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ATROPHY OF CORTICAL BONE CAUSED BY RIGID INTERNAL FIXATION PLATES

An Experimental Study in the Dog

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The cortical atrophy induced by a rigid internal fixation plate on diaphyseal bone was studied on the femora of seven dogs. When the plate, which had been in position for 7 months without previous osteotomy, was removed, a pronounced reduction of the cortical bone was observed in the previously plated section of the diaphyseal bone. The atrophy took the form of loss of cortical bone mainly caused by endosteal resorption with enlargement of the medullary cavity. Neither periosteal resorption nor formation of woven bone under the site of the plate were observed. The process of adaption to the changed stress and strain conditions, caused by the mechanical joint, i.e., implants and bone, was studied by means of a histological technique, and was still in progress after a period of seven months.

Key words: internal plate fixation; adaption of cortical bone to functional demands; measurement of cortical bone atrophy

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Metal plates for internal fixation have been used to an ever increasing extent for almost a century. Clinical experience from fracture treatment with internal fixation plates shows, however, that a considerable number of refractures occur (Richon et al. 1967, Wade 1970). In a previous paper (Strömberg & Dalén 1976), we demonstrated that the dog femur stabilized with a rigid internal fixation plate (AOI-type) for 7 months displays, on removal of the plate, and compared with the contralateral control bone, a significantly different distribution of bone material and a marked reduction in maximum angle of torsion.

The present investigation was designed to elucidate the morphologic changes which develop concomitant to the weakening of long bones caused by internal fixation plates.

METHODS

Anaesthesia

The surgical procedures for bone plating according to the AO-group were performed under general anaesthesia, which was induced with thiomebumalnatrium (Pentothal Sodium®, Abbott Laboratories, Chicago, Ill., USA). By means of an endotracheal tube, the dogs were connected to an Engström ventilator supplied with a gas mixture of oxygen and nitrous oxide. Small doses of thiomebumalnatrium were administered intermittently during the operations.

Surgical procedure

Seven fully grown, healthy male dogs (Swedish harriers), weight 14–16 kg were used. An AOI-plate 50 mm long with four holes designed for internal compression fixation on dogs (Synthes, Waldenburg, Switzerland) was applied under sterile conditions to both femora. An incision was made through the skin and underlying fascia. Both femora were exposed up to the linea aspera by an approach behind and under the vastus lateralis muscle of the quadriceps along the intramuscular septum (the "mailbox" approach). The underlying periosteum was not detached from the bone and no osteotomy was performed. The perforating vessels in the distal part of the intramuscular septum were used as reference points, so that the plates could be similarly fitted on both femora. The plates were applied to both femora immediately in front of the linea aspera and fastened according to the AO-method, after the plate had been modelled to the bone (Müller et al. 1970). One of the plates (chosen at random) was removed and the screws refastened into the bone. The soft parts were sutured in stages, using catgut in the fascia and non-absorbable sutures in the skin.

Pre- and postoperative care

During the operations, 500 ml of Ringer solution was administered intravenously. A daily prophylactic dose of 0.5 g of ampicillin (Pentrexyl®, Bristol-Myers, New York, N.Y., USA) was given during the first postoperative week. The dogs spent an uneventful postoperative period of 7 months in kennels. They were checked daily and received adequate food and exercise.

Seven months after the operations, the animals were given tetracycline (Terramycin®, Pfizer Inc., New York, N.Y., USA), 0.5 g per kg body weight per os.

Sacrifice

One week after administration of tetracycline, the dogs were sacrificed with intravenous lethal doses of mebumalnatrium (Nembutal®, Abbott Laboratories).

Bone preparation

All femora were dissected from the surrounding soft tissue, but not from the periosteum. The femora, the test bones and the control bones, were cut in 4.0 mm thick cross-sectional slices. They were frozen to −40°C. All the slices were submitted to X-ray examination. After the radiological examination, every second slice was chosen for ashing and the rest for histological studies.

Radiological study

The radiological examinations were performed with the X-ray beams parallel to the long axis of the femora. The porosity of the cortical bone and the amount of newly formed periosteal bone were estimated by means of the radiograms from the cross section of the bones. The cross-sectional areas of the cortical bone and those of the medullary cavities were measured with a planimetric technique. The areas were compared and the differences between those from the test bones and the corresponding ones from the control bones were noted. In the measurement of cross-sectional areas, the periosteal formed bone ridges were excluded.

Histological study

The slices chosen for histological studies by means of a fluorescence technique were freeze-dried to constant weight and then immediately embedded in methylmethacrylate (Olerud & Lorenzi 1970). Thin pieces were cut from the embedded slices and then reduced to a thickness of about 60 μ. This process had no effect on the fluorochromes present. The colours were fixed by a freeze-drying process, as they would have been partly dissolved by other dehydration procedures. The prepared histological slides were studied by fluorescence microscopy. The differences between corresponding parts of the test bones and their controls were estimated.

Measurement of ash weights

The amount of non-organic material in the test bones and their controls was estimated by means of an ashing procedure. The slices chosen were ashed to constant weight at 600°C. The differences in ash weight between the ashes from corresponding slices from the same animal were registered.

RESULTS

Dispersed areas of periosteal formed bone were observed on the radiograms. The areas where the plates had been located were defined by ridges formed of periosteal bone, most pronounced at the ends of the sites of the plates. Where the tips of the screws had penetrated the periosteum, sub-periosteal bone had formed a cone around the tips. The radiograms of the cross sections under the midpoint of the internal fixation plates showed increased porosity compared with corresponding sections from the control bones. Areas of newly formed periosteal bone

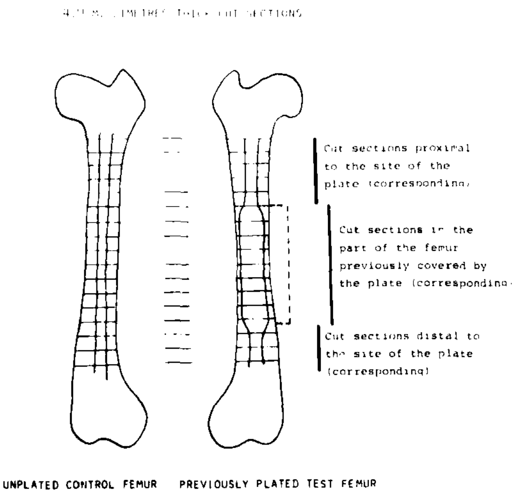

Figure 1. Cut sections of femur in which a rigid internal fixation plate (AOI-type) has been applied for 7 months and of the corresponding control femur not affected by a plate.

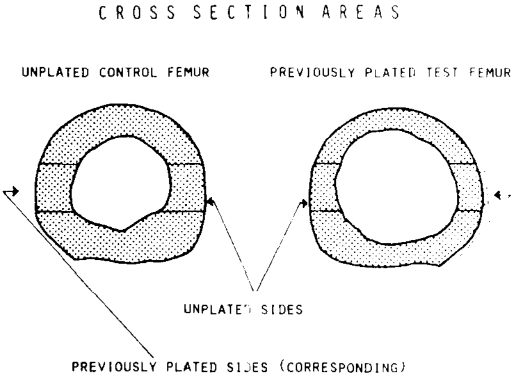

Figure 2. Standard partial cortical areas of cortical cross section from femur in which an internal fixation plate (AOI-type) has been applied for 7 months and the analogous areas of the corresponding control femur.

Table 1. The mean values of the total areas (cortical bone + bone marrow) (Figure 2) from ten cross sections under the site of the plate (Figure 1) in seven femora to which an internal fixation plate (AOI-type) had been applied for 7 months and from the seven control femora. The areas are given in relative numbers. The deviation of the previously plated femora is expressed as a percentage of the corresponding values of the respective control femora.

	Control bone	Test bone	
Dog no.	Femur not affected by a rigid plate	Femur affected by a rigid plate	Percentage deviation
1	352	353	−0.3
2	327	321	1.8
3	324	319	1.5
4	272	272	0.0
5	319	322	−0.9
6	300	297	1.0
7	303	298	1.6

The areas of the cross sections had not decreased under the site of the plate (mean = 0.67 per cent; S.D. = 1.06). Paired observation tests: $t = 1.63$; $P > 0.05$.

were observed on both the test and control bones.

Planimetry of the total cross sectional areas of the bones, including the marrow cavity, under the sites of the plates, displayed no significant reduction compared with the corresponding areas from the previously non-plated control bones (Table 1, Figure 1, Figure 2).

The cortical areas of the cross sections of those parts of the bones which had been covered by the plates showed a significant reduction as compared with the contralateral control cross sections (Table 2a, Figure 1, Figure 2).

The cortical cross-sectional areas on the plated side of the stabilized femora, excluding the periosteal formed bone, were not reduced in comparison with the opposite side of the same bone (Tables 3a, 3b, Figure 2).

There was however a pronounced enlargement of the medullary cavities of that part of the test bones previously covered by the plate compared with those of the control bones (Table 4, Figure 1, Figure 2).

The cortical cross-sectional areas proximal and distal to the sites of the plates showed no

Table 2. The mean values of parts of the cross-sectional areas representing the cortical bone (Figure 2) from ten cross sections under the site of the plate (Figure 1) in seven femora to which an internal fixation plate (AOI-type) had been applied for 7 months and from the seven control femora. The areas are given in relative numbers. The deviation of the previously plated femora is expressed as a percentage of the corresponding values of the respective control femora.

(a) *Cross-sectional parts (cortical bone) proximal to the site of the plate (Figures 1, 2) (corresponding).*

Dog no.	Control bone Femur not affected by a rigid plate	Test bone Femur affected by a rigid plate	Percentage deviation
1	200	185	−7.5
2	186	180	−3.2
3	181	199	9.9
4	157	187	6.4
5	196	196	0.0
6	154	150	−2.8
7	175	172	−1.7

The areas had not changed proximal to the site of the plate (mean = 0.2 per cent; S.D. = 5.98). Paired observation tests: t = 0.00; $P > 0.05$.

(b) *Cross-sectional parts (cortical bone) under the site of the plate (Figures 1, 2) (corresponding).*

Dog no.	Control bone Femur not affected by a rigid plate	Test bone Femur affected by a rigid plate	Percentage deviation
1	222	194	−12.6
2	205	176	−14.1
3	197	167	−15.2
4	187	170	−9.2
5	191	174	−18.9
6	201	177	−11.9
7	185	173	−6.5

The areas had decreased under the site of the plate (mean = 11.2 per cent; S.D. = 3.13). Paired observation tests: t = 8.37; $P < 0.05$.

(c) *Cross-sectional parts (cortical bone) distal to the site of the plate (Figure 2) (corresponding).*

Dog no.	Control bone Femur not affected by a rigid plate	Test bone Femur affected by a rigid plate	Percentage deviation
1	172	182	5.8
2	180	169	−6.1
3	184	197	7.1
4	184	173	5.5
5	187	173	−3.2
6	183	182	−0.5
7	166	181	9.0

The areas had not changed distal to the site of the plate (mean = 2.5 per cent; S.D. = 5.76). Paired observation tests: t = 0.67; $P > 0.05$.

differences between the test and the control bones (Tables 2a, 2c, Figure 1, Figure 2).

Histological studies of the cortical bone previously covered by the plate showed a uniform distribution of increased osteoblast activity compared with the corresponding contralateral control femora.

Furthermore, porosity was most pronounced in the endosteal part of the cortical bone of the test femora. Proximal to the site of the plates, there was no difference in porosity between the test and the control bones.

Histologically, there was evidence of activity of periosteal bone formation in the previously mentioned ridges close to the internal fixation plates. This activity had, however, ceased in the areas of periosteal bone without connection with the internal fixation plates.

The ashing procedure disclosed clearly reduced ash weights of the cross-sectional slices under the plates as compared with those of the control femora (Table 5b). There was no marked difference in the ash weights proximal to the site of the plate and the corresponding part of the control bone (Table 5a).

Table 3a. The mean values of parts of the cross-sectional areas representing the cortical bone on the plated side and on the opposite unplated side of the same bone in seven femora to which an internal fixation plate had been applied for 7 months and from the seven control femora. The areas are given in relative numbers.

	Unplated side of the femur		Plated side of the femur	
Dog no.	Femur not affected by a rigid plate	Femur affected by a rigid plate	Femur not affected by a rigid plate	Femur affected by a rigid plate
1	38	33	34	31
2	30	26	28	26
3	26	21	31	26
4	26	22	25	24
5	27	22	25	23
6	29	27	29	25
7	27	25	27	24

DISCUSSION

When a rigid internal fixation plate is fastened to a diaphyseal bone a changed load situation is created. The loads will be partly carried by the internal fixation material, and thus the load on the cortical bone will decrease.

The bone adapts itself to the actual functional demands (Wolff 1892). Earlier we have measured the adaption in terms of decreased torsional capacity (Strömberg & Dalén 1976).

Our present results indicate that the changed load situation is followed by a loss of material in the cortex. The adaption is

Table 3b. Percentage deviation of the part of the cross-sectional area representing the cortical bone on the unplated side in seven femora to which an internal fixation plate had been applied for 7 months compared with the corresponding area of the control femora.

Dog no.	Percentage deviation of the part of the cross-section area from the UNPLATED side of the plated femur as compared with the corresponding area of the unplated femur	Percentage deviation of the part of the cross-section area from the PLATED side of the plated femur as compared with the corresponding area of the unplated femur
1	−13.2	−8.8
2	−13.3	−7.1
3	−19.2	−16.1
4	−15.4	−4.0
5	−18.5	−8.0
6	−6.9	−13.8
7	−7.4	−11.1

There was no difference between the deviations of the unplated and the plated sides of the previously plated femora as compared with the corresponding areas of the control femora. Paired observation tests: $t = 1.38$; $P > 0.05$.

Table 4. The mean values of the bone marrow areas (Figure 2) from the cross sections under the site of the plate (Figure 1) in seven femora to which an internal fixation plate (AOI-type) had been applied for 7 months and from the seven control femora. The areas are given in relative numbers. The deviation of the previously plated femora is expressed as a percentage of the corresponding values of the control femora.

	Control bone	Test bone	
Dog no.	Femur not affected by a rigid plate	Femur affected by a rigid plate	Percentage deviation
1	130	159	22.3
2	122	145	18.9
3	127	152	19.7
4	85	102	20.0
5	128	148	15.6
6	99	117	18.2
7	118	125	5.9

The areas had increased under the site of the plate (mean = 17.2 per cent; S.D. = 5.39). Paired observation tests: $t = 7.47$; $P < 0.05$.

visualized by the markedly decreased total cross-sectional cortical area.

The diameter of the medullary cavity increased. It was not, however, associated with a change in the outer diameter of the test bone. This was taken as evidence that the reduction of material occurs in the endosteal parts of the stabilized bone sections in accordance with the results of Akeson et al. but in disagreement with the suggestion of Tonino et al. (1976).

The weakening of the cortical cylinder, measured as a reduced resistance to bending and torque loads, acting in combination or individually, is thus minimized due to the fact that the reduction takes place in the endosteal parts of the cortical wall.

The decrease in bone material asserted itself not only as reduced cortical cross section area, but also in increased porosity. The ash weight determinations were in accordance with the decreased bone material content in the stabilized sections. This does

Table 5a. The mean values of the ash weights from the cut sections proximal to the site of the plate (Figure 1) in seven femora to which an internal fixation plate (AOI-type) had been applied for 7 months and from the seven control femora. The weights are given in mg. The deviation of the previously plated femora is expressed as a percentage of the corresponding values of the control femora.

	Control bone	Test bone	
Dog no.	Femur not affected by a rigid plate	Femur affected by a rigid plate	Percentage deviation
1	0.5057	0.5038	0.4
2	0.4510	0.4493	−0.4
3	0.5064	0.4971	−1.8
4	0.4079	0.4261	4.5
5	0.4468	0.4558	2.0
6	0.3746	0.3833	2.3
7	0.4181	0.3989	−4.5

The ash weights had not changed proximal to the site of the plate (mean = 0.3 per cent; S.D. = 2.98). Paired observation tests: $t = 0.11$; $P > 0.05$.

Table 5b. The mean values of the ash weights from the cut sections under the site of the plate (Figure 1) in seven femora to which an internal fixation plate (AOI-type) had been applied for 7 months and from the seven control femora. The weights are given in mg. The deviation of the previously plated femora is expressed as a percentage of the corresponding values of the control femora.

	Control bone	Test bone	
Dog no.	Femur not affected by a rigid plate	Femur affected by a rigid plate	Percentage deviation
1	0.5876	0.4848	−16.8
2	0.4172	0.3459	−17.1
3	0.4903	0.4025	−17.9
4	0.4308	0.3808	−11.6
5	0.4134	0.3616	−12.5
6	0.4277	0.3486	−18.5
7	0.5026	0.4166	−17.1

The ash weight had decreased in the part of the bone previously covered by the plate (mean = 15.9 per cent; S.D. = 2.72). Paired observation tests: $t = 10.29$; $P < 0.05$.

not seem to be in full agreement with the observation of Woo et al. (1976) that the mechanical changes due to internal fixation plating were a result of reduction in the cortical bone structure by thinning of the cortex rather than a reduction in the mechanical properties of the bone substance.

In the present study no increased cross-sectional area or elevated ash weight proximal or distal to the sites of the plates were observed as signs of increased quantity of bone material. This was to be expected as according to mechanical principles there should be increased stress and strain concentrations and, thus, an increased bone formation.

In the present experiments, however, the plates were long when compared with plated diaphyseal bones. The non-covered parts of the bones formed rather short mechanical joints, which together with the geometry of these parts probably explains why the bone substance had markedly increased proximal to the site of the plate.

The operative procedure with the application of the rigid metallic plate by means of screws will cause compression of the periosteum and the underlying bone. There will be damage to the periosteum and this affects the blood flow situation in the cortical bone and may be partly responsible for the formation of woven bone as observed by Matter et al. (1974). This woven bone was placed as a reflection of the plate in the cortex immediately covered by the plate. The dynamic process of altering the blood flow in the cortical bone has been discussed (de Marneffe 1957, Göthman 1960, Brookes 1971). However, the cortical bone is able to compensate for the loss of limited periosteal blood flow, and, 7 months after surgery, we could not find any local effects on the cortical bone due to disturbed blood supply.

These observations are in accordance with those of other investigators (Akeson et al. 1976, Tonino et al. 1976, Woo et al. 1976), but as mentioned above do not harmonize in this respect with the results reported by Matter et al. (1974) or the clinical observations reported by Diel & Mittelmeier (1974). The differences in species and postsurgical observation times are probably the reasons for this discordance between our results and those of Matter et al. (1974).

In contrast to earlier reports, we could not demonstrate that the adaption was most pronounced in that portion of the cross section previously covered by a plate. Akeson et al. (1976) and Woo et al. (1976) in their joint material, and Matter et al. (1974), observed a decreased thickness of the cortical bone under the site of the rigid plate due to an endosteal resorption. The entire section of the long bone and the fastened rigid metallic plate covering the bone section formed the mechanical joint. Thus there was a changed load situation in the whole bone part of the thus formed mechanical joint with decreased stress and strain in the part covered by the plate as well as in the opposite part.

Despite the fact that we have excluded the small periosteally formed bone ridges in our cross-sectional area measurements, it is difficult to explain the dissimilarity of the observed cortical atrophy under the plate in our material and that of the previous reports.

The results of the present investigation are in agreement with our earlier findings (Strömberg & Dalén 1976). The decreased amount of bone material, the observed porosity and the reduction of the cortical wall of the bone with unchanged outer diameter are, according to the principles of strength of materials and solid mechanics, consistent with a decreased maximum torque capacity and maximum angle of torsion at torsional tests reported in previous papers.

The histological findings indicated, in this study, an increased osteoblast activity in the test bones compared with the control ones, which would suggest that the reconstruction, i.e., the adaption, was not completed after 7 months. Furthermore, neither the momentum of the adaption process nor of the following re-adaption process or its mechanism are yet known. A diaphyseal fracture in a dog femur is generally considered clinically healed within a shorter period than 7 months when treated by means of rigid internal plate fixation. These facts, together with our previous and present results, indicate the importance of minimizing the period that the internal fixation plate should protect the bone during fracture treatment from loads, as the protection has an ongoing detrimental effect upon the strength qualities of the bone.

The use of internal fixation plates made from less rigid materials than stainless steel is reported in the literature (c.f. Woo et al. 1974, Akeson et al. 1976, Woo et al. 1976). The aim seems to be to decrease the weakening effect on the stabilized non-fractured part of the bone. To attain the desired rigidity of an internal fixation plate, it would be more practical to design a suitable stainless steel plate than to experiment with other materials of less rigidity. The elastic modulus of the material from which the plate is made is of minor interest in this respect. It is the stiffness of the designed plate that defines the quality of the performed internal fixation. Equal stiffness can be achieved even if the plates are made from different materials. Experiments with plates made from weaker materials than stainless steel are thus only of academic interest concerning the influence of the weakening effect on a non-fractured diaphyseal bone.

To achieve primary fracture healing, the fracture surfaces must be kept compressed and fixed against each other. The fractured limb may be expected to bear loads early during the healing process, and this can be sustained only if a rigid mechanical joint is formed, e.g., by means of a rigid plate according to the AO-method. Otherwise the conditions for primary bone healing will not exist.

However, the problem remains of when to remove the implants and how to avoid unnecessary deterioration of the cortical bone, thus minimizing the time required for a fractured diaphyseal bone to regain its normal strength and architecture. Until this problem is solved, it cannot be considered that the principles of the treatment of fractures by means of rigid internal fixation plates have been fully clarified.

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