

THE STRESS-PROTECTING EFFECT OF METAL PLATES ON THE INTACT RABBIT TIBIA

TERJE TERJESEN & PÅL BENUM

Department of Orthopaedic Surgery, Trondheim University Hospital, Trondheim, Norway

The purpose of the present study was to find the extent of stress-protection by a steel plate ($45 \times 5 \times 1$ mm) on the rabbit tibia. The animals were sacrificed after 6, 12 and 18 weeks. The median strength after plate application was 84, 73 and 72%, respectively. The elastic stiffness of plated bones was also reduced, while the deformation at fracture showed no significant reduction. The mineral content in the bone segment previously covered by a plate was measured by photon absorptiometry; it was reduced after 12 and 18 weeks. The stress-protecting effect caused by this thin steel plate was less pronounced than that previously reported by groups using more rigid plates on rabbit tibiae. The stress-protecting effect increased up to 12 weeks, but subsequently no further increase occurred.

Key words: bone minerals; bone plates; steel, stainless; stress, mechanic

Accepted 30.v.83

The stress-protecting effect of rigid metal plates on diaphyseal bone is a well-known phenomenon. It results from the partial protecting from functional stress afforded to the bone by load sharing with the plate, and is characterized by bone atrophy and reduced strength in the plated bone segment (Uthoff & Dubuc 1971, Strömberg 1975, Tonino et al. 1976).

The extent of stress-protection has been found to vary according to species, duration of plate application, and dimensions of plate relative to the bone. Animal studies have shown that less rigid plates cause less bone atrophy (Tonino et al. 1976, Woo et al. 1976, Moyon et al. 1978). Ideally, the plate used in animal experiments should cause biomechanical effects in the animal bone equivalent to the commonly used plates in corresponding human bone. Previous *in vitro* studies have shown a good agreement between the biomechanical effects of a tibial plate on the in-

tact human tibia, and those of a thin steel plate ($45 \times 5 \times 1$ mm) on the intact rabbit tibia (Terjesen & Benum 1983a). The purpose of the present study was to find the *in vivo* effects caused by this plate on rabbit tibiae. On the assumption that diaphyseal bone from different species react in a similar way to the application of a plate, we hope thereby to give an adequate estimate of the extent of stress-protection caused by tibial plates on human tibiae.

MATERIAL AND METHODS

Operative procedure

Eighteen Chinchilla rabbits of both sexes, weighing from 2425 to 3785 g, were operated. The rabbits were anaesthetized with intramuscular injections of Hypnorm® Vet. (Leo). All operations were performed under strictly sterile conditions. A straight anterior incision was made over the middle part of the tibia of both



Figure 1. Postoperative radiograph showing the plate on one tibia and screws on the control bone.

legs, and the anterolateral aspect of the bone exposed by retracting the tibialis anterior muscle. A straight, six-hole, stainless steel plate (Zimmer, USA) was fastened to the anterolateral aspect of the tibia. The plates measured $45 \times 5 \times 1$ mm, and were fixed with screws of 2.0 mm diameter. Compression was not applied. The tibio-fibular junction served as a landmark for the positioning of the midpoint of the plate. The plate from one of the tibiae, chosen at random, was removed and the screws were reinserted into their holes. This bone thus served as control. The fascia and skin were sutured with Dexon®. Both tibiae were radiographed immediately after the operation (Figure 1).

Postoperative treatment

The rabbits were kept in separate cages where they could move freely. They received adequate food and

water supply, and were observed daily. The postoperative course was uneventful. No wound infections occurred.

The animals were divided into three groups, and sacrificed with injections of lethal doses of mebumal after 6, 12 and 18 weeks, respectively.

After sacrifice, the plate and screws were removed and both tibiae dissected free of all soft tissue. The fibulae were also removed. The tibiae were radiographed (Figure 2), and then wrapped in towels soaked with Ringer's solution, and stored at -18°C until testing.

Bone mineral content

The bones were thawed to room temperature before testing. The bone mineral content was measured by photon absorptiometry (Cameron & Sorensen 1963). A

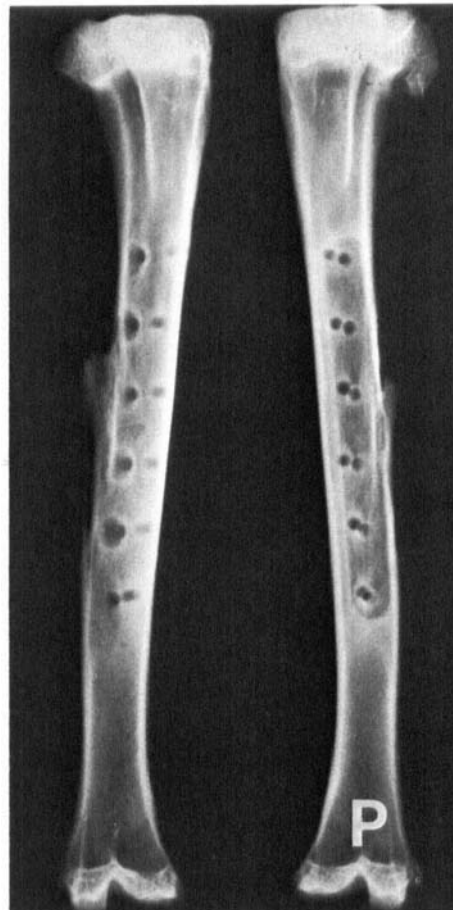


Figure 2. Radiograph of both tibiae after sacrifice of a rabbit with plate application for 12 weeks. Bone atrophy beneath the plate is seen in the plated tibia (P).

commercially available scanning device with 60 kev gamma radiation from ^{241}Am was used (AB Gambro, Lund). Scanning was performed across both tibiae at two levels: Through the bone segment between the two central screw holes, and 1 cm distal to the most distal screw hole. The mineral content was expressed in g/cm, and the value for the bone where a plate had been applied was expressed as the percentage of the value for the control bone.

Biomechanical tests

The bones were tested in three-point bending in the anteroposterior direction in an Instron testing machine as previously described (Terjesen & Benum 1983a). The deformation of a 3 cm long bone segment of the previously fixated part of the tibia was measured with a linear, variable, differential transformer (LVDT). The load was applied halfway between the two central screw holes. All tibiae were loaded to fracture. From the load-deformation diagrams the bending strength, elastic stiffness and deformation at fracture were obtained. The tibiae of one animal were excluded because of technical failure during the mechanical testing.

Measurements of bone dimensions

These measurements were done after the biomechanical testing, during which some of the bones fractured in such a manner that accurate bone dimensions could not be determined. The outer, periosteal diameters in the transversal and anteroposterior directions were measured with a caliper at the mid-diaphyseal level of both tibiae of 11 rabbits. The cortical thickness of the anterolateral aspect of bone, directly beneath the plate, as well as of the medial and dorsal aspect was measured in eight animals. The values for the plated bone were expressed as the percentage of the values for the control bone.

Histological examination

The intention of the histological examination was to determine whether or not increased intracortical porosity had developed in the bones after plating. For practical reasons, all the bones could not be examined, as the applied techniques are not used in our hospital. The bone structure of the cross-section between the two central screw holes was studied by reflected-light microscopy of sections prepared by metallographic techniques (Pugh et al. 1972) in four rabbits, and by microradiography in two. A point-counting method was used to determine the percentage of intracortical porosity.

Statistical analysis

The Wilcoxon signed-rank test for paired samples (one-tailed test) was used to calculate the statistical differ-

ences between paired bones with and without plate application. The Wilcoxon two-sample test (two-tailed test) was used to calculate the difference between the groups of plate application for 6, 12 and 18 weeks, respectively. Differences were considered significant at P -values below 0.05.

RESULTS

The bending strength of the bones varied considerably in all groups in plated as well as control tibiae (Table 1). The median bending strength of bones after plate applications for 6, 12 and 18 weeks was 84, 73 and 72%, respectively, in relation to the control bones (Table 2). The strength reduction was significant in all the groups. The

Table 1. Bending strength (Newton metres) of rabbit tibiae after plate application, and of control bones

| | 6 weeks n=6 | 12 weeks n=6 | 18 weeks n=5 |
|-------------------------------|----------------|-----------------|-----------------|
| Bones after plate application | | | |
| Median | 4.37 | 3.58 | 3.47 |
| Range | 3.75-5.25 | 3.18-5.69 | 3.00-3.71 |
| Control bones | | | |
| Median | 5.47 | 4.99 | 5.12 |
| Range | 4.55-5.96 | 4.35-6.62 | 4.33-5.89 |

Table 2. Bending strength, elastic stiffness and deformation at fracture of the tibiae after plate application, expressed as the percentage of the values for the control bones

| | 6 weeks n=6 | 12 weeks n=6 | 18 weeks n=5 |
|-------------------|----------------|-----------------|-----------------|
| Bending strength | | | |
| Median | 84 | 73 | 72 |
| Range | 67-91 | 70-86 | 51-76 |
| Elastic stiffness | | | |
| Median | 84 | 76 | 82 |
| Range | 72-104 | 72-99 | 50-97 |
| Deformation | | | |
| Median | 95 | 96 | 88 |
| Range | 88-110 | 79-111 | 64-107 |

reduction was significantly greater at 18 weeks than at 6 weeks ($P = 0.030$), but no significant reduction was found between 12 and 18 weeks.

The elastic stiffness of the plated bones was also reduced in the three groups (Table 2). The reduction was significant after 12 and 18 weeks, but not after 6 weeks.

The deformation at fracture (Table 2) was not significantly reduced either after 6, 12 or 18 weeks.

The bone mineral contents measured by photon absorptiometry at the mid-diaphyseal level of plated and control bones are given in Table 3. A significantly reduced mineral content was found in plated bones after 12 and 18 weeks, but the reduction was not significant after 6 weeks (Table 4). The reduction was significantly greater after 12 weeks than after 6 weeks ($P =$

Table 3. Bone mineral content (g/cm) at the mid-diaphyseal level of rabbit tibiae after plate application, and of control bones

| | 6 weeks n=6 | 12 weeks n=6 | 18 weeks n=5 |
|--------------------------------------|----------------|-----------------|-----------------|
| Bones after plate application | | | |
| Median | 0.244 | 0.183 | 0.173 |
| Range | 0.208–0.258 | 0.153–0.270 | 0.121–0.190 |
| Control bones | | | |
| Median | 0.264 | 0.237 | 0.206 |
| Range | 0.225–0.274 | 0.177–0.284 | 0.172–0.213 |

Table 4. Bone mineral content at the mid-diaphyseal level and 1 cm distal to the plate of the bones after plate application, expressed as the percentage of the values for the control bones

| | 6 weeks n=6 | 12 weeks n=6 | 18 weeks n=5 |
|---------------------------------|----------------|-----------------|-----------------|
| Mid-diaphyseal level | | | |
| Median | 93 | 84 | 81 |
| Range | 88–114 | 63–110 | 67–99 |
| 1 cm distal to the plate | | | |
| Median | 99 | 99 | 95 |
| Range | 87–120 | 94–107 | 88–101 |

Table 5. Outer diameter and cortical thickness at the mid-diaphyseal level of the tibiae after plate application, expressed as the percentage of the values for the control bones

| | 6 weeks n=4 | 12 weeks n=2 | 18 weeks n=5 |
|---------------------------------|----------------|-----------------|-----------------|
| Transversal diameter | | | |
| Median | 98.2 | 99.6 | 100.0 |
| Anteroposterior diameter | | | |
| Median | 97.5 | 111.7 | 97.1 |
| | n=3 | n=2 | n=3 |
| Cortical thickness | | | |
| Anterolateral aspect | | | |
| Median | 85 | 84 | 88 |
| Medial aspect | | | |
| Median | 100 | 111 | 100 |

Table 6. Intracortical porosity expressed as the percentage of porosity in relation to the entire area of transverse bone sections

| | 6 weeks n=3 | 12 weeks n=1 | 18 weeks n=2 |
|----------------------------------|----------------|-----------------|-----------------|
| Plated bones | | | |
| Beneath the plate | 8.4 | 13.5 | 17.7 |
| Other parts of the cross-section | 5.5 | 2.6 | 2.0 |
| Control bones | 4.3 | 1.9 | 2.7 |

0.041), but no significant difference was found between 12 and 18 weeks. The mineral content in the diaphysis distal to the plate is also shown in Table 4. No significant reduction was found in the plated bones either after 6, 12 or 18 weeks.

No significant differences were found in outer diameter in the transversal or anteroposterior direction between plated and control bones (Table 5). The cortical thickness was significantly reduced in the anterolateral aspect, directly beneath the plate, where it was about 85% in relation to the control tibiae. However, no significant changes in cortical thickness were found in either the medial or dorsal aspect of the bone.

The intracortical porosity varied considerably,

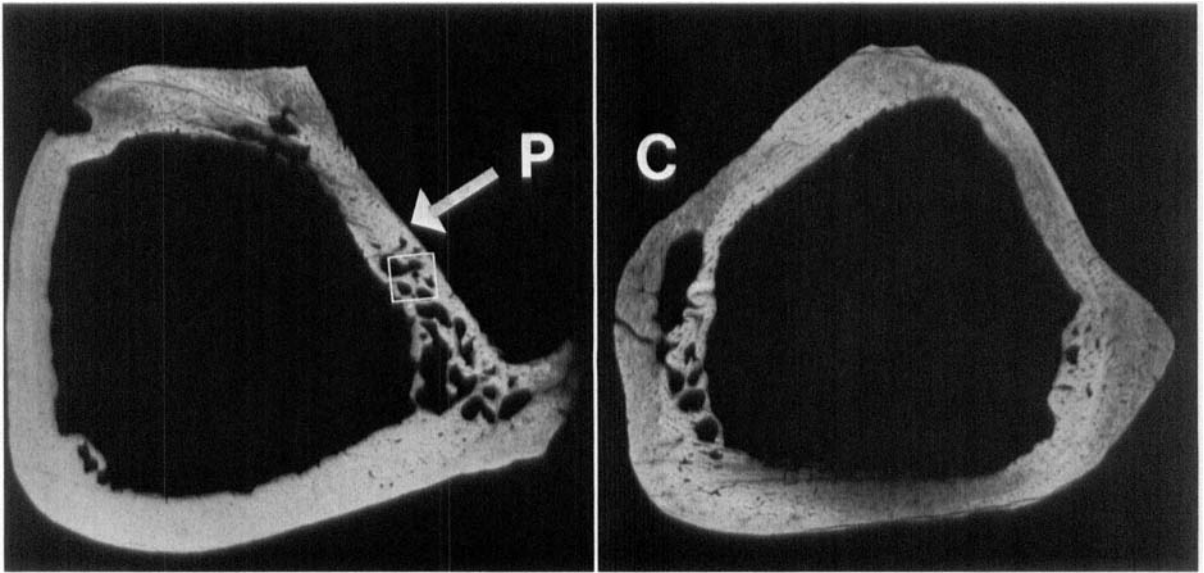


Figure 3. Microradiograph ($\times 8$) of a plated tibia (P) and control tibia (C) after 18 weeks of plate application. The arrow points to the anterolateral aspect where the plate was applied. Note the increased porosity directly beneath the plate. The area in the inset is shown in greater detail in Figure 4a.

especially in plated bones (Table 6). Areas of increased porosity were found in plated as well as control bones (Figure 3). However, the porosity was significantly increased only in the cortical wall directly beneath the plate (Figures 4 and 5).

DISCUSSION

A high degree of symmetry regarding biomechanical properties and mineral content between paired bones in rabbits has been reported (White et al. 1974, Paavolainen 1978, Låftman et al. 1980, Terjesen & Benum 1983b). This justifies the use of one tibia as test bone and the other as control in the present investigation. We wanted to examine the effects on the bone of the plate itself. This was the reason why screws only were inserted in the control bone, as has also been done in other investigations (Strömberg 1975, Låftman et al. 1980).

In animal studies of the stress-protection caused by plates, both the type and the extent of bone atrophy varied considerably (Uthoff & Dubuc 1971, Matter et al. 1974, Akeson et al.

1976, Tonino et al. 1976, Moyen et al. 1978, Paavolainen et al. 1978, Låftman et al. 1980). Whether the divergent findings result from the different test models used, or whether there are real differences between various species and bones, is still an unsolved question. The most important single factor is probably the stiffness of the plate (Slätis et al. 1980, Baggott et al. 1981, Claes et al. 1981). This view is supported by experiments which have shown that the stress-protection is less pronounced after application of less rigid plates (Tonino et al. 1976, Woo et al. 1976, Moyen et al. 1978).

Consequently, if animal experiments are designed primarily to throw light on the stress-protecting effect of plate application on human bones, plates should be used that have biomechanical effects on the animal bone equivalent to the effects of the commonly used clinical plates on the corresponding human bone. This was not done in the previously mentioned studies. Thus it is uncertain whether the chosen plates have been of adequate stiffness or not. In a previous paper, the *in vitro* biomechanical effects of tibial plates on human tibiae and of thin steel

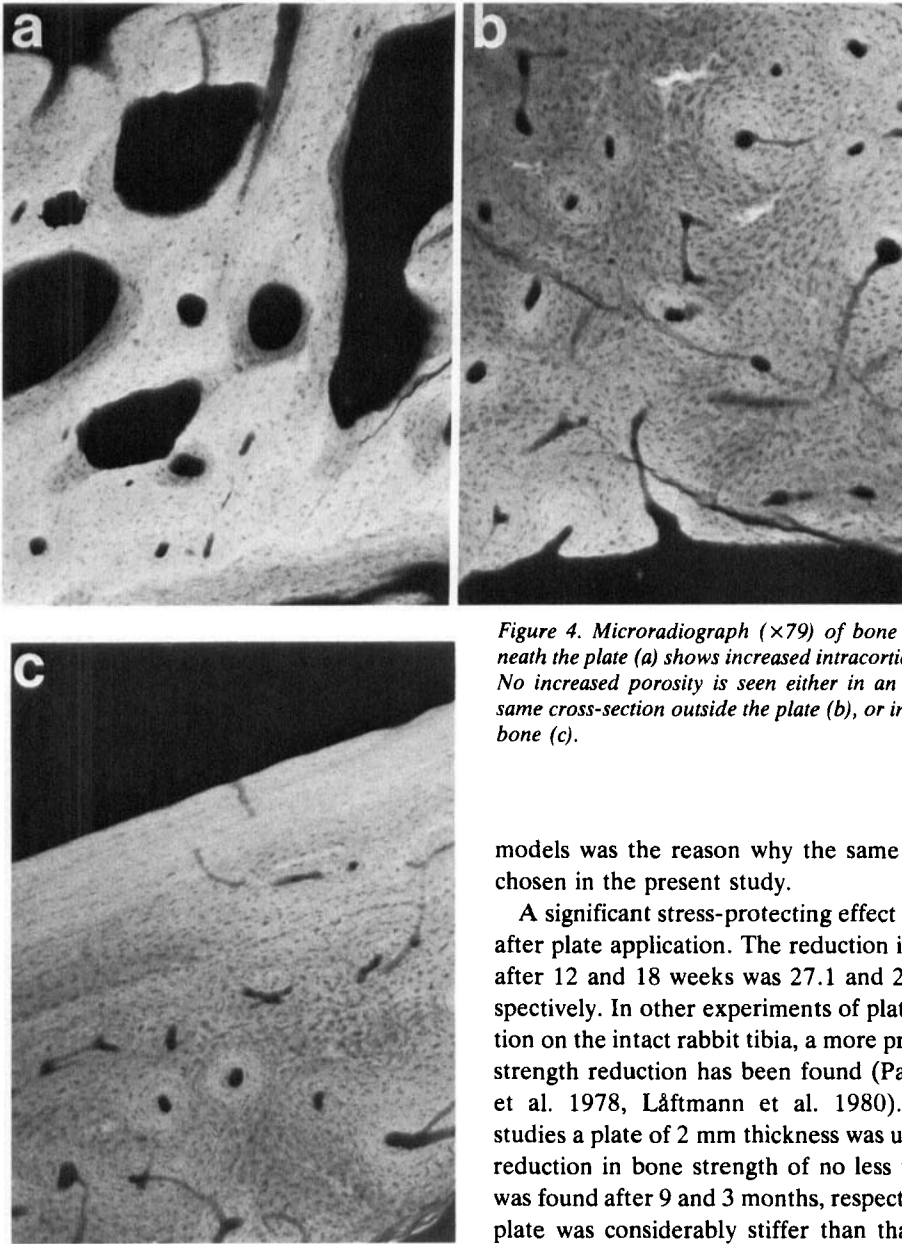


Figure 4. Microradiograph ($\times 79$) of bone directly beneath the plate (a) shows increased intracortical porosity. No increased porosity is seen either in an area of the same cross-section outside the plate (b), or in the control bone (c).

plates ($45 \times 5 \times 1$ mm) on rabbit tibiae were reported (Terjesen & Benum 1983a). In both cases the bending stiffness in the plated bone segment increased about 30% in relation to the stiffness before the plate was applied. The good agreement between the results in the two test

models was the reason why the same plate was chosen in the present study.

A significant stress-protecting effect was found after plate application. The reduction in strength after 12 and 18 weeks was 27.1 and 27.6%, respectively. In other experiments of plate application on the intact rabbit tibia, a more pronounced strength reduction has been found (Paavolainen et al. 1978, Låftmann et al. 1980). In these studies a plate of 2 mm thickness was used, and a reduction in bone strength of no less than 50% was found after 9 and 3 months, respectively. The plate was considerably stiffer than that used in the present study. It has been assumed that the bone loss after plating is more pronounced in rabbits than in dogs and sheep (Slätis et al. 1980). The findings in the present study do not support this view. The fact is that our results harmonize well with those reported from dogs. Strömberg & Dalen (1976) found a reduction in maximum torque capacity of 18.3%, while Tonino et al. (1976) reported a mean reduction in ultimate bending

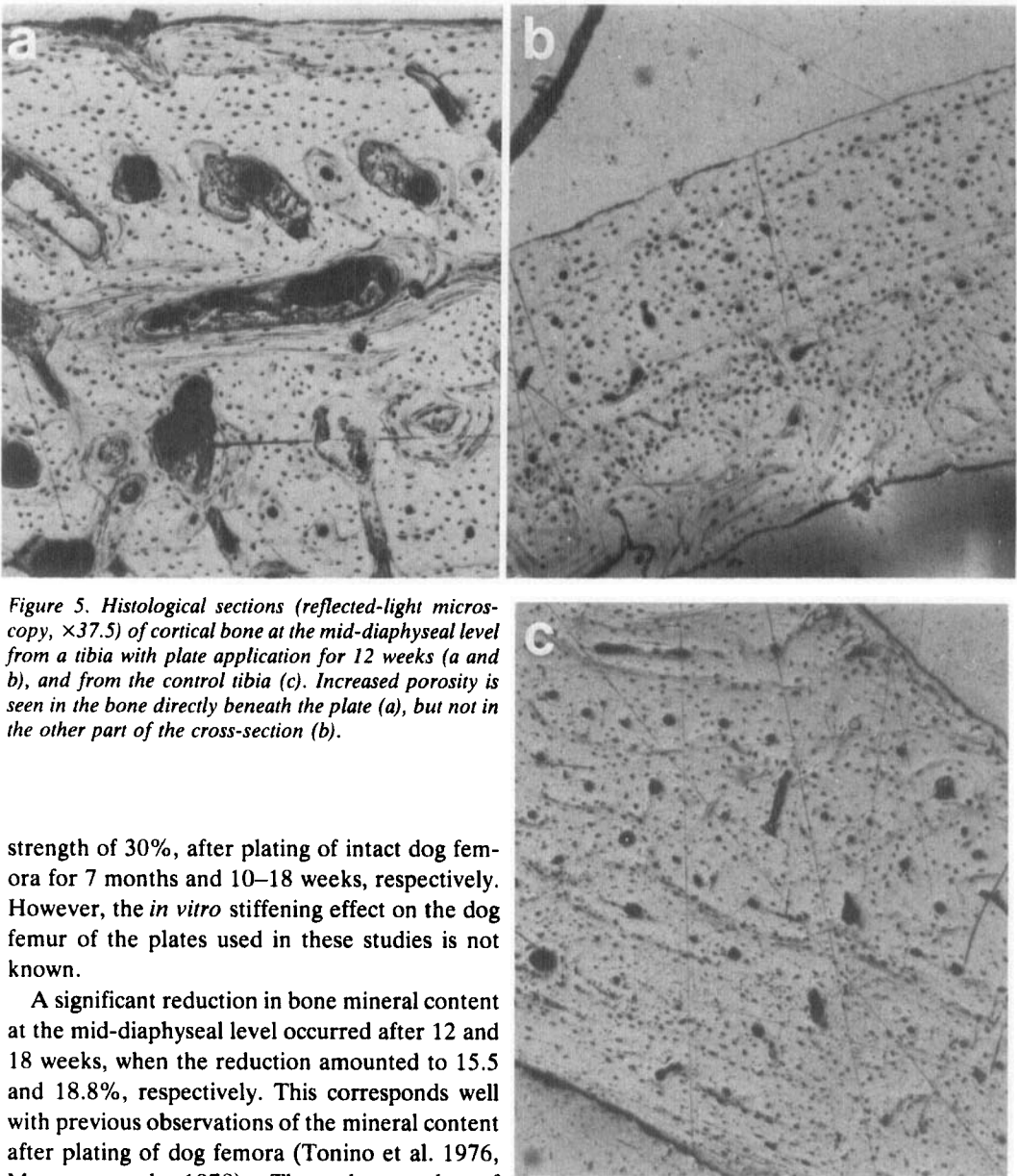


Figure 5. Histological sections (reflected-light microscopy, $\times 37.5$) of cortical bone at the mid-diaphyseal level from a tibia with plate application for 12 weeks (a and b), and from the control tibia (c). Increased porosity is seen in the bone directly beneath the plate (a), but not in the other part of the cross-section (b).

strength of 30%, after plating of intact dog femora for 7 months and 10–18 weeks, respectively. However, the *in vitro* stiffening effect on the dog femur of the plates used in these studies is not known.

A significant reduction in bone mineral content at the mid-diaphyseal level occurred after 12 and 18 weeks, when the reduction amounted to 15.5 and 18.8%, respectively. This corresponds well with previous observations of the mineral content after plating of dog femora (Tonino et al. 1976, Moyen et al. 1978). Thus the results of biomechanical testing and photon absorptiometry after plate application do not indicate any substantial difference in the extent of stress-protection between rabbit and dog bones.

In the diaphysis distal to the plate no significant decrease in mineral content occurred, indicating that the plate has no deleterious effects on the bone outside the plate.

The bone loss and strength reduction have

been found to be progressive in most reports (Refior et al. 1975, Akeson et al. 1976, Moyen et al. 1978, Paavolainen et al. 1978). In contrast with these findings is a report that the induced porosis was reversible in sheep tibiae (Perren & Rahn 1980). The porotic area present at 10 weeks was completely filled 1 year after plating.

They assumed that the porosis could be interpreted as a temporary phenomenon associated with internal remodelling of bone. No other information in the literature seems to support this view. In the present study the stress-protecting effect was found to be progressive up to 12 weeks, but thereafter no significant changes occurred. It is likely that the stress-protecting effect will reach a stationary state after a certain time in animal as well as in human bone. This steady state will probably occur later in large bones and after plating with very stiff plates.

There are also considerable differences in the published series regarding the type of bone loss caused by plate application. In most reports endosteal resorption, cortical thinning and enlargement of the medullary canal have been found (Akeson et al. 1976, Tonino et al. 1976, Moyen et al. 1978, Slätis et al. 1978, Strömberg & Dalén 1978). However, Baggott et al. (1981) did not find any cortical thinning after plating of the dog radius. Increased intracortical porosity has been reported in most series (Uhthoff & Dubuc 1971, Matter et al. 1974, Refior et al. 1975, Tonino et al. 1976, Slätis et al. 1978, Strömberg & Dalén 1978, Claes et al. 1981), but not in others (Akeson et al. 1976, Moyen et al. 1978). In the present study increased porosity and cortical thinning occurred only in the cortical wall directly beneath the plate. This is in accordance with the reports of others, who found most pronounced bone changes in that part of the cross-section previously covered by the plate (Uhthoff & Dubuc 1971, Matter et al. 1974, Akeson et al. 1976, Slätis et al. 1978, Claes et al. 1981). On the other hand, Strömberg & Dalén (1978) did not find any difference between the bone directly beneath the plate and that of other areas around the cross-section. In contrast with other reports, Tonino et al. (1976) found cortical resorption mainly on the anterior and posterior aspects of dog femora plated laterally. These differences in type of bone loss are possibly due to differences in choice of bone and in duration of plate application.

Less rigid plates, instead of plates made of steel or cobalt-chromium alloy, may be used in order to reduce the stress-protecting effect. Plates of titanium alloy, which is about half as stiff as

stainless steel, but has approximately the same mechanical strength, have been used successfully in animal studies as well as clinical practice (Holzach & Matter 1978, Moyen et al. 1978, Uhthoff et al. 1981). More flexible plates made of reinforced polymers have also recently been introduced in clinical cases (Tayton et al. 1982). Although less rigid plates cause less osteopenia during the remodelling phase, there is no unambiguous proof that bony healing after fractures takes place more rapidly with these plates.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to the Materials Technology Division, The Foundation of Scientific and Industrial Research at the Norwegian Institute of Technology, for expert assistance in the mechanical testing.

We are also indebted to Medisinsk Utstyr A/S, Oslo, for generous supplies of internal fixation plates and screws.

This work was supported by grants from the Norwegian Research Council for Science and the Humanities.

REFERENCES

- Akeson, W. H., Woo, S. L.-Y., Rutherford, L., Coutts, R. D., Gonsalves, M. & Amiel, D. (1976) The effects of rigidity of internal fixation plates on long bone remodeling. *Acta Orthop. Scand.* **47**, 241–249.
- Baggott, D. G., Goodship, A. E. & Lanyon, L. E. (1981) A quantitative assessment of compression plate fixation *in vivo*: An experimental study using the sheep radius. *J. Biomech.* **14**, 701–711.
- Cameron, J. R. & Sorensen, J. (1963) Measurement of bone mineral *in vivo*: An improved method. *Science* **142**, 230–232.
- Claes, L., Kinzl, L. & Neugebauer, R. (1981) Experimentelle Untersuchungen zum Einfluss des Plattenmaterials auf die Entlastung und Atrophie des Knochens unter Osteosynthesplatten. *Biomed. Techn.* **26**, 66–71.
- Holzach, P. & Matter, P. (1978) The comparison of steel and titanium dynamic compression plates used for internal fixation of 256 fractures of the tibia. *Injury* **10**, 120–123.
- Läftman, P., Sigurdsson, F. & Strömberg, L. (1980) Recovery of diaphyseal bone strength after rigid internal plate fixation. *Acta Orthop. Scand.* **51**, 215–222.

- Matter, P., Brennwald, J. & Perren, S. M. (1974) Biologische Reaktion des Knochens auf Osteosynthesepplatten. *Helv. Chir. Acta Suppl.* 12.
- Moyen, B. J.-L., Lahey, P. J., Weinberg, E. H. & Harris, W. H. (1978) Effects on intact femora of dogs of the application and removal of metal plates. *J. Bone Joint Surg.* 60-A, 940-947.
- Paavolainen, P. (1978) Studies on mechanical strength of bone. *Acta Orthop. Scand.* 49, 497-505.
- Paavolainen, P., Slätis, P., Karaharju, E. & Holmström, T. (1978) Studies on mechanical strength of bone. *Acta Orthop. Scand.* 49, 506-511.
- Perren, S. M. & Rahn, B. A. (1980) Biomechanics of fracture healing. *Can. J. Surg.* 23, 228-232.
- Pugh, J. W., Rose, R. M. & Radin, E. L. (1972) Techniques for the study of the structure of bone. *Microstructures* 3, 23-27.
- Refior, H. J., Meister, P. & Matzen, K. (1975) Untersuchungen zum Verhalten der Mikrostruktur der menschlichen Corticalis nach Druckplattenosteosynthese. *Arch. Orthop. Unfall-Chir.* 81, 45-56.
- Slätis, P., Karaharju, E., Holmström, T., Ahonen, J. & Paavolainen, P. (1978) Structural changes in intact tubular bone after application of rigid plates with and without compression. *J. Bone Joint Surg.* 60-A, 516-522.
- Slätis, P., Paavolainen, P., Karaharju, E. & Holmström, T. (1980) Structural and biomechanical changes in bone after rigid plate fixation. *Can. J. Surg.* 23, 247-250.
- Strömberg, N. E. L. (1975) Diaphyseal bone in rigid internal plate fixation. *Acta Chir. Scand. Suppl.* 456.
- Strömberg, L. & Dalén, N. (1976) Influence of a rigid plate for internal fixation on the maximum torque capacity of long bones. *Acta Chir. Scand.* 142, 115-122.
- Strömberg, L. & Dalén, N. (1978) Atrophy of cortical bone caused by rigid internal fixation plates. *Acta Orthop. Scand.* 49, 448-456.
- Tayton, K., Johnson-Nurse, C., McKibbin, B., Bradley, J. & Hastings, G. (1982) The use of semi-rigid carbon-fibre-reinforced plastic plates for fixation of human fractures. *J. Bone Joint Surg.* 64-B, 105-111.
- Terjesen, T. & Benum, P. (1983a) Mechanical effects of metal plate fixation. *Acta Orthop. Scand.* 54, 256-262.
- Terjesen, T. & Benum, P. (1983b) Stress-protection after external fixation on the intact rabbit tibia. *Acta Orthop. Scand.* 54, 648-654.
- Tonino, A. J., Davidson, C. L., Klopper, P. J. & Linclau, L. A. (1976) Protection from stress in bone and its effects. *J. Bone Joint Surg.* 58-B, 107-113.
- Uthoff, H. K. & Dubuc, F. L. (1971) Bone structure changes in the dog under rigid internal fixation. *Clin. Orthop.* 81, 165-170.
- Uthoff, H. K., Bardos, D. J. & Liskova-Kiar, M. (1981) The advantages of titanium alloy over stainless steel plates for the internal fixation of fractures. *J. Bone Joint Surg.* 63-B, 427-434.
- White, A. A., Panjabi, M. M. & Hardy, R. J. (1974) Analysis of mechanical symmetry in rabbit long bones. *Acta Orthop. Scand.* 45, 328-336.
- Woo, S. L.-Y., Akeson, W. H., Coutts, R. D., Rutherford, L., Doty, D., Jemmot, G. F. & Amiel, D. (1976) A comparison of cortical bone atrophy secondary to fixation with plates with large differences in bending stiffness. *J. Bone Joint Surg.* 58-A, 190-195.