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FRACTURE HEALING IN COMPRESSION OSTEOSYNTHESIS

An experimental study in dogs with an avascular, diaphyseal, intermediate fragment

By

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INTRODUCTION

The term « Soudure autogène », introduced by Danis in 1949, has been used to characterize the roentgenological healing pattern in compression osteosynthesis with a plate or screws and implies that a fracture gap is gradually eliminated during the healing phase. This type of fracture healing, at which the AO group aims, goes under the name « primary bone healing » (Müller et al. 1961). Characteristic of this healing process is considered to be the absence of roentgenologically visible periosteal callus, which means that the compression osteosynthesis gives satisfactory stability. Provided that the medullary circulation is intact, the development of callus obviusly shows an inverse relationship to the degree of stability (Yamagishi & Yoshimura 1955, Andersson 1965), and periosteal callus in compression osteosynthesis would thus seem to be a sign of disturbed healing (Wieser & Allgöwer 1962). The compression as such probably only means increased stability, while the healing rate is hardly accelerated. Geiser (1963) and Charnley (1965) claim that increased periosteal destruction during the operative procedure can be a cause of reduced callus development. In experiments on the sheep radius, Shenk & Willenegger (1963) showed that regenerating osteones pass over an osteotomy line. These authors consider that this form of healing, which with its secondary osteone formation resembles the rebuilding of normal cortical bone is worth striving for. They consider that under stable conditions the devitalized marginal layer of the cortex would induce regeneration of the Haversian systems (Shenk & Willenegger 1967). Geiser (1963) claims, however, on the basis of studies on rabbits, that all bone healing arises from periosteum and endosteum. This bone formation primarily fills out the fracture gap, while at the same time there is creeping substitution of the necrotic marginal layer. On the basis of microangiographic and fluorescence microscopic studies in compression osteosynthesis on the dog tibia, Olerud & Danckwardt-Lillieström (1968) consider that new bone is formed mainly from blood vessels arising fom the medullary cavity and periosteum, but that at the same time, under certain conditions, intracanalicular bone formation is possible.

Thus, opinion on the importance of the different healing courses are somewhat divergent. By introducing an avascular intermediate fragment into the compression zone, we have found it possible to study more closely the way in which the revascularization of an « extended » marginal zone takes place and the source of the main vascular supply. With the microangiographic technique used especially by Göthman (1960), Rhinelander (1962, 1968) has studies the revascularization of diaphyseal fractures. He has pointed out that the healing area in non-dislocated fractures obtains its essential vascular supply from the medullary cavity.

The aim of the present study was to elucidate the healing course on the incorporation of a completely devascularized, diaphyseal intermediate fragment, comprising the whole circumference of the diaphysis in a compression osteosynthesis with a plate.

Method

The study was performed on adult, mongrel dogs.

From an incision immediately lateral to the anterior tibial margin, the medial facet of the tibia was dissected free subperiosteally. A 6-hole AO plate was placed in position and fixed with screws through the 3 distal holes. The upper part of the plate was anchored with the compression instrument developed by AO. The fitting of the compression plate before the osteotomy was of great importance for the subsequent osteosynthesis. The plate was bent to that the osteotomy gaps of the fibular side should be compressed slightly before the gaps of the medial side. When the plate had been removed after the fitting, a double osteotomy was performed with a Gigli saw, corresponding to the area between the middle holes of the plate. The intermediate fragment was made somewhat broader againts the plate side. The ring-shaped intermediate fragment then obtained was lifted out of its bed and was thereby completely freed from vascular communications. The osteotomy surfaces were smoothed with a file until they were quite even, after which they were washed with physiological NaCl solution. The intermediate fragment was replaced in its position and the AO plate was secured in place. After fine adjustment of the fractures to an exact position, the compression was performed. On compression, the intermediate frag-

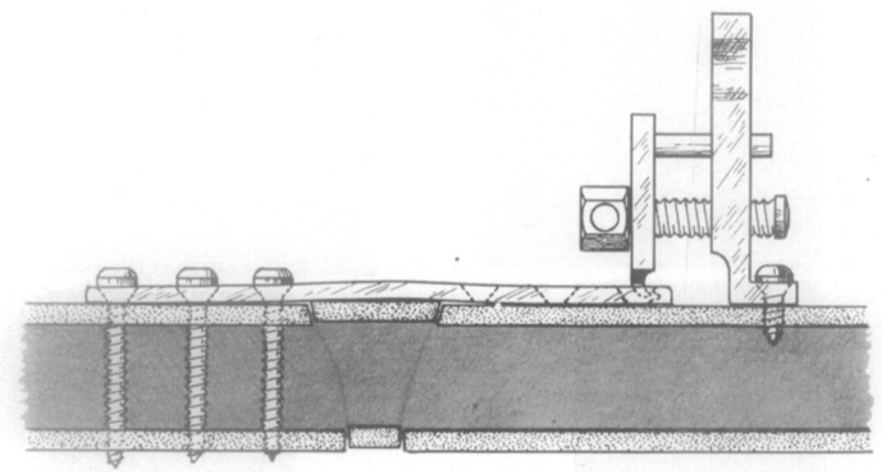


FIG. 1. - Diagram of the experimental arrangements. On compression, the fibular side is first adapted, on further compression the plate is straightened and the plate side is brought under compression. The intermediate fragment is pressed down into its bed when the inner screws in the right and left main fragment finally are tightened.

ment, owing to its shape, was pressed firmly between the main fragments and the plate, so that the internal fixation was maximally stable. The part of the fibula between the levels of the osteotomy was resected, so that a continuity defect was produced at this site. The main incision was closed with single intracutaneous nylon sutures. The operation area was drained for 24 hours with a Kofferdam strip. The experimental set-up is presented schematically in Fig. 1.

All operations were performed on both tibiae, as a rule with an interval of 4 - 6 weeks. In order to label the newly formed bone, the dogs were given two injections of Terramycin® (Pfizer).

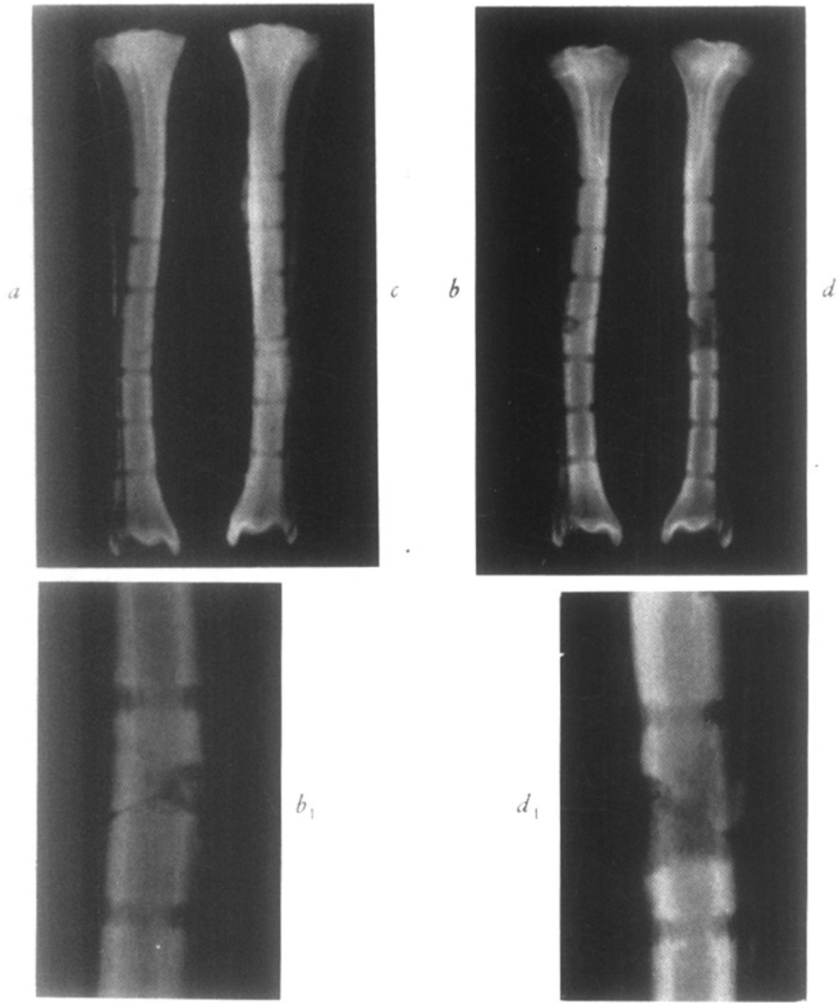


FIG. 2. - **Roentgenograms** showing the position of **the intermediate** fragment in the tibial diaphysis and the healing of the osteotomies: *a* - After an observation time of 4 weeks: The osteotomy gaps are still well visible but endosteal callus is present, especially in level with the lower gap. *b* - After an observation time of 6 weeks: The lower osteotomy gap is almost completely filled, and the upper gap is partially open. The fibular part of the intermediate fragment is undergoing pronounced reconstruction. *c* - After an observation time of 8 weeks: The lower osteotomy gap shows a tendency to delayed union, and the upper gap is almost filled. The structure and mineral content of the intermediate fragment are essentially retained. *d* - After an observation time of 10 weeks: Both osteotomy gaps healed. Considerable reconstruction of the intermediate fragment and especially the marginal zone of the upper main fragment. b_1 - enlargement of the 6 week preparation. d_1 - enlargement of the 10 week preparation.

These were given intraperitoneally (50 mg/kg body weight), one of them 1 - 2 weeks after the second operation and the other 2 days before the end of the experiment. The experiment was arranged so that specimens were obtained during the healing process at 4 weeks and up to 14 weeks, at intervals of 1 - 2 weeks.

At the end of the experiment the dogs were again anaesthetized. After primary heparinization (500 U Vitrum/kg), a catheter with an internal diameter of 1.5 mm was introduced into the carotid artery in the direction towards the heart. Through this catheter an Indian ink mixture (200 ml Günther Wagner Pelikan Indian ink in 800 ml isotonic NaCl» was infused with an ordinary Record syringe, at the beginning with excess pressure. After infusion of about 100 - 200 ml the animal usually died, after which the infusion was continued slowly for a further few hours until 5 litres of Indian ink mixture had been given from a height 120 cm above heart level. During the period of the infusion the dogs were kept in an upright position so that the Indian ink solution should gradually sediment in as many vessel branches as possible in the freely dependent limbs.

After the Indian ink filling procedure the extremities were amputated at the knee joint and fixed in 96% alcohol which was changed daily or on every alternate day for 14 days. The soft tissues were cut away except on the area nearest to the osteotomy. The osteosynthesis plate was removed, and the specimens were photographed roentgenologically. The specimens were divided into two halves; one half was embedded in methyl methacrylate and the other was delcalcified for paraffin embedding.

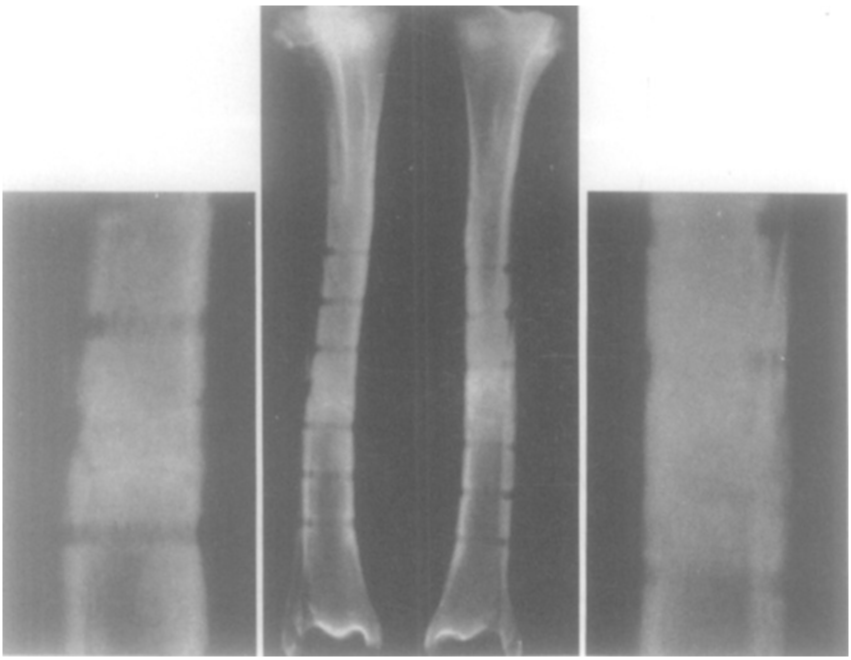
The paraffin embedded specimens were sawn into 1 mm thick sections, the paraffin was dissolved in xylol, and the sections were then placed in sodium benzoate and wintergreen oil according to the Spalteholz technique.

The plastic-embedded halves were sawn into ½ mm thick sections, parallel with the longitudinal axis of the bone, and were then ground down to a thickness of about 80 - 100 μ. These sections were studies microscopically with ultraviolett light with a filter combination suiting Terramycin fluorescence.

Some of the ground, plastic-embedded sections were photographed microroentgenologically for a study of the roentgenological microstructure, and examined in polarised light with respect to the course and orientation of the collagen fibrils.

Results

In spite of the mechanically rather unfavourable experimental arrangements, with double osteotomy, only about one week elapsed before the dogs bore weight on the affected limb when walking. There was some limp, however, for a period of up to 3 weeks in the dogs which healed without complications. In 2 of the 8 experiments pseudarthrosis occurred in the distal osteotomy, and pronounced swelling of



a_1 a b b_1

Fig. 3. - Roentgenograms showing the incorporation of the intermediate fragment after 7 (a) and 11 (b) weeks, respectively: a_l - Partial enlargement after observation time of 7 weeks. The osteotomy gaps are almost completely filled; moderate endosteal callus. b_l - Partial enlargement of roentgenogram at observation time of 11 weeks. The two osteotomy gaps are no longer visible. Decreased mineral content in the interemdiate fragment as a sign of reconstruction in progress. A tendency to spongious transformation within th distal main fragment.

the lower leg developed in these dogs. The remaining 6 dogs showed only moderate swelling 4 weeks after the operation and later. There were no infections. The roentgenograms showed a distinct osteotomy gap in the 4-weeks specimens (Fig. 2). These gaps were almost completely filled after an experimental period of 8 weeks, in accordance with Danis « Soudure autogène ». At 10 - 11 weeks the fracture gap could no longer be visualized roentgenologically (Fig. 3). In the 2 pseudarthrosis cases the upper gap had healed after 8 and 10 weeks, respectively.

On several roentgenograms a cloudy callus reaction a few mm high was observed on the medial side of the tibia. The intermediate fragment showed on some roentgenograms a considerable reduction of the calcium content in comparison with the main fragment (Fig. 2).

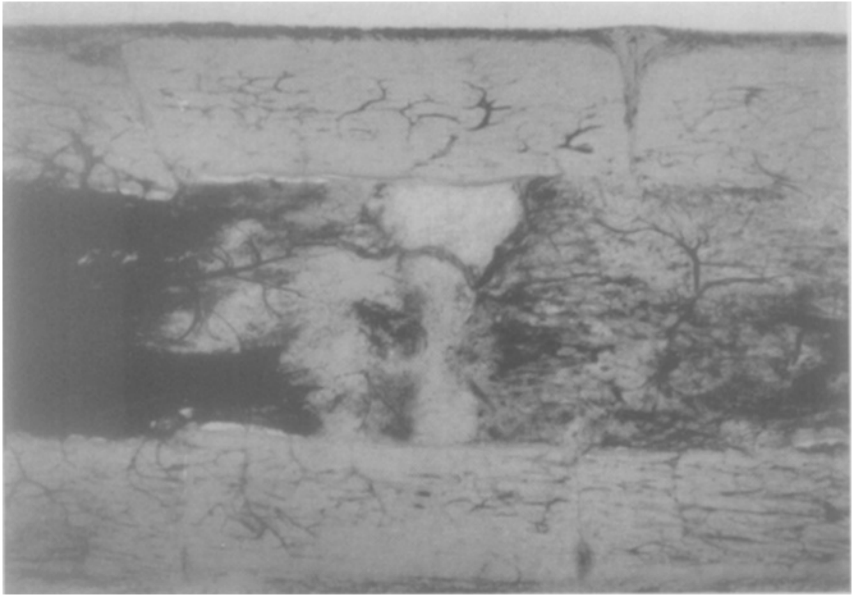


FIG. 4 - Spalteholz specimen 4 weeks after osteotomy. Microangiography shows that vascular communication has been established between the main fragments through the medullary cavity of the intermediate fragment. A vein is here connecting the vascular systems of the two main fragments through the previous avascular intermediate fragment. More than the inner 2/3 of the cortex of the intermediate fragment is vascularized from the medullary cavity. The intermediate fragment is surrounded by a thin periosteal vascular network, which is revascularizing the outer part of the cortex.

In specimens from experiments of the shortest period (4 weeks) the medullary circulation had become reestablished, with vascular communications crossing the two osteotomy lines (Fig. 4). With all probability, the well filled vessel constitutes an artery, and the broader vessel with less Indian ink density is probably a vein. Specimens from the 4th week also show that a large proportion of the primarily avascular fragment contained Indian ink filld vessels, the source of wich was almost solely the medullary cavity. Fig. 5 demonstrates besides a well vascularized medullary cavity also a vascular system wich extends from the medullary cavity almost to the outer layer of the cortex. This is found in Fig. 6, wich is an enlargement of Fig. 5. The type of vascularization is the same. This held for

FIG. 5 - Spalteholz specimen 6 weeks after osteotomy. The medullary cavity circulation is restored in the form of a relatively fine-meshed vascular network of the type seen in proliferative callus formation. Four-fifths of the fibular side cortex of the intermediate fragment is revascularized here from the medullary cavity. Negligible periosteal revascularization, which is taking place during the formation of resorption cavities. Cartilage immediate outside the cortex between fibular fragment end (bottom to the right) and the intermediate fragment is undergoing enchondral ossification.

both the plate side of the tibia and its lateral side. At the same time, in only exceptional cases were periosteal vessels (perhaps better expressed as vessels arising from the soft tissues, since the periosteum was largely destroyed) found to pass deeper into the cortex than some mm, i.e. 1/4 - 1/5 of the thickness of the cortex. This applied both to the plate side of tibia and its fibular side. Between the plate and the cortex a relatively richly vascular, fibrous soft tissue layer always extended (Fig. 7).

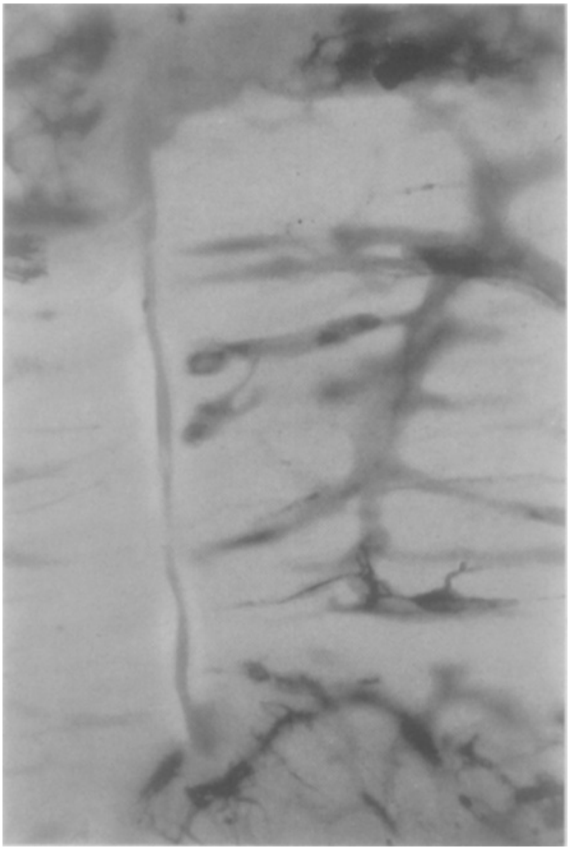


FIG. 6 - Spalteholz specimen 6 weeks after osteotomy. Absolute bone contact between the fracture fragments at the fibular side. More than 4/5 of the cortex of the intermediate fragment is vascularized from the marrow canal. The osteotomy line is on the way to being crossed over by cutting heads from vessels in the intermediate fragment to the right. (Partial enlargement of Fig. 5.).

An abundance of newly formed vessels were observed 4 weeks after the osteotomy in the fracture gap, where any form of space was present. The vessels originated mainly in the medullary cavity. It was often observed that medullary cavity vessels first entered the intermediate fragment or the main fragments and then passed further via Haversian canals to the fracture gap, there to connect with vessels with direct communication from the medullary cavity or from the periosteum (Fig. 8). When there was very close or absolute contact

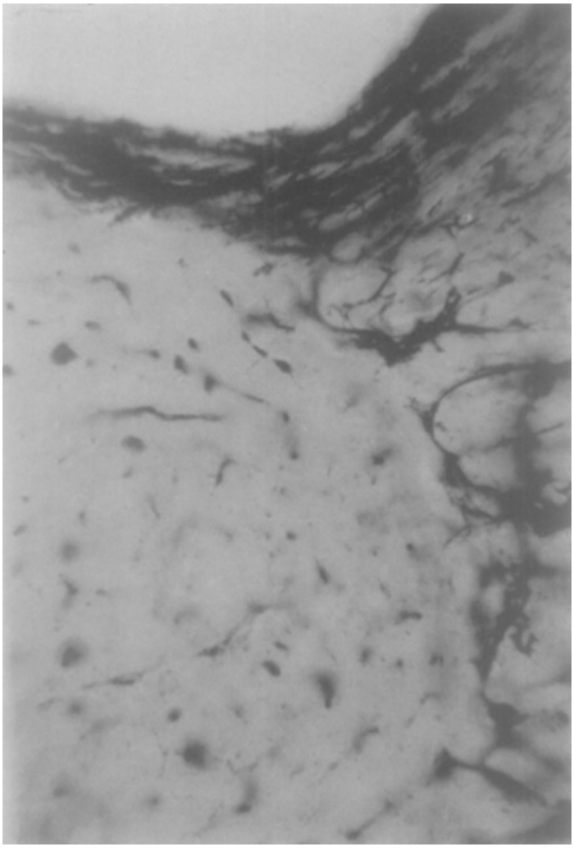


FIG. 7 - Spalteholz specimen 6 weeks after osteotomy: In the upper part of the specimen there is an empty space, which represents the position of the metal plate. Numerous vessels in a fibrous layer are invading the area between the cortex and the plate. The periosteal vessels seem to be contributing very little to the vascular supply of the cortex.

between the fracture fragments, there was no space for vascular invasion. The vascular supply then developed mainly into canals leading from the medullary cavity, lying in the fragments close to the fracture line. Blood vessels passed into these canals, and made contact with vessels from the other side of the fracture gap (Fig. 8). This took place partly via so called cutting heads (Fig. 9), which drilled their canals possibly quite independently of previous canals in the bone.

In specimens 6 - 8 weeks after osteotomy, a considerable widening of the Haversian canal systems was found both in

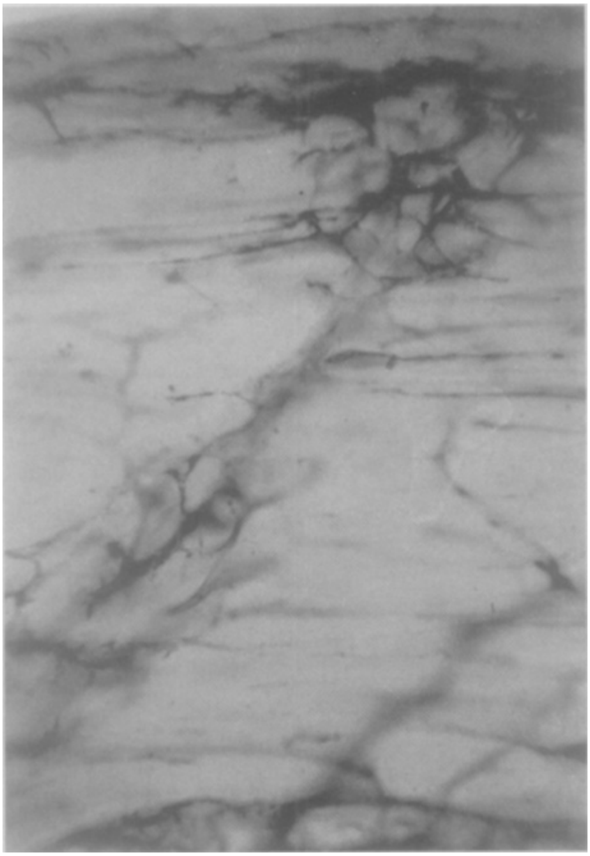


FIG. 8 - Spalteholz specimen 5 weeks after osteotomy. Osteotomy line on the plate side of the tibia (top of the picture). Vascular invasion from both the periosteal and the endosteal side. The entire osteotomy line is vascularized. Several vascular communications with the Haversian systems of both the intermediate and the main fragment.

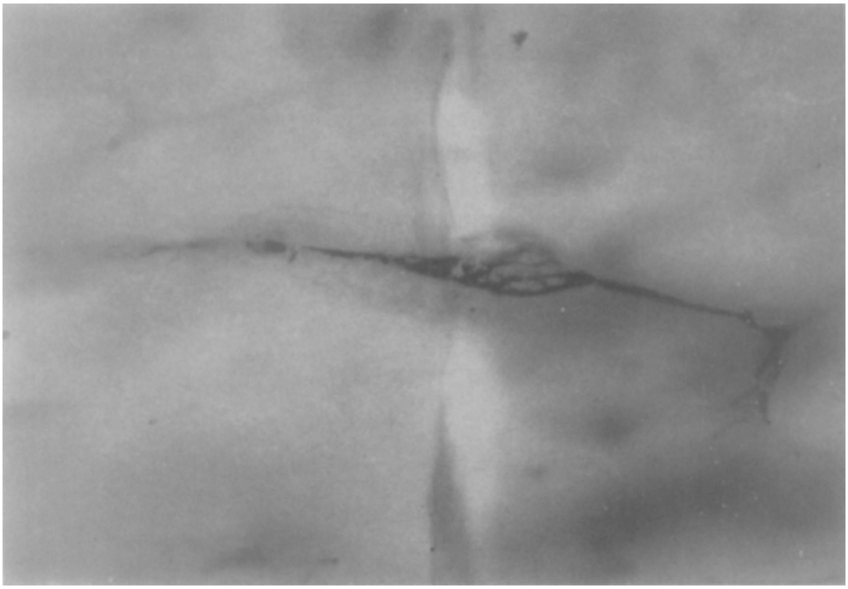


FIG. 9 - Spalteholz specimen 4 weeks after osteotomy. The fracture line, which otherwise is not vascularized, has been traversed by the vessels in a secondary osteone. The foregoing cutting head in the intermediate fragment can be seen to the left of the gap.

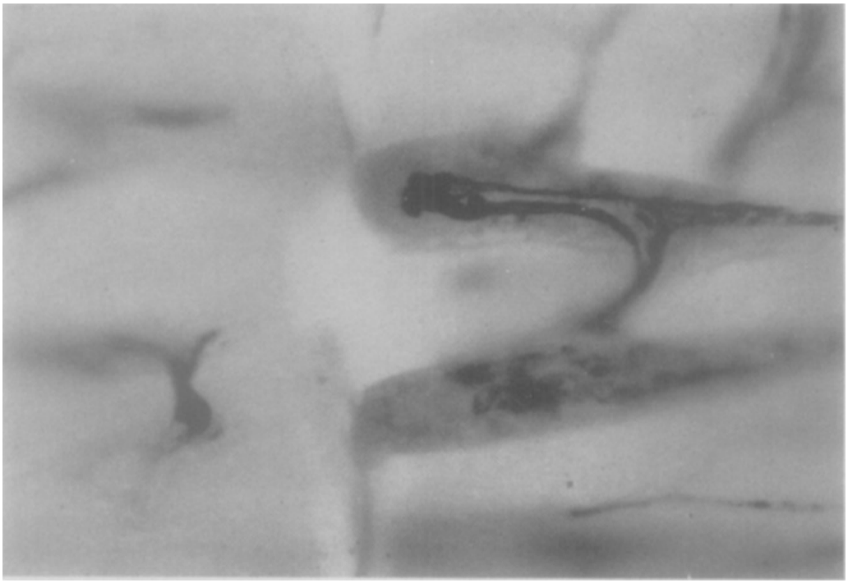


FIG. 10 - Spalteholz specimen 4 weeks after osteotomy. Cutting head with well-filled vessel loop is just about to traverse the fracture line.

the main and in the intermediate fragment. Not seldom, several vessels were then observed in the same canal. As described above, these canals can be completely newly formed by so called cutter heads. In cases with several vessels in the same canal, one vessel was often found to be narrower than another, i.e. the former was probably an artery and the latter probably a vein.

The cutting head mechanism was also observed regularly into the fracture gap, from both the periosteal and endosteal side. On either side of the fracture line of a closely

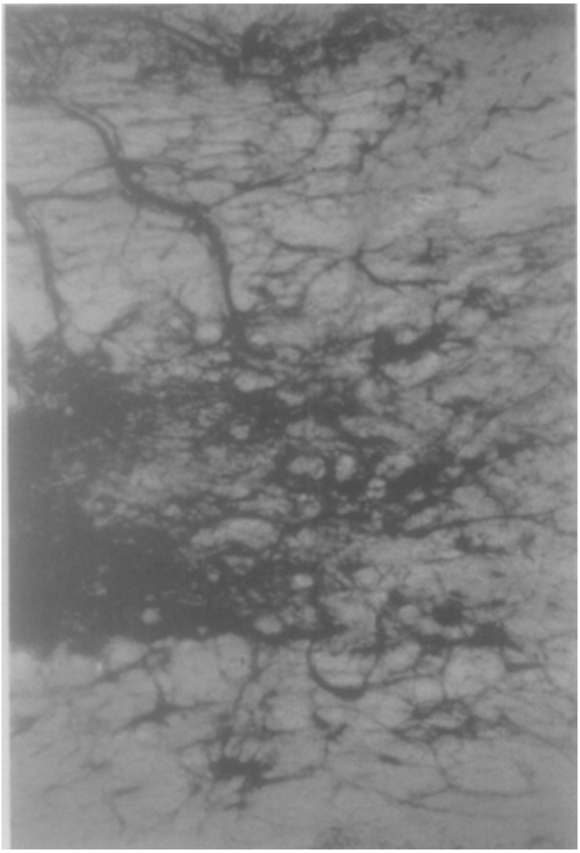


FIG. 11 - Spalteholz specimen 10 weeks after osteotomy. The intermediate fragment, which is seen to the left of the photograph, is penetrated by relatively wide vessels. The bone canals often contain more than one vessel. The vascular pattern in the medullary cavity indicates resorption of endosteal callus.

adapted fracture, a vessel loop was seen, wich worked its way forwards into the marginal zone. The mechanism was most clearly evident on fluorescence specimens, however (Fig. 19).

The fracture gap and its immediately surrounding area became more and more vascularized with time. After an observation time of 10 - 11 weeks the fracture gap itself was only just distinguishable - so evenly was the vascular pattern distributed within the intermediate and main fragments. Some specimens

FIG. 12 - Spalteholz specimen 11 weeks after osteotomy. The osteotomy gap can be identified in relation to the divided fibula (in the lower part of the photograph). The cortical vessels in the osteotomy area are evenly distributed and show signs of maturity. They are mainly orientated in the longitudinal direction of the cortex. The intermediate fragment is to the right side of the photograph.

(Fig. 11) showed considerable absorption of cortical bone. Fig. 12 gives a general picture of the angiographic pattern of an inbuilt intermediate fragment 11 weeks after the osteosynthesis. At this stage, direct vessels from the medullary cavity and periosteum to the fracture gap were seldom seen, so that these communications had probably re-formed even after this short time.

Fluorescence microscopy - Periosteal reaction

Four weeks after osteotomy, periosteal activity with newly formed bone was noted both over the main and the intermediate fragments. The bone formation was characterized by active tissue formation on the surface and resorption cavities in the deep areas immediately outside the original cortical bone (Fig. 13). At the level of the opening of the fracture gap new bone had developed in the form of almost fan-shaped trabecular bone (Fig. 14). On the fibular side, partly calcified cartilage had formed between the ends of the fibula and the intermediate fragment (Fig. 15).

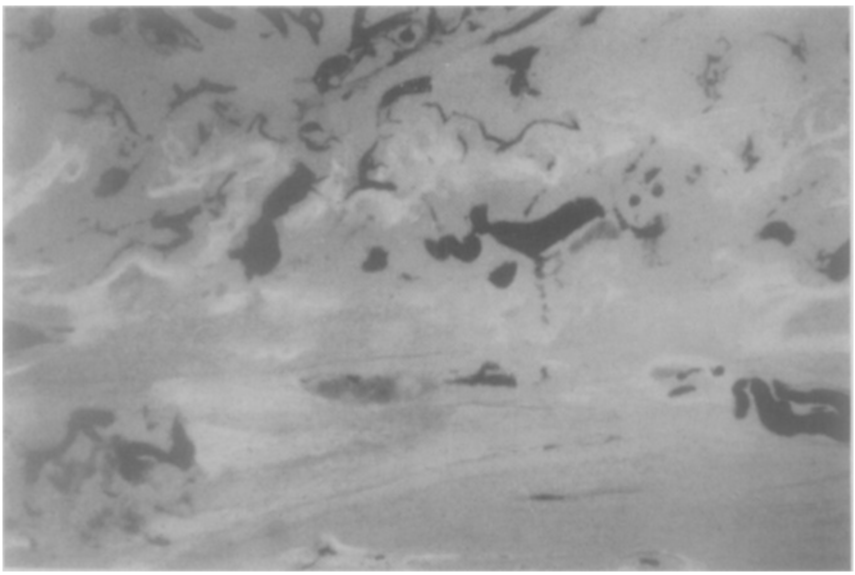


Fig. 13 - Fluorescence specimen 4 weeks after osteotomy. Periosteal callus is seen with active tissue formation on the surface, and resorption cavities containing wide vessels in towards the cortex.

Six weeks after osteotomy, patches of active bone formation were observed in the subperiosteal tissue. Fairly large resorption cavities were found in the primarly formed periosteal callus, and the periosteal superficial activity seemed to be considerable decreased, although the surface seemed to be still

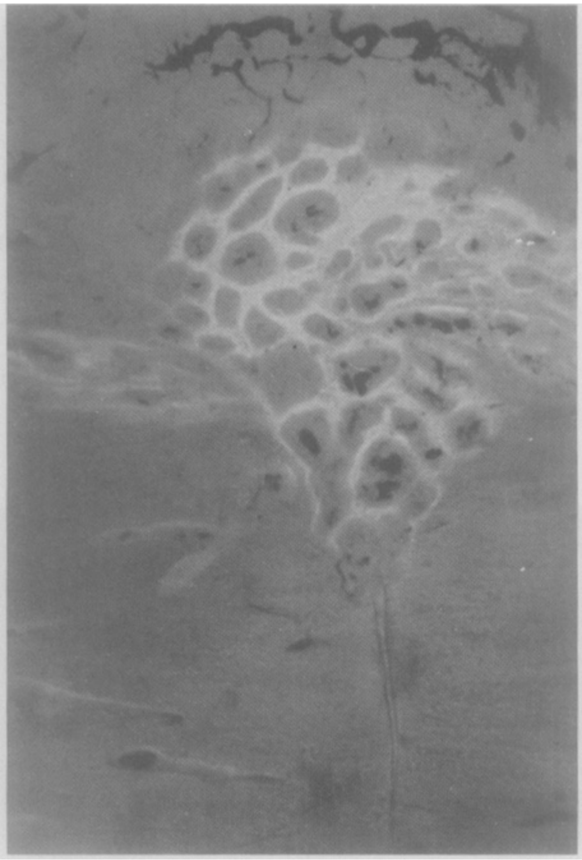


FIG. 14 - Fluorescense specimen 4 weeks after osteotomy. Trabecular bone under development is seen outside an osteotomy gap. Active bone formation is in progress, both periosteally and in towards the fracture gap.

FIG. 16 - Fluorescence specimen 6 weeks after osteotomy. Nearest to the cortex, a resorption cavity with wide vessels is being formed. The callus outside this area is undergoing condensation, while the peripheral surface of the cortex shows resorption. First labelling 4 weeks after the osteotomy, second labelling 2 days before the end of the experiment.

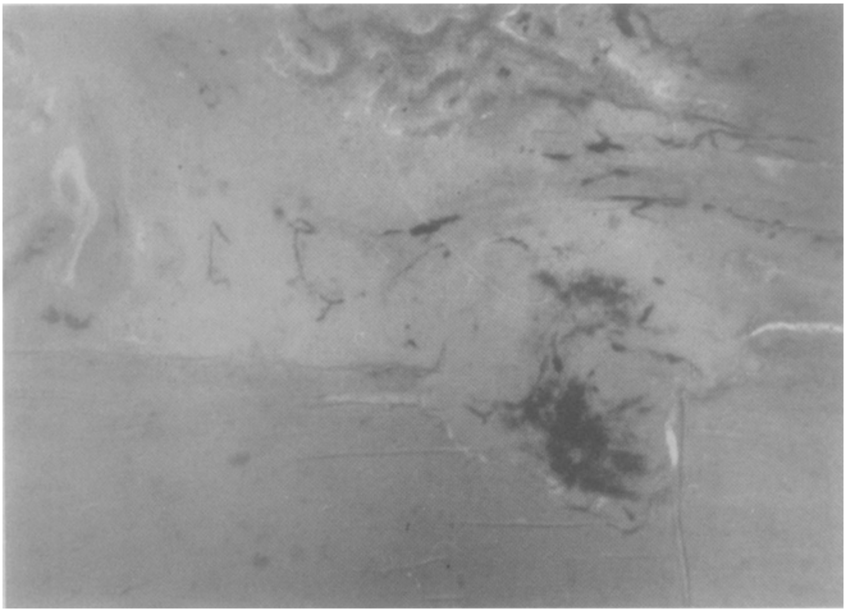
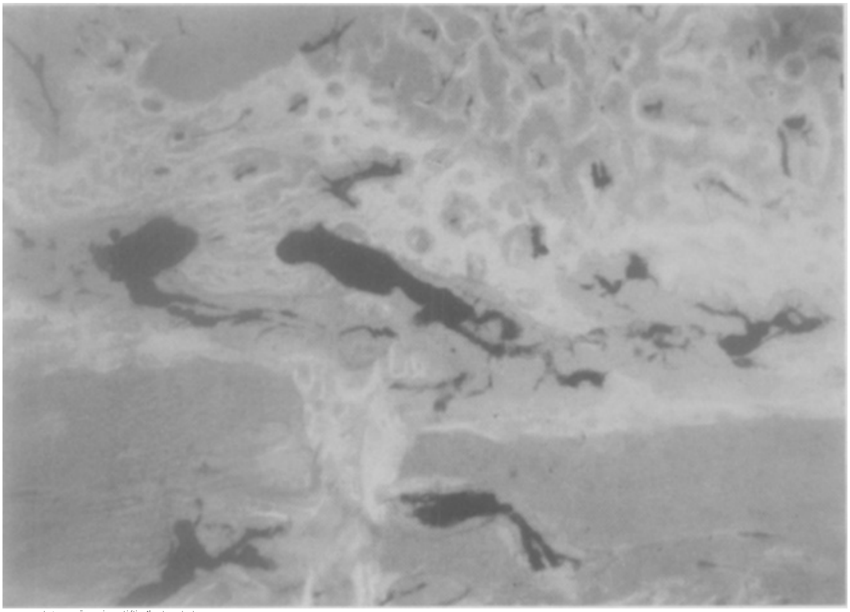


FIG. 15 - Fluorescence specimen 5 weeks after osteotomy. Intermediate fragment to the left. There is resorption of the cortical corner on the periosteal side of both the intermediate and main fragment. Cartilage tissue is observed above the intermediate fragment, and also trabecular bone formation.



under construction. The second terramycin labelling 2 weeks after the first supported this observation (Fig. 16). The periosteal activity outside the fracture gap had decreased greatly in intensity, as indicated by the presence of resorption areas.

After an observation time of 8 weeks reconstruction of the periosteal callus and the subperiosteal bone had become more extensive, with a change-over to a new cortical structure (Fig. 17). Superficial activity within the periosteum was practically no longer observed, and this was also true at the level of the fracture gaps. Neither were any signs of active periosteal bone formation seen in specimens examined 10 weeks after the osteotomy. On the other hand, numerous resorption cavities were found within the area between the ends of the fibulae and the intermediate fragment, where endochondral bone formation was still observed.

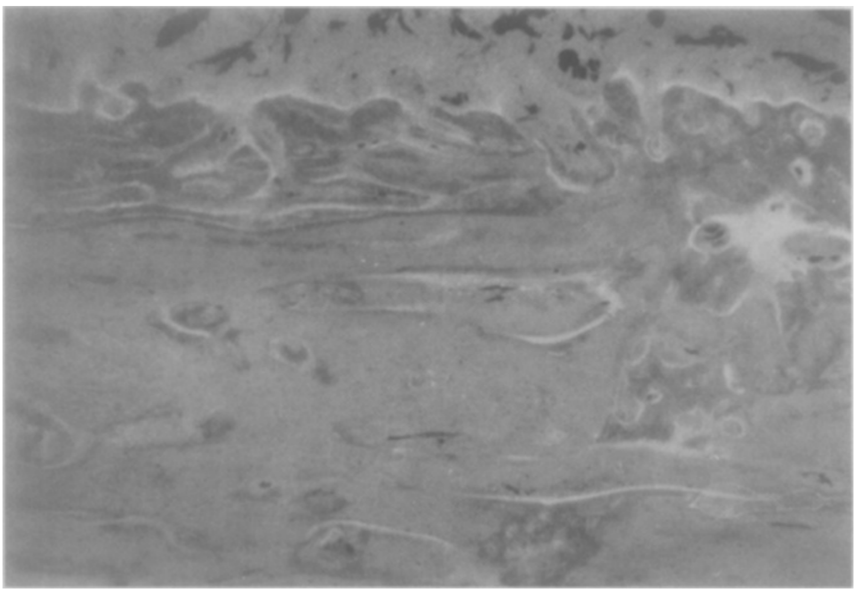


FIG. 17 - Fluorescence specimen 8 weeks after osteotomy. Reconstruction and condensation of the periosteal callus. The borderline between the cortex and periosteal callus has disappeared. The superficial activity is of a different character than that observed at shorter periods after the osteotomy. The primary callus in the osteotomy gap is partially resorbed and penetrated by secondary osteones orientated in the longitudinal direction of the bone.

Four weeks after osteotomy, active endosteal callus formation was seen, especially at the level of the fracture gaps. At a relatively short distance from the fractures gaps · resorption areas were observed.

Five weeks after osteotomy there was still considerable activity at the level of the fracture gap, but it was more limited and concentrated. The resorption powers seemed to be clearly predominant (Fig. 18).

At an observation time of 6 weeks, the specimens showed practically only resorption in the medullary cavity, and 8 weeks after osteotomy the previously formed endosteal callus was almost completely resorbed. At later observation times endosteal bone formation activity was noted only exceptionally.

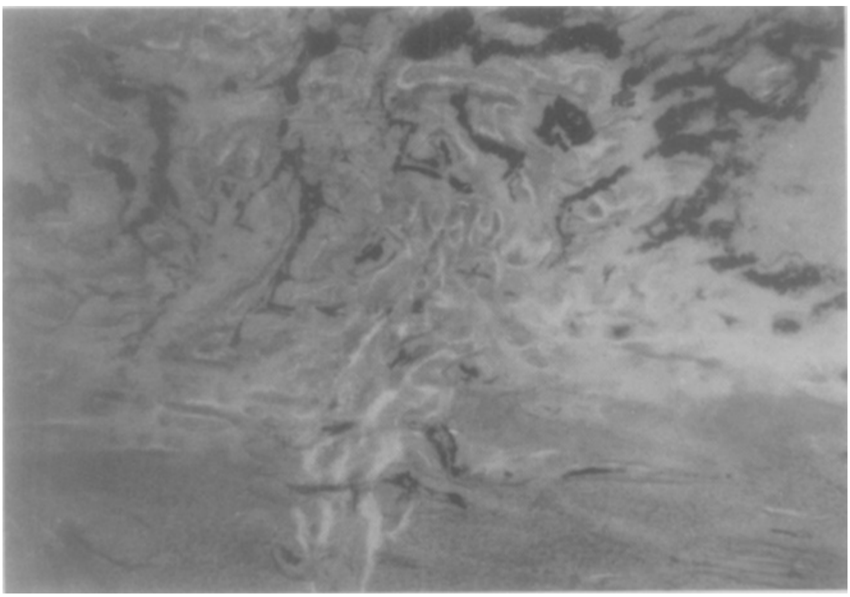


FIG. 18 - Fluorescence specimen 5 weeks after osteotomy. Considerable activity within the endosteal callus at the level of the fracture line (visible in the lower middle part of the picture), although in other places resorption forces predominate.

Four weeks after osteotomy the fracture gaps in some of the specimens were completely filled with primary bone. In some places there was a tendency to vascular communication from the main to the intermediate fragment. In cases where there had been immediate contact between the fragment. In cases where there had been immediate contact between the fragments, no interfragmentary newly formed bone was found. From both the periosteal and the endosteal side, vascular

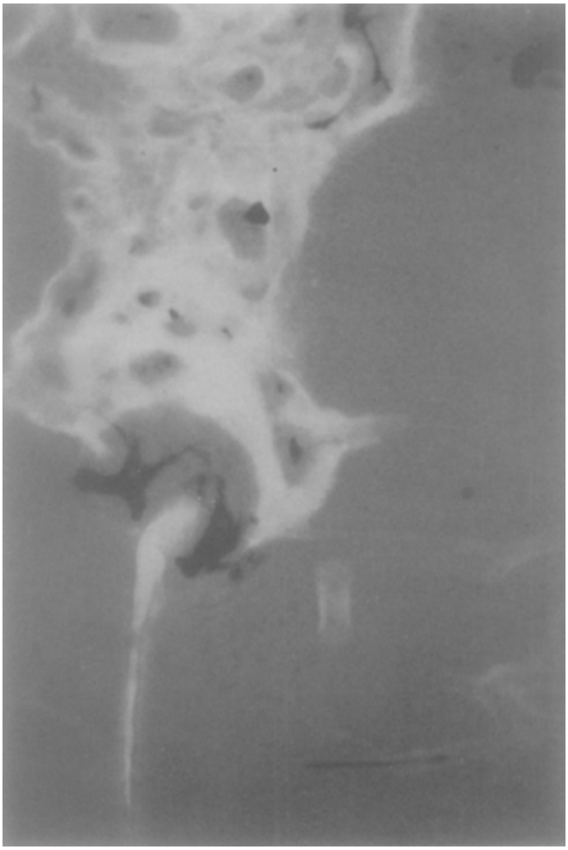


FIG. 19 - **Fluorescence specimen 4 weeks after osteotomy.** Eroded fracture ends **within the intermediate fragment and the main fragment,** with formations of typical Howship's lacunae. The erosion is followed first by formation of fibrous bone and later of lamellar bone.

arches, one on either side of each osteotomy, had invaded the end of the fragments and eroded them (Fig. 19). Behind these eroding vessels (osteoclastic activity), bone was formed in the usual way (osteoblastic activity). The previously active resorptive forces were indicated by the formation of Howship's lacunae, which often filled rapidly with new bone, which formed a sharp borderline against the necrotic, avascular bone in the marginal zone.

Reconstruction zones with tetracycline labelling were found both in intermediate and main fragments. In dogs observed at

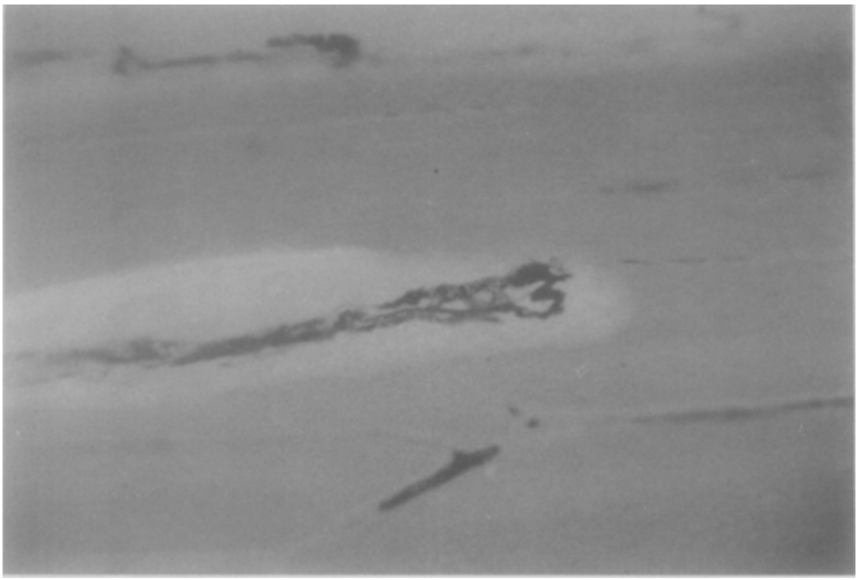


FIG. 20 - Fluorescence specimen 6 weeks after osteotomy. Cutting head in the main fragment on the way towards the osteotomy gap during formation of a secondary osteone. The thin arteriolae divids into wide venous sinusoids.

4 weeks, on the right tibia only one labelling was observed in the intermediate fragment, and double-labelling in the main fragment was only seen at a distance of 1 cm and further from the osteotomy gap. At the time of the first labelling in this dog, i.e. 1 week after osteotomy on the right leg, no new bone formation was observed in the intermediate fragment or

in the area nearest to the fracture gap, but at that time there were probably already some functioning vessels.

In the specimens observed 4 weeks after osteotomy, Indian ink filled vessels were relatively numerous in the main fragment but considerably fewer in the intermediate fragment, which as yet showed only few resorption centres and isolated so called cutting heads (Fig. 20).

Five weeks after osteotomy, interfragmentary bone formation was seen to have taken place via vessels arising mainly from the medullary cavity but also from the periosteal side.

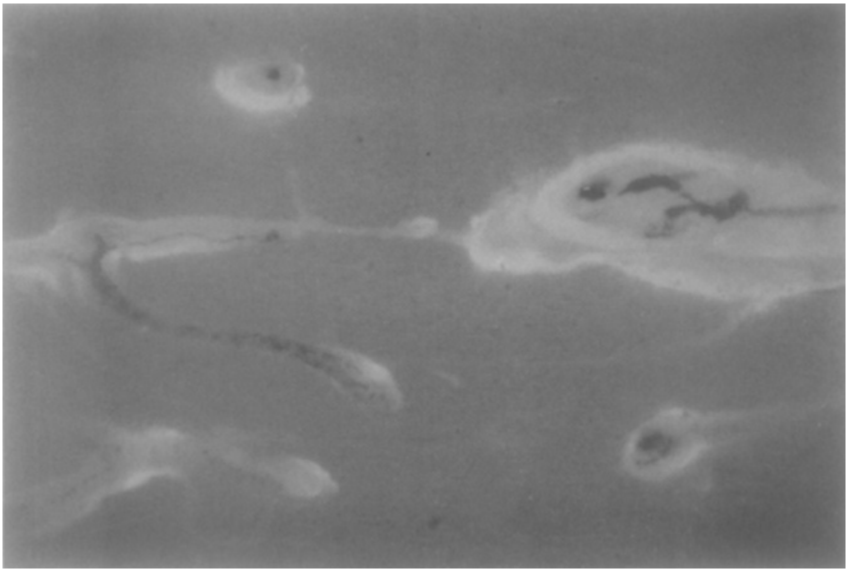


FIG. 21 - Fluorescence specimen 6 weeks after osteotomy. Centre of intermediate fragment. Double-labelled secondary osteones show that bone formation has occurred in the intermediate fragment as early as 2 weeks after the double osteotomy.

These vessels often formed communications with vessels in Haversian canals on either side of the osteotomy gap. Double labelling was observed within one single osteone inside the intermediate fragment and very close to the fractura gap in the main fragment, indicating, in accordance with the labelling of the specimens, that bone formation had occurred at these sites after only 2 weeks following the osteotomy. Compared with the 4-week specimen, more numerous and larger resorption cavities were found (Fig. 21).

Six weeks after osteotomy, resorption cavities were seen within the bone primarily formed in the fracture gap (Fig. 22). The cavities also showed bone formation in the wall. A large number of vessels and osteones traversed the fracture gap (Fig. 23). In some areas where the fracture gap was not completely vascularized, the bone formation and bone resorption activities seemed to be completely ceased (Fig. 24), even

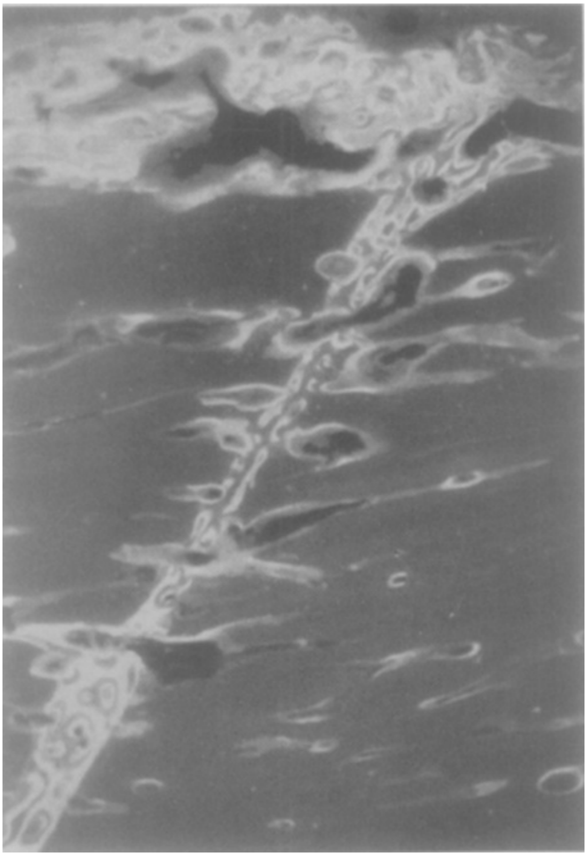


FIG. 22 - Fluorescence specimen 6 weeks after osteotomy. Resorption within the bone primarily formed in the fracture gap, through traversing secondary osteones.

in front of vessels arising from the medullary cavity. The intermediate fragment showed an abundance of double-labelled osteones and many cutting heads (Fig. 25). The same held for the main fragments.

In specimens labelled at 5 and 10 weeks and observed at 10 weeks, considerable reconstruction of the bone in the fracture gap was seen, with numorous secondary osteones crossing the gap. In one of the specimens, direct contact was observed between the fragments, however, in a small area, with apparently arrested activity in the immediately surrounding region

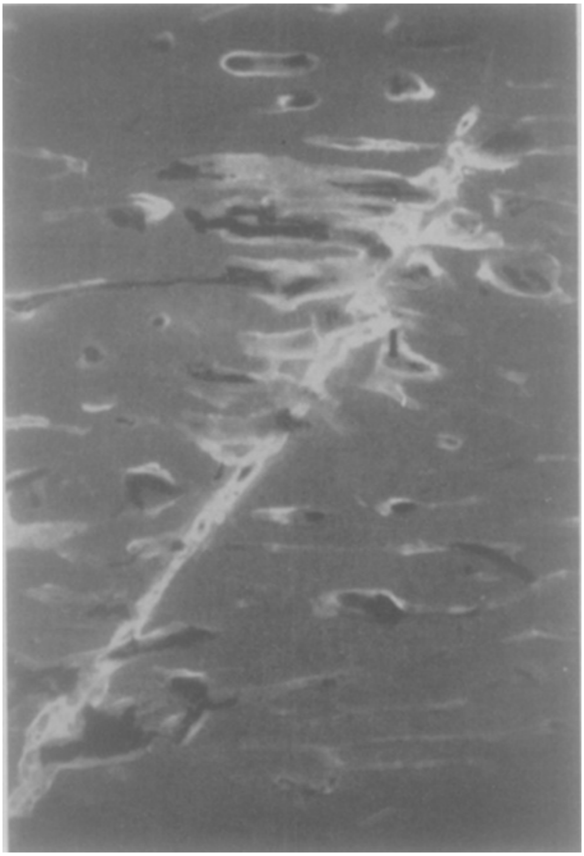


FIG. 23 - Fluorescence specimen 6 weeks after osteotomy. Pronounced formation of secondary osteones crossing the fracture gap. Within the upper part of the fracture gap the activity seems to be extinguished.

cf. Fig. 24). The intermediate fragment seemed to be well vascularized, with many double-labelled areas, and appeared thus to be under considerable reconstruction. In specimens observed 10 weeks after the osteotomy, and labelled at 6 and 10 weeks, there was much reconstruction of the bone primarly formed in the fracture gap. The region between this bone and the original bone had become largely resorbed and replaced by traversing secondary osteones. All parts of the intermediate frag-

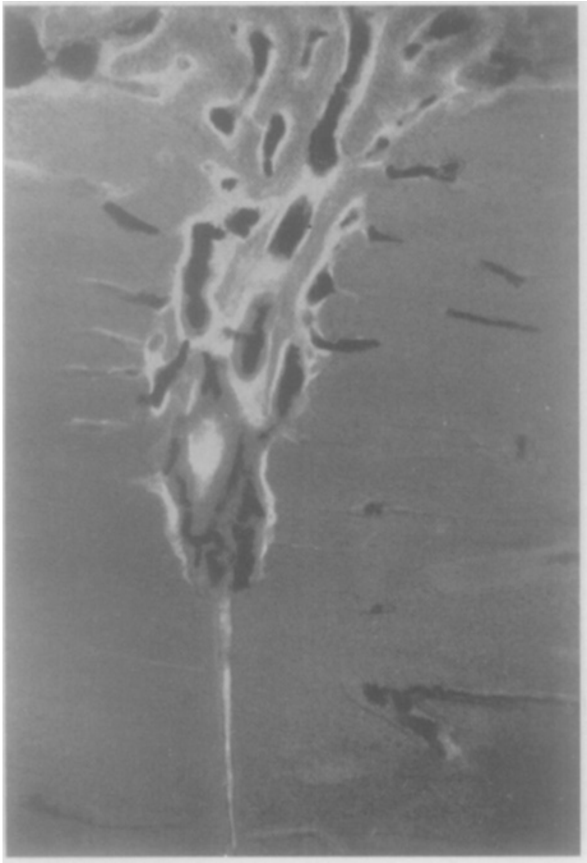


FIG. 24 - Fluorescence specimen 5 weeks after osteotomy. The vascular invasion into the fracture gap, the resorption of the fragment ends and the subsequent bone formation have come to a stop before the entire fracture gap has become vascularized. The vascularization has taken place from both endosteal and periosteal directions but has left the central part of the osteotomy gap undisturbed. Deficient induction?

ments, with the possible exception of the tibial subperiosteal (compression side) area, were penetrated by relatively wide longitudinal canals with large Indian ink filled vessels. The walls of the canals were double-labelled almost throughout (Fig. 26).

At a yet longer period after the osteotomy, i.e. 11 weeks or more, the fracture gap became less and less distinct and the intermediate fragment increasingly reconstructed, so that

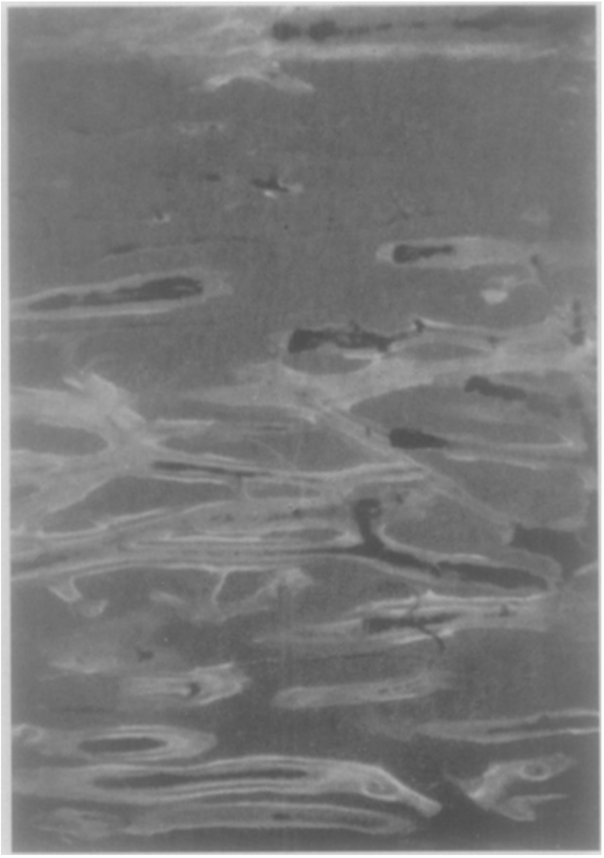


FIG. 25 - Fluorescence specimen 8 weeks after osteotomy. The main fracture ends are under active reconstruction by cutting heads. The endosteal part of the cortex — the lower half of the photograph — shows double labelling as a sign of earlier rebuilding than in the upper part (the periosteal side of the cortex), where only single labellings are seen.

the original structure of old bone was hardly distinguishable any longer.

In specimens observed 11 weeks and more after the osteotomy the structure of the fracture line could hardly be differentiated from that of the intermediate and main fragments.

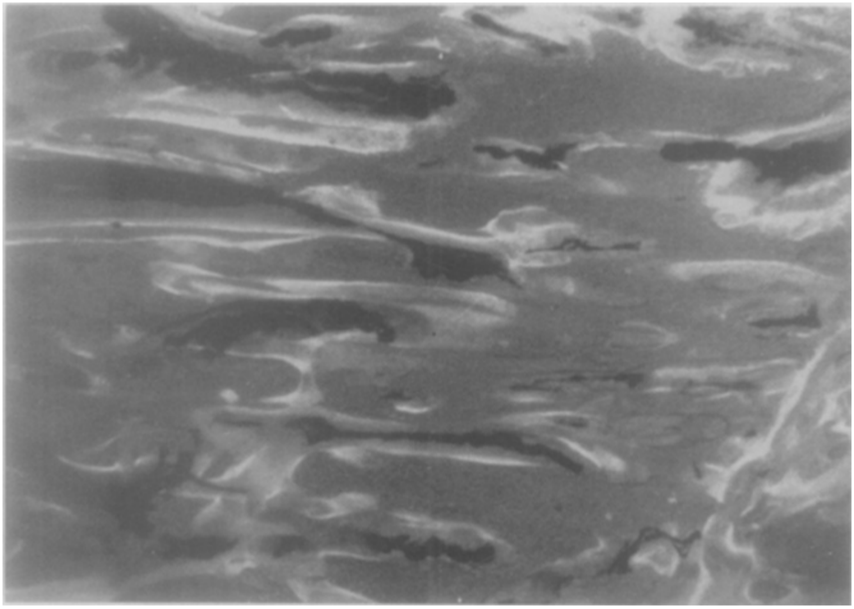


FIG. 26 - Fluorescence specimen 11 weeks after osteotomy. Intermediate fragment with osteotomy gap in the lower right-hand part of the photograph. A large number of wide resorption canals. A high percentage of the secondary osteones show double labelling. Formation of new bone predominates.

MICROROENTGENOLOGICAL STUDIES

These studies showed the occurrence of low mineralized newly formed bone in the fracture gap in specimens observed at 4 weeks after the osteotomy, but only, however, in gaps wide enough to be invaded by blood vessels (Fig. 27). After a longer period, i.e. 6 - 8 weeks, on the other hand, profuse interfragmentary bone formation was seen (Fig. 28). This was easily distinguishable from the original bone by its lower mineral content and by the fact that the osteocyte lacunae were somewhat larger and rounder than in older bone.

Eight weeks after osteotomy, there was resorption of bone previously formed in the fracture gap, which favoured reorientation of the bone in the longitudinal direction of the cortex. Several specimens showed, in this situation, a relatively small

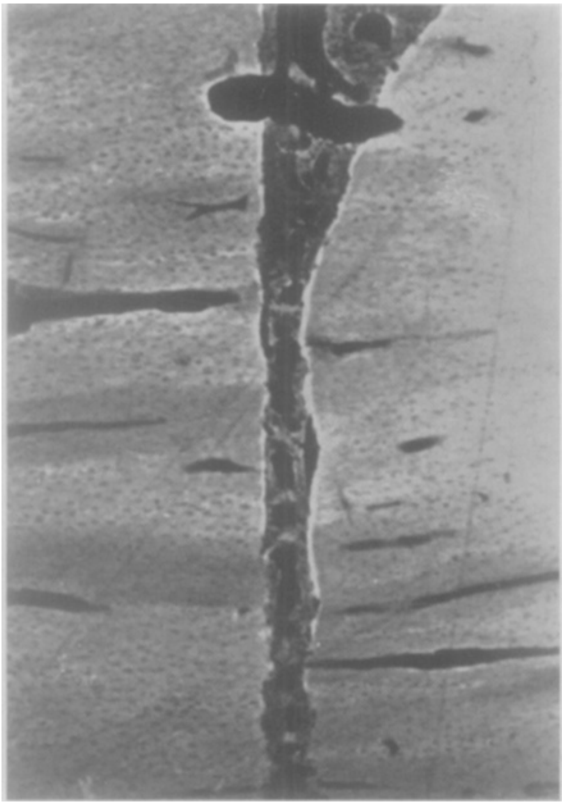


FIG. 27 - Microroentgenogram 4 weeks after osteotomy. The osteotomy gap is filled with newly formed bone. Regenerating longitudinally directed osteones have just started to develop. Intermediate fragment to the left.

amount of new bone formation in the large resorption cavities (Fig. 29).

Microroentgenography of specimens 10 weeks after osteotomy showed that a considerable area of old bone on either side of the osteotomy gap and within the intermediate fragment seemed to have been replaced by new bone. The originally formed bone in the gap with its orientation in the direction along the fracture line was traversed by new osteones with a structure oriented longitudinal to the cortex (Fig. 30). Even on

FIG. 28 - Microroentgenogram 6 weeks after osteotomy. Enlargement of Haversian canal systems occurs to a large extent, and osteone formation across the fracture gap is not yet observed, but on the other hand bone resorption is seen along the fracture gap, with subsequent bone formation. The intermediate fragment is to the right.

microroentgenograms of higher magnification at an observation time of 10 weeks, the fracture gaps could only be distinguished by the difference in structure between old and new bone. An abrupt ending of an osteone in the gap, i.e. without a bow-

FIG. 29 - Microroentgenogram 8 weeks after osteotomy. Intermediate fragment to the left. Resorption cavities fairly evenly distributed within the marginal zone of both the intermediate and the main fragment. The bone primarily formed in the fracture gap is undergoing the same reconstruction as the surrounding cortical bone. Reorientation of the structure in the fracture gap is evident.

FIG. 30 - Microroentgenogram 10 weeks after osteotomy. Intermediate fragment to the right. The osteotomy line in the main fragment is only just distinguishable. The structure of the newly formed bone in the fracture gap can be followed in form of osteone formations into the intermediate fragment, which still contains bone not yet rebuilt.

FIG. 31 - Microroentgenogram of a detail of the marginal zone of the main fragment from a specimen 10 weeks after osteotomy. The old osteotomy line can just be distinguished. The newly formed bone on the right of the photograph is in contact with well-developed newly formed osteones, which fill out the centre of the left half of the photograph. The bone yet not rebuilt is easily distinguishable by its greater mineral density and by the shape and size of the osteocyte lacunae.

Fig. 30

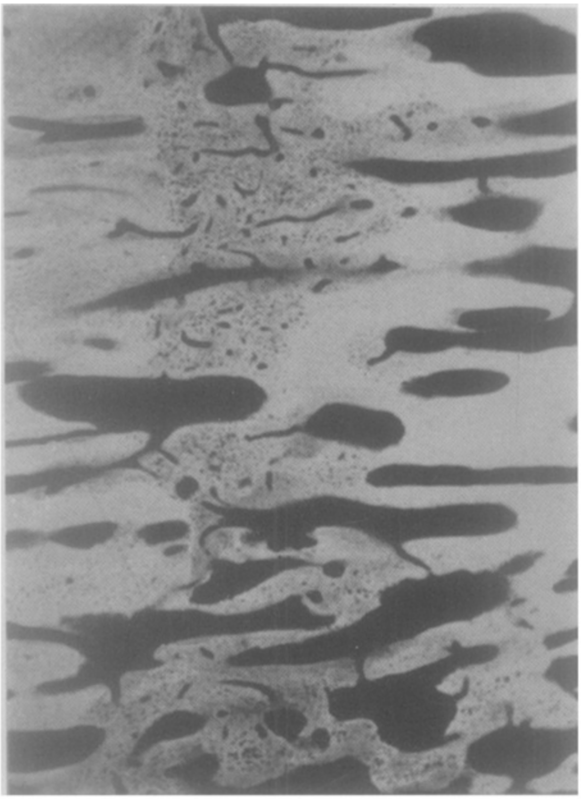
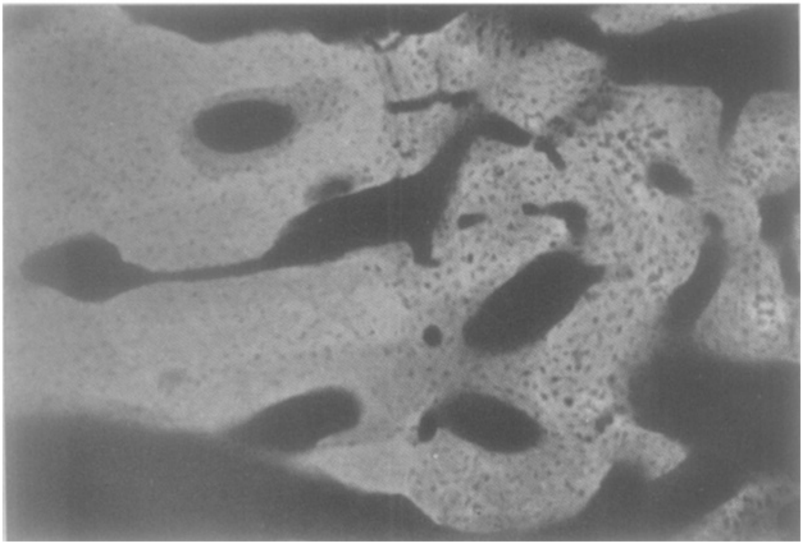


Fig. 31



shaped Howship's attachment into a fragment, means a defective anchorage which would only be reliable if there was contact with the deeper located osteones (Fig. 31). In specimens observed 11 weeks after osteotomy, the original bone was only seen in patches around the osteotomy gap which in this case was not

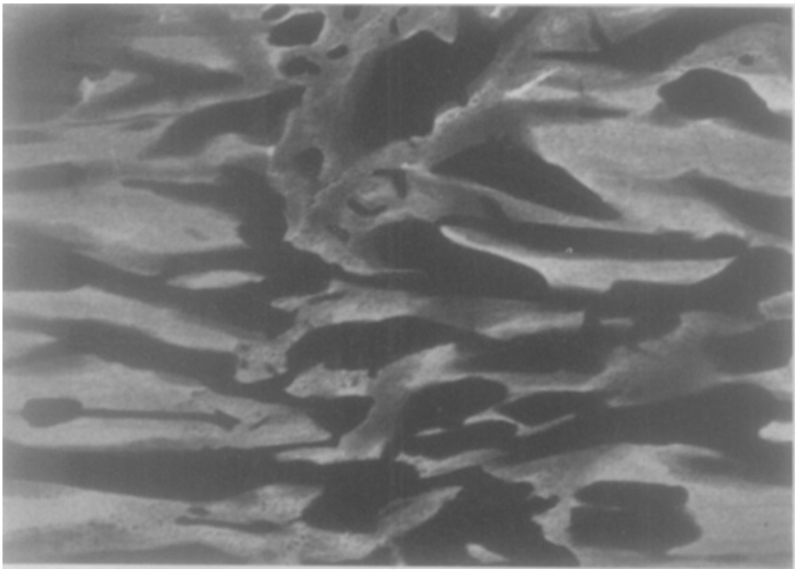


FIG. 32 - Microroentgenogram from specimen 11 weeks after osteotomy. Intermediate fragment to the left. The old osteotomy line is just distinguishable immediately to the left of the midline. Reorientation of the bone newly formed in the fracture gap seems to be largely completed. The resorption is pronounced both in the intermediate fragment to the right and in the main fragment to the left. Bone from the time prior to the osteotomy is seen only in occasional patches. The bone is spongious in structure. Compare fluorescence specimen in Fig. 26.

delimitable (Fig. 32). Both the fracture ends of the main fragments and the intermediate fragment itself thus exhibited considerable reconstruction, although this was still not completed within the total observation period of the experiment.

STUDIES IN POLARISED LIGHT

Examination of the specimens in polarised light showed that 6 weeks after the osteotomy the collagen fibres ran to a large extent in the longitudinal direction of the osteotomy gap, with a few connections into the cortex on either side of the gap (Fig. 33). This held mainly for gaps in which direct angiogenic, i.e. primary bone formation had occurred. In specimens observed 8 weeks after the osteotomy, newly formed secondary osteones were seen, which traversed the fracture gap and which had produced resorption cavities in the primary bone formed in the gap (Fig. 34). Collagen fibrils were found here to be partly oriented in the longitudinal direction of the cortex. The primary orientation of large parts of the collagen was seen to persist for a relatively long period, i.e. 10 weeks

FIG. 33 - Polarisation photograph 5 weeks after osteotomy. The collagenous structures are mainly oriented along the osteotomy gap but have attachments here and there in the surrounding cortex. Intermediate fragment to the right and main fragment to the left.

and possibly even longer (Fig. 35). Several specimens exhibited numerous resorption cavities, especially within the intermediate fragment, an expression of active reconstruction and spongious transformation of the cortical bone due to decreased elasticity and a reduced demand for strength on the bone fixed by the

FIG. 34 - **Polarisation photograph from specimen 8 weeks after osteotomy.** The osteotomy gap is only slightly distinguishable. In the centre of the photograph, however, there is a well-developed collagenous formation passing from the right side of the main fragment to the left side of the intermediate fragment, straight through previously formed collagenous structures in the fracture gap.

FIG. 35

compression plate. 10 - 12 weeks after the osteotomy a confusion of collagen fibres was seen within the ends of the fragments and within the bone formed in the fracture gap, but with a tendency, however, to orientation in the longitudinal direction of the cortex (Fig. 36). The fragment end was still apparent with some sharpness, however, indicating that the reconstruction was far from complete, in spite of the fact on macroroentgenograms the osteotomy gap showed complete bridging.

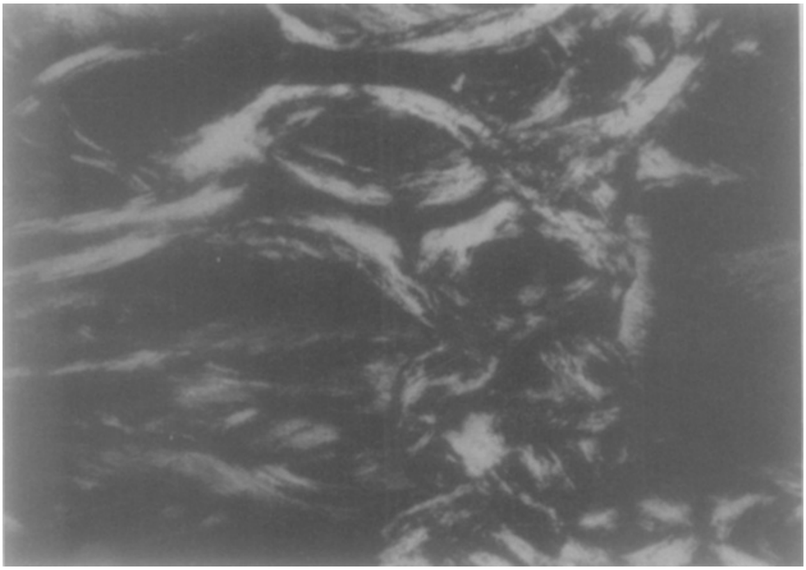


FIG. 36 - Polarisation photograph from specimen 11 weeks after osteotomy. Main fragment to the right, where the osteotomy gap is identified by bone which has not yet been rebuilt, easily seen at the level of the middle of the photograph. The osteotomy gap itself is filled by relatively irregularly layered collagen fibres. In the upper half of the photograph, to the left, there is a longitudinal orientation of rebuilt bone in the intermediate fragment.

FIG. 35 - Polarisation photograph from specimen 9 weeks after osteotomy. The orientation of the collagenous structure in the fracture gap has been maintained, but reorientation is in progress.

Discussion

The degree of stability is an essential factor for fracture healing. In the present investigation the prerequisites for satisfactory stability were fewer than in compression osteosynthesis of a simple, transverse osteotomy gap. This was indicated by the occurrence of pseudarthroses. A compression plate osteosynthesis will hardly give complete stability, since it is probably impossible to produce, by compression over the plate, exactly the same pressure conditions within the fracture gap on the compression plate side of a diaphysis as on the other side, which must obviously be a prerequisite for absolute stability. In the investigations by Shenk & Willenegger (1963) on the sheep radius, the stability was certainly favoured by the undisturbed ulna.

During the healing course, a roentgenologically just visible periosteal callus reaction was seen outside the double osteotomy lines. In our earlier study on compression osteosynthesis in simple osteotomy (Olerud & Danckwardt-Lillieström 1968), where the stability was probably considerably better, there was no roentgenologically visible periosteal callus reaction. The operative procedure in the two series were essentially similar and thus cannot explain the difference in callus reaction. For a certain period of time, however, it must be assumed that there will be a total elimination of the medullary circulation in the intermediate fragment, a circumstance which can have a contributory effect on the development of callus. The smaller degree of stability in the double osteotomy might also contribute to the increased periosteal surface activity.

Even after reaming the medullary cavity on ostetomized rabbit tibias, stabilized by nails, only small amount of periosteal bone was produced when the cortical damage was limited (Danckwardt-Lillieström, Lorenzi & Olerud 1970). In case of large cortical damage, because of intracortical fat embolization produced during reaming (Danckwardt-Lillieström 1969), the periosteal bone formation was extensive (Danckwardt-Lillieström et al. 1970).

The microscopic study of the fluorescence specimens showed an essentially increased periosteal activity in comparison with corresponding specimens with single osteotomy. Thus, periosteal growth still occurred during the 4th - 6th week after a double osteotomy, an observation which was not made in the previously studied single osteotomy (Olerud & Danckwardt-Lilliestrōm 1968). The periosteal growth took place rather slowly, however, and extensive resorption cavities developed in the bottom layer of the periosteal callus. Cartilage formation, as an expression of instability, occurred within the endosteum and on the compression plate side of the tibia only in cases of pseudarthrosis. On the other hand, cartilage formation was observed in all cases in the area between the fibular ends and the intermediate fragment. Thus there would seem to be more pronounced instability on the fibular side than on the plate sida of the tibia. Two factors contribute to this. As mentioned previously, a screw-attached compression plate hardly fixed any other region than that close to the plate. On weight-bearing with such an osteosynthesis, movements always occur, which become increasingly greater the further the distance from the fixation centre of the plate. Another reason for the cartilage formation on the lateral side of the tibia may be the movements produced by the osteotomixed but not fixed fibular ends.

The operative trauma in transverse osteotomy results not only in damage to the periosteal circulation but also to a cortical circulatory disturbance nearest to the osteotomy gap. The normal intracortical vascular supply arises mainly from the medullary cavity, and to the extent that screws cause damage to the medullary blood flow, a disturbance of the intracortical circulation occurs, with subsequent enlargement of the so called avascular marginal zone. This is certainly a factor of importance in bones with a small marrow canal. In several types of fracture, however, intracortical vascular damage is probably considerably greater because of extensive periosteal and endosteal destruction of blood vessels, caused by local thrombosis and possibly also fat embolisation.

The revascularization pattern in the enlarged, cortical avascular area which an avascular intermediate fragment comprises, does not differ from the revascularization system in single osteotomy. The medullary circulation would seem to play the largest role, since almost 4/5 of the cortex is revascularized from the endosteum. This also holds for the lateral side of the tibia, the periosteal circulation of wich is not disturbed by the osteosynthesis material. The finding that the medullary circulation involves the greater part of the medial facet of the tibia is more easily explained, since the osteosynthesis material lies here in the way of periosteal revascularization. Peculiarly enough, however, the relatively abundant circulation in the fibrous layer surrounding the plate seemed not to have communication with the cortical circulation, either.

Bone canals from the medullary cavity widen both for widening old vessels and newly formed vessels, which bud further in towards the Haversian canal systems. Within the main fragments, contact is made with previously undamaged vascular systems on the one side, and new formed vessels on the other side. The outgrowth of vessels takes place up to the fracture gap, and to the extent that direct bone contact occurs here, communication is made with vessels arising from the fragment of the opposite side. If space allows, the osteotomy gap is also filled with newly formed vessels, mainly from the medullary cavity, which often make contact with the vessels growing from the Haversian canals. The primary vascular invasion is accompanied by bone resorption and bone formation both within the marginal zone of the main fragment and in the intermediate fragment.

The revascularization with the aid of the so called cutting heads is a process which, to judge by the number of cutting heads in the sections, seems to occur somewhat later than the primary revascularization. According to Shenk & Willenegger, such a cutting head erodes 50 - 80 μ per day, which means that 1 mm bone would be revascularized in 12 - 20 days. This revascularization process is thus very slow, and it must be asked whether it alone can be responsible for the total revascularization and bone reconstruction.

With a marginal zone of only 2 - 3 mm, and often it is considerably larger, blood vessels would hardly reach the fracture gap within the course of 6 weeks. By means of double labelling with Terramycin, we estimated the cortical avascularity in the end of the main fragment in this type of experiment to be about 8 mm.

The cutting heads followed by their vessel loops seem to be able, however, to traverse the fracture gap from the main fragment side or from the intermediate fragment side. They then form direct secondary osteones. The primary bone formation according to Shenk & Willenegger then seems to take place but requires ideal conditions.

A third variation of vascular invasion into avascular bone occurs within the osteotomy gap itself. Vessels bore their way into the avascular edges of the fragment ends on either side of the actual fragment contact and form Howship's lacunae. The angiographic pattern is very characteristic and uniform and is most closely reminiscent of a pair of tongs which grasp the fracture gap from both sides. In principle, this activity is perhaps not greatly different from that represented by cutting heads. Close on the heels of these vessel loops follows newly formed bone, which fills out the gap between the fracture ends. By means of vascular contact across the Haversian canal systems, intracortical attachment occurs. Resorption alone, or predominantly, within the fracture area is seen from time to time but is not a general finding. Neither does resorption of marginal zones, as suggested by Böhler, occur in the avascular fragment. The reconstruction of the avascular fragment ends and the avascular intermediate fragment takes place gradually via established vascular canals, so to speak from the inside, and via cutting heads. The avascular structures thereby retain their stability and function. In this way new bone gradually takes over the functional stresses.

In those cases where space exist for endosteal and periosteal vascular invasion of the fracture gap, the gap often seems to be filled with bone after only 4 - 6 weeks. This primary new bone has relatively poor attachment in the avascular bone ends until vascular communications are made with the Haversian systems in the main fragment. In any case the newly formed bone is primarily orientated along the direction of the fracture line. Six to eight weeks after osteotomy, considerable resorption takes place within the bone newly formed in the fracture gap, to advantage of the formation of new secondary osteones, which cross over the fracture gap. This osteone formation corresponds the direct osteone formation (intracanalicular bone formation) and also that osteone formation which takes place when newly formed vessels have to take a roundabout way over the cortical fragment end in order to cross the fracture gap. Thus in cases of large avascular marginal zones the primary bone healing, acvording to Schenk & Willenegger, means a timeconsuming healing process.

The above mentioned resorption cavities appearing in the bone primarily laid down in the fracture gap, can in detail be seen on microroentgenograms, where the course can be followed clearly. It is striking, however, that the resoption often seems to predominante over the process of osteone formation; in those cases where this rebuilding can be determined, the newly formed bone in the longitudinal resoption canals seem to be fairly sparse. This is possibly an expression of much too little strain in a diaphyseal area wich is under the influence of a relatively inelastic metal plate. It would seem that a spongious transformation — the occurrence of a number of resorption cavities — of the cortex can develop if the bone is not subjected to the mechanical forces for which it is intended.

The number of newly formed secondary osteones which traverse the osteotomy gap will be decisive for the strength of the bone. The primarily formed bone in the fracture gap will have, in comparison with the secondary osteones, considerably weaker anchorage in the fracture ends, which will result in inadequate strength of the bone for a considerable length of time, despite the fact that roentgenologically the fracture is filled with bone. In this respect the polarisation studies complement particularly the microroentgenological studies. In polarised light, this experimental material relatively seldom showed collagen fibres with direct attachment on both sides of the osteotomy gap. This seemed to hold also for specimen from 10 - 12 weeks after the osteotomy, where despite a general longitudinal orientation the collagenous structures were still located relatively irregularly and as yet far from filling the entire cross section of the osteotomy.

The microroentgenological and polarisation studies thus indicated that a long period of reconstruction remained before the bone structure became normal. It may be asked whether normalization would, in fact, occur as long as the metal plate remained.

CONCLUSIONS

Instability seems to be an important factor in the development of periosteal callus. With adequate stability, the callus undergoes regressive changes long before the fracture is healed. With relative stability there is extended, though not especially active, periosteal callus proliferation, while at the same time regressive changes can be observed.

The development of blood vessels within avascular areas in the fracture region is favoured by rigid fixation and followed by early filling of interfragmentary spaces with primary osteones or trabecular bone though with relatively poor attachment to the avascular, cortical bone. Under certain conditions, viz. absolute bone contact across the fracture gap, intracanalicular bone formation can occur with direct formation of secondary osteones crossing over the fracture line. This process is time-consuming and thus cannot be solely responsible for the bone healing. A practically identical process with formation of cutting heads is developed on either side of the fracture gap if this does not permit primary vascular invasion. Reestablished circulation in already existing Haversian canals may join the rebuilding by direct local resorption and bone formation. The microangiographic technique used shows extensive and relatively rapid revascularization of the medullary cavity and of preformed cortical canals, where vascular invasion from the periosteal side into avascular cortex seems to play a secondary role. Intracanalicular bone formation over the fracture gap is dependent, as regards time, upon the size of the avascular marginal zone, and therefore bone formation from the endosteal and periosteal direction can often predominate. Primary osteones, i.e. the new formed bone laid down in the longitudinal direction of the fracture gap and the trabecular bone laid down within the fracture defect, are rebuilt simultaneously with the formation of secondary osteones across any fracture gap. The reconstruction of the avascular intermediate fragment takes place, under the conditions of this experiment, approximately concomitantly with the reconstruction of the fracture gap. Roentgenologically the fracture gap seems to be bridged after an experimental period of 10 - 12 weeks, but examination of the bone structure by microroentgenography and in polarised light indicates that further rebuilding is required before a normal structure can be expected, if, in fact, normalization can be expected at all as long as the bone is fixed by a plate and screws.

SUMMARY

The healing course of a fracture with a compression-fixed, avascular diaphyseal intermediate fragment comprising the whole circumference of the bone was studied by Indian ink microangiography, the Spalteholtz technique and labelling with Terramycin, among other methods. The two-levelled osteotomy was performed on dog tibias with a Gilgi saw. The osteosyntheses were produced by mean of compression over a metal plate according to AO.

1. Four-fifths of the revascularization of the intermediate fragment took place from regenerated medullary circulation. The marginal zones of the main fragments and the fracture gaps were revascularized in the same way.

2. Under the experimental conditions used, the intermediate fragment seemed within 2 weeks to be supplied primarily with some vessels through existing Haversian canal systems. In a secondary phase revascularization of the cortex took place via so called cutting heads.

3. As far as space allowed, the osteotomy gaps were invaded rapidly by newly formed vessels, which were followed, under stable conditions, by angiogenic bone formation.

4. Periosteal callus was developed both over the intermediate fragment and the main fragments. The extended period of proliferation of this callus indicated some instability in the compression system. Simultaneous with this proliferation, however, regressive changes occurred within the callus.

5. The intermediate fragment was rebuilt by simultaneous bone resorption and bone construction from the inside of the Haversian canal systems containing functioning vessels. A large part of the rebuilding process took place by means of cutting heads, which directly formed secondary osteones. The same process applied to the avascular marginal zone in the main frag-

ments and to the primarily formed bone in the fracture gap, in preparation for reorientation of the collagenous structures according to functional demands.

6. The osteotomy zones were rebuilt without any collapse and the intermediate fragment kept its size throughout the healing period.

7. Whether the endosteal-periosteal bone formation predominates over the intracanalicular bone formation in the gap would seem to depend upon the size of the avascular zones. Regeneration of secondary osteones with cutting heads is a slow rebuilding process and is therefore easily surpassed by endosteal and periosteal new bone formation if prerequisites for such bone formation exist.

8. An osteosynthesis plate gives the bone essential support, which can contribute to early regressive changes on reconstruction of callus and cortical bone. The bone will thus become adapted to functional demands, which is evident in the occurence of an increased number of resorption cavities and big canals. This gives so called spongious transformation of the cortical bone.

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