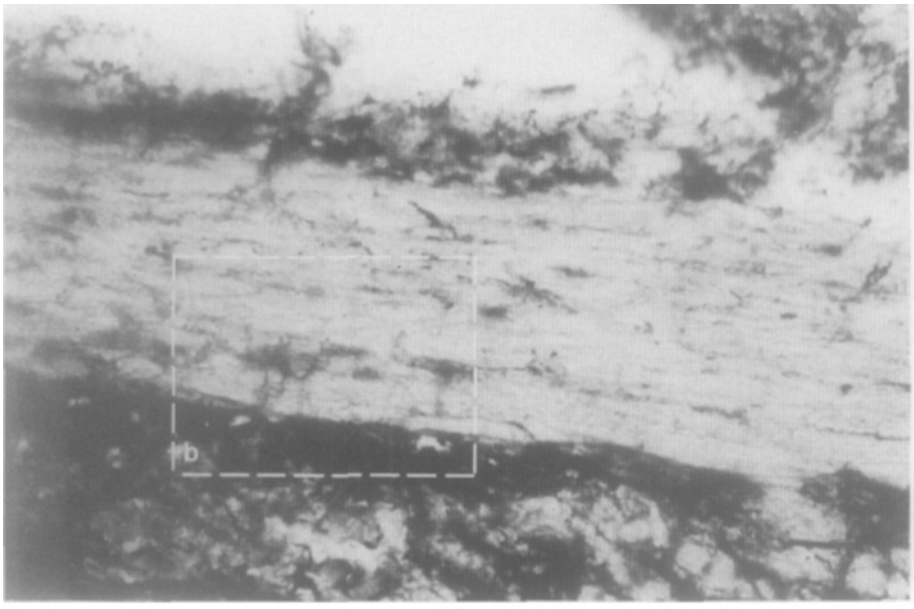
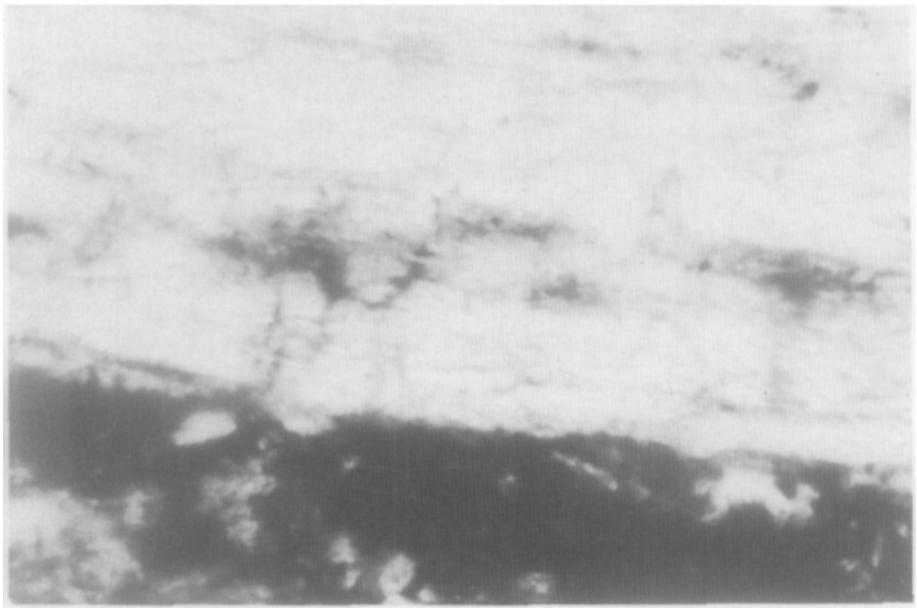


Figure 14. (Animal 196) Fluorescence preparation (3p + 6n) (L.C. 21, 45, 54, 61) of the plate side, zone 0. Cortex almost completely necrotic and resorbed (bottom). Outside of these necroses a continuous cuff of mature corticalized callus.



a



b

Figure 15. (Animal 187) (a) Spalteholz preparation (3p +3n) of the plate side, zone 2 and 3. Well restored periosteal and endosteal circulation. Revascularization of cortex in progress. (b) is an enlargement showing the revascularization of the cortex from the periosteal vascular system.

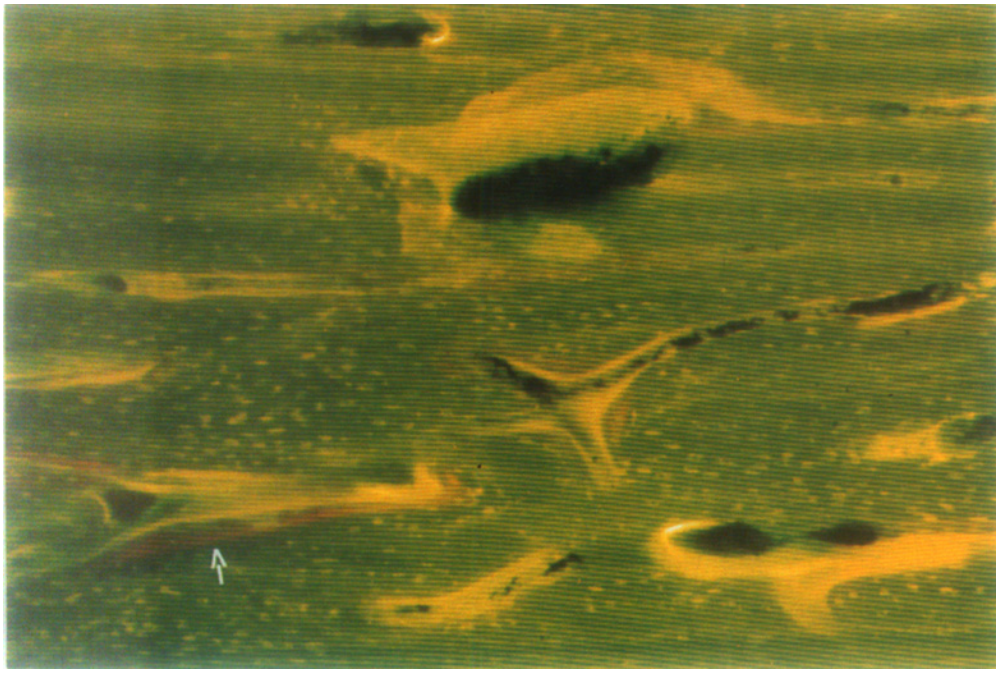


Figure 16. (Animal 197) Fluorescence preparation (3p + 6n) (L.C. 21, 45, 54, 61) from the plate side, zone 3. Relatively good revascularization with small resorption cavities. Moderate intracanalicular bone formation in process (→).

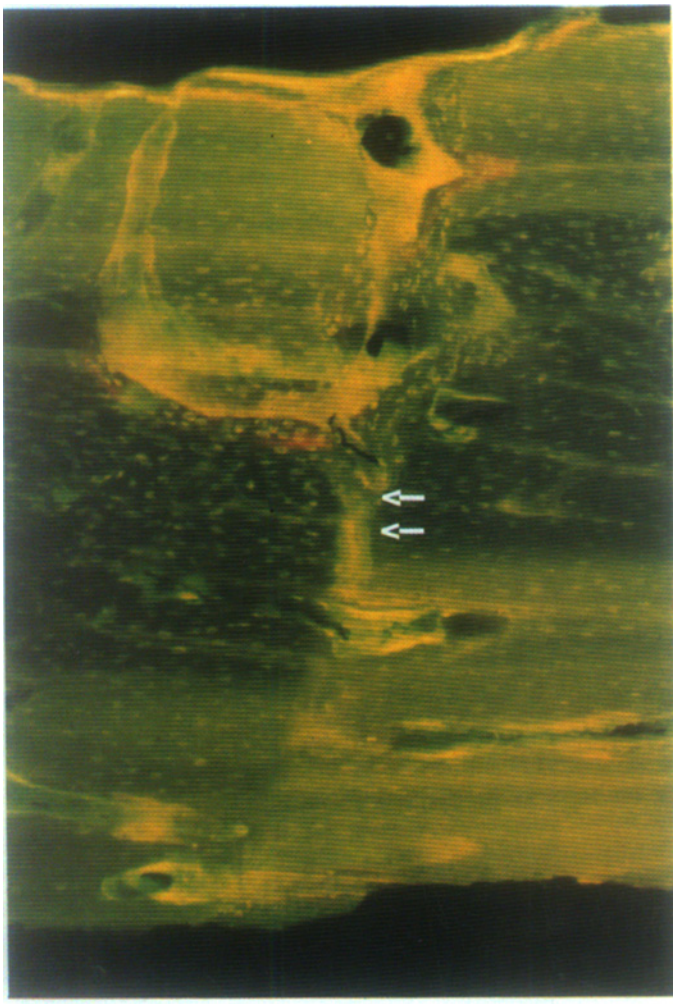


Figure 17. (Animal 197) Fluorescence preparation (3p + 6n) (L.C. 21, 45, 54, 61) of the osteotomy on the plate side. The osteotomy (⇒) is well healed with isolated osteons crossing the osteotomy line.

Figure 18. (Animal 196) Fluorescence preparation (3p + 6n) (L.C. 21, 45, 54, 61) of the osteotomy (→) on the lateral side. Resorption of the osteotomy ends, replaced by well vascularized newly formed relatively mature bone. Adjoining the newly formed peripheral bone, many resorption zones in the original cortex. Labelling of the bone shows that the resorption has mainly taken place up to the 3rd week after the intramedullary nailing. Bone formation has begun somewhat later, but proceeded parallel to the resorption and seems to have been especially lively during the 3rd and 4th week after secondary intramedullary nailing (yellow and red labelling).

Figure 19. (Animal 217) Fluorescence preparation (6p + 3n) (L.C. 42, 50, 55, 61) of the osteotomy on the plate side. The osteotomy (⇒) line is to a large extent not remodelled in this illustration. A certain amount of direct bone healing can be seen. Compare Figure 20.

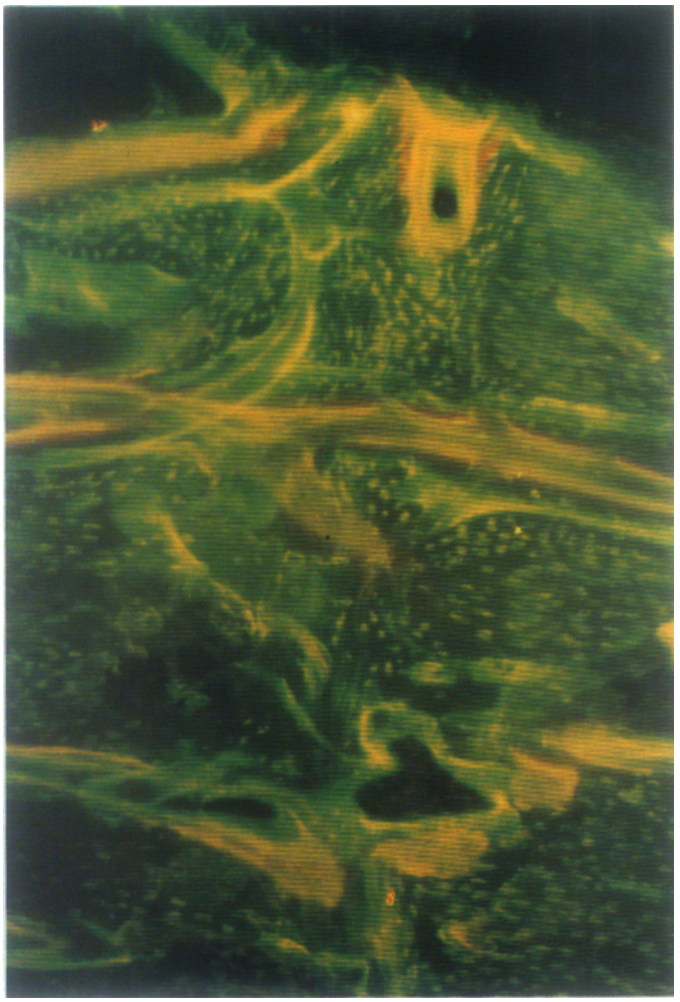


Figure 20. (Animal 217) Fluorescence preparation (6p + 3n) (L.C. 42, 50, 55, 61) of the same osteotomy as Figure 19. This illustration shows typical gap healing with both transverse osteons in the gap and intracanalicular bone formation over the gap. Tendencies to retrograde vascularization of the osteotomy ends can be found here.

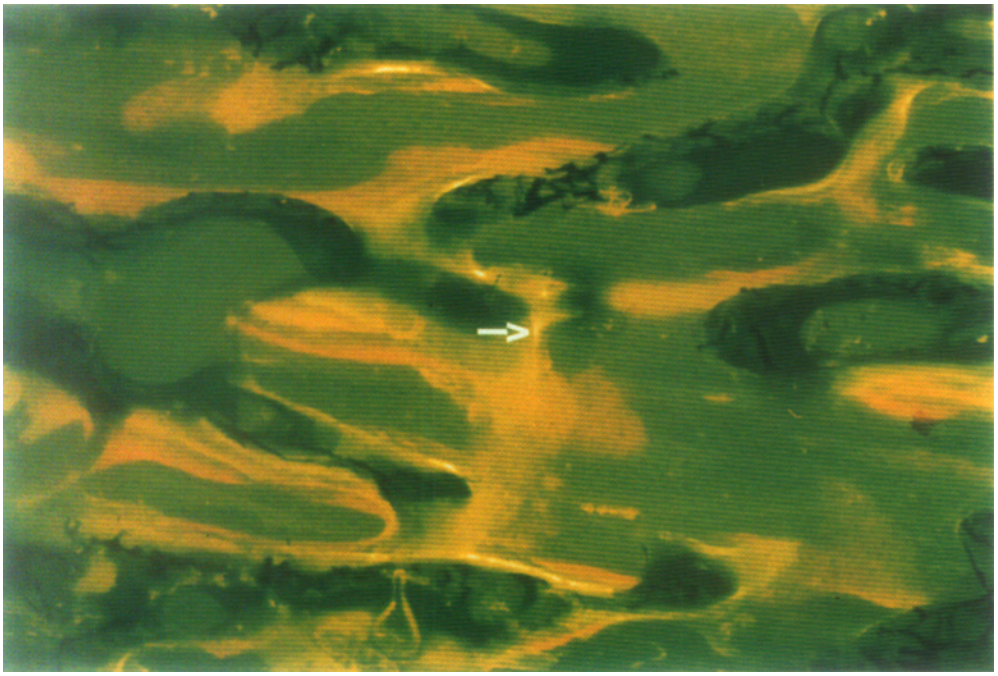


Figure 21. (Animal 272) Fluorescence preparation (6p + 6n) (L.C. 42, 68, 76, 82) of an osteotomy with a primary gap. The original osteotomy zone (→) is replaced by mature lamellar bone with large resorption cavities containing vessels.

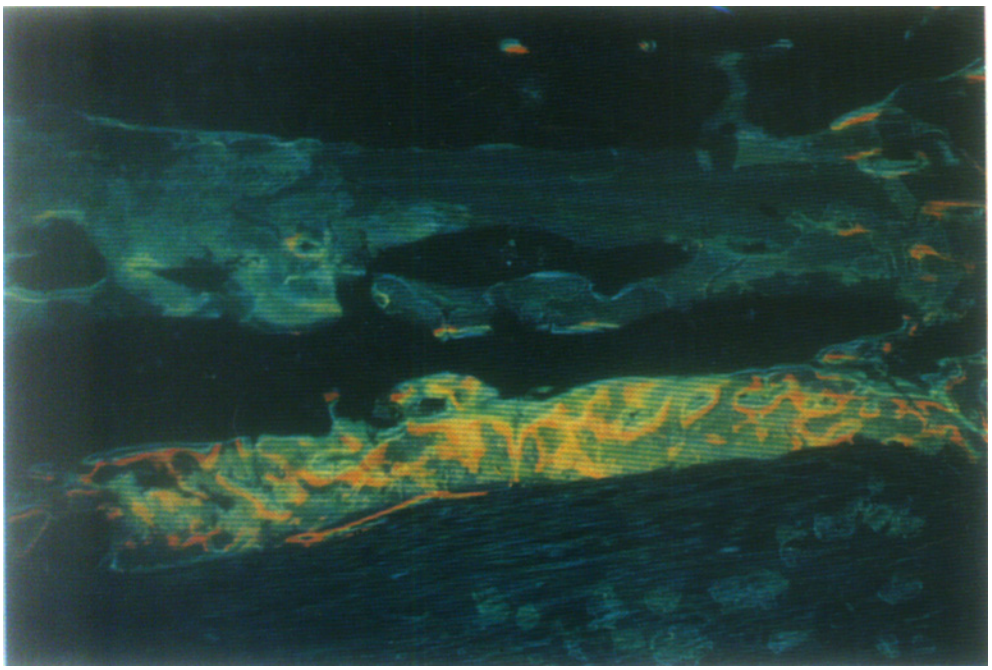


Figure 22. (Animal 343) Fluorescence preparation (group 6n + 6p) of the lateral side, zone 1. (L.C. 42, 66, 74, 82 – DCAF). The cortex is only partially revascularized. Extensive resorption subperiosteally. A number of resorption cavities can also be seen more centrally in the cortex. Well developed and mature periosteal callus cuff, where labelling indicates lively bone formation.

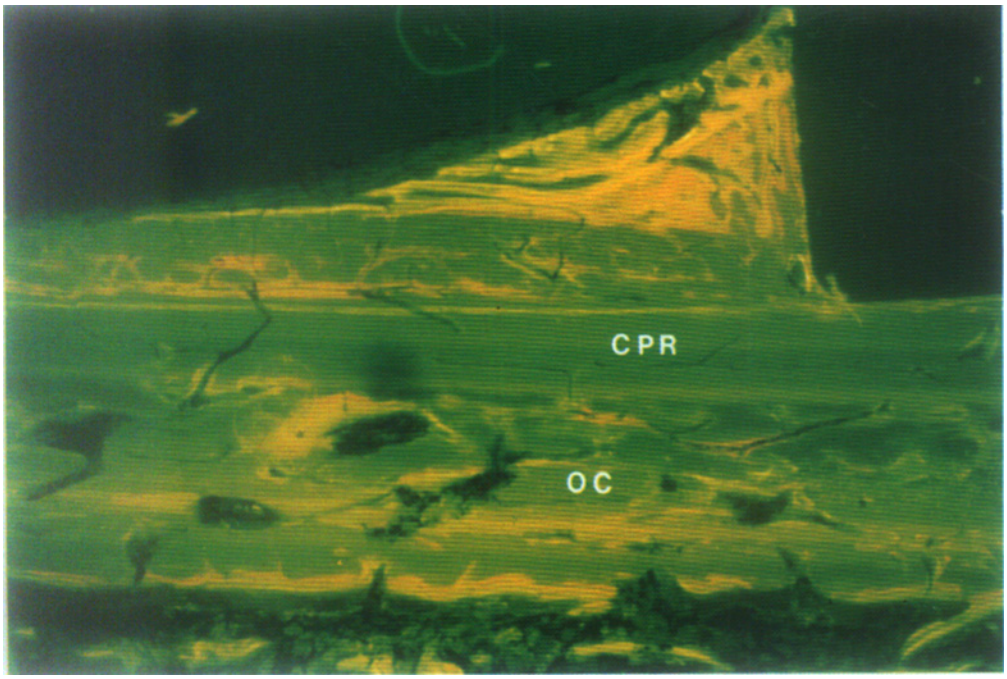


Figure 23. (Animal 311) Fluorescence preparation (group 3n + 6p) of the plate side, zone 2 and 3 (L.C. 21, 45, 53, 61). Formation of new mature bone after the nailing but before plating – corticalized periosteal reaction (CPR). Intramedullary bone formation in process. Some trabecular bone has been formed endosteally. (OC = Original Cortex).

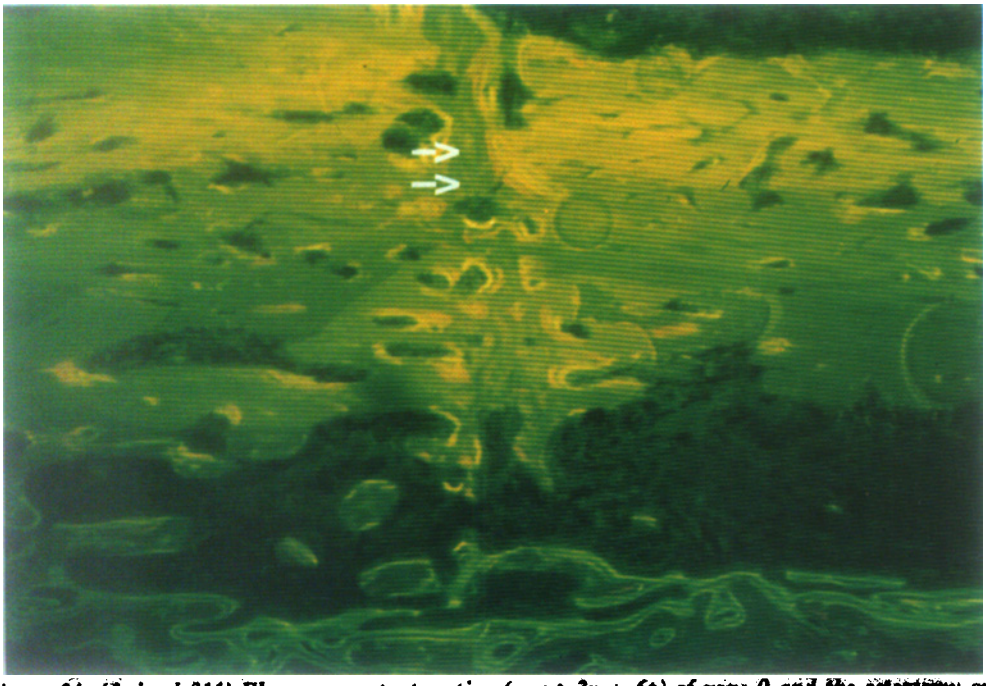


Figure 24. (Animal 311) Fluorescence preparation (group 3n + 6p) of zone 0 and the osteotomy on the lateral side (L.C. 21, 45, 53, 61). Large confluent resorption cavities are seen subperiosteally as well as a number of smaller cavities more centrally in the cortex. The osteotomy (⇒) gap is filled by mature bone. Beginning restructuring of the osteotomy by secondary longitudinal osteons.