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Effect of animal species and age on plate-induced vascular damage in cortical bone

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Summary. Plates used for fracture fixation produce vascular injury to the underlying cortical bone. During the recovery of the blood supply, temporary osteoporosis is observed as a result of Haversian remodeling of the necrotic bone. This process temporarily reduces the strength of the bone. We tackled the postulate that quantitative differences exist between animal species, and in different bones within the same species, due to variations in the relative importance of the endosteal and periosteal blood supplies. Using implants scaled to the size of the bone, we found comparable cortical vascular damage in the sheep and in the dog, and in the tibia and femur of each animal. We observed a significant reduction in cortical vascular damage using plates that had a smaller contact area with the underlying bone. No significant difference in cortical vascular damage was noted in animals of different ages.

The complication rate following the internal fixation of fractures using plates is small. In a well-documented series of 323 closed/95 open fractures, Rüedi et al. [15] found 3/11 cases with infection, 3/5 cases with pseudarthrosis, 4/7 implant or fixation failures, and 1/1 refractures. A recent review of the same group showed a refracture rate of less than 2% [9]. A higher rate of refracture was observed when plates were removed too early [14].

Refracture has been attributed to stress shielding and secondary disuse osteoporosis [10]. Moyen et al. [11] have shown that this osteoporosis is temporary and that its only long-term effect is a slight reduction in cortical thickness. To avoid this problem, the use of less rigid plates has been advocated [12, 17, 19]. However, a theoretical analysis of stress shielding did not show a significant difference in bone stress with plates made of less rigid material [3].

Another suggested cause of refracture is the effect of the plate on the underlying bone vascularization [1, 13, 14]. Gunst et al. [7] demonstrated that the bone becomes temporarily osteoporotic under the plate relative to the extent of vascular damage. Other authors [5, 8, 18], using the plated sheep tibia model, correlated the extent and pattern of osteoporosis with the disruption of the blood supply, and with the area of contact between the plate and the bone. No correlation between osteoporosis and plate rigidity was noted.

However, Eitel et al. [4] have stated that extrapolation from the sheep to man may not be valid. They observed that the sheep cortex contains a higher proportion of primary Haversian lamellae than does human bone. They proposed the use of the dog model. Additionally, Schenk [16] postulated that differences in the age of the animal could be important, since the cortical bone blood supply of older animals is more dependent on endosteal than on periosteal vessels, and that these animals have more secondary Haversian systems.

The goal of the present study was to investigate plate-related vascular damage in cortical bone in the dog and in the sheep, and to search for interspecies difference.

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Table 1. Distribution of the animals used

	Sex	Age	Weight	Group
Dog				
1	Male	2.7 y	11.3 kg	Young
2	Female	8.1 y	10.3 kg	Old
3	Male	2.7 y	15.0 kg	Young
4	Female	8.6 y	13.5 kg	Old
5[a]	Male		13.5 kg	Young
6	Female	6.7 y	10.0 kg	Old
7	Female	4.0 y	12.1 kg	Young
8	Female	6.7 y	10.5 kg	Old
9	Female	2.8 y	9.8 kg	Young
Sheep				
1	Female	10.8 y	51 kg	Old
2	Female	2.9 y	48 kg	Young
3	Female	11.1 y	46 kg	Old
4	Female	3.0 y	46 kg	Young

[a] Dog no. 5: Due to inadequate coloration based on a technical error, this animal had to be excluded from the experiment and was replaced by dog no. 9

Materials and methods

Animals and materials

The investigation was carried out in nine adult beagle dogs and four adult female Swiss white alpine sheep. The dogs were divided into two groups; the sheep were similarly divided (Table 1). Three types of two-hole plates were utilized, namely round-hole plates with and without an underlying silicone layer and the experimental plate without the silicone layer. These plates were used in two sizes in order to accommodate dogs and sheep, according to the rule of equivalent axial stiffness described by Steinemann (1984; Table 2).

For the beagles, round-hole plates with a conventional undersurface were specially constructed with a radius similar to the cross-sectional radius of the bone. For the sheep, conventional AO/ASIF dynamic compression plates were used. Experimental plates with a comparable cross-section were constructed (S.T.) in order to maintain a gap of 1 mm between the plate and the bone. After unicortical drilling and tapping to minimize and standardize medullary damage, unicortical conventional AO cortical screws (3.5 mm for the dogs and 4.5 mm for the sheep) were inserted using a torque-measuring screwdriver (Rumul, Russenberger and Mueller, Schaffhausen, FRG).

Table 2. Description of plates used

Dogs

Titanium round-hole plate (RHP):
- Cross-section: length 24 mm, width 87 mm, thickness 2 mm
- Distance betwee screw holes 12 mm
- Radius of the undersurface 4 mm
- 3.5-mm AO cortical screws

Titanium plate with silicone undersurface (S-RHP):
- RHP with undersurface consisting of a layer of 2-mm of silicone (Silastic)
- 3.5-mm AO cortical screws

Experimental shifted titanium plate (BEP):
- Special plate of same cross-section as RHP, designed to maintain a gap of 1 mm between the undersurface of the plate and the bone
- 3.5-mm AO cortical screws

Sheep

Narrow AO/ASIF titanium dynamic compression plate (DCP):
- Length 31 mm, width 12 mm, thickness 4 mm
- Distance between the screw holes 16 mm
- Radius of the undersurface 6 mm
- 4.5-mm AO cortical screws

Experimental shifted titanium plate (SEP):
- Special plate of similar cross-section to DCP, designed to maintain a gap of 1 mm between the undersurface of the plate and the bone
- 4.5-mm AO cortical screws

Table 3. Application of plates

	Group	R tibia	L tibia	R femur	L femur
Dog					
1	Young	RHP	BEP	BEP	RHP
2	Old	RHP	BEP	BEP	RHP
3	Young	BEP	RHP	BEP	RHP
4	Old	BEP	RHP	BEP	RHP
6	Old	S-RHP	BEP	BEP	S-RHP
7	Young	S-RHP	BEP	BEP	S-RHP
8	Old	BEP	S-RHP	S-RHP	BEP
9	Young	BEP	S-RHP	S-RHP	BEP
Sheep					
1	Old	DCP	SEP	SEP	DCP
2	Young	SEP	DCP	DCP	SEP
3	Old	DCP	SEP	SEP	DCP
4	Young	SEP	DCP	DCP	SEP

For abbreviations see Table 2

Planning of the experiment

Plates were applied to both intact tibiae and femora. In order to avoid uncontrolled effects of age or side, the different plates were distributed systematically to the different limbs and across the age groups (Table 3).

Surgical procedure

The animals were operated on in randomized order and under general anesthesia. The tibia was approached medially, the plate being positioned at the junction of the middle and distal third of the bone. The femur was approached anterolaterally and the plate positioned on the midschaft. One tibia and the contralateral femur were operated on with the animal on its side. The animal was then turned in order to operate on the remaining tibia and femur.

In all cases the periosteum was left intact. Following surgery the animal was maintained under general anesthesia and turned every 90 min to avoid circulatory difficulties. Cardiorespiratory homeostasis was maintained until the animal was killed 7 h after operation. The injection of Disulfin blue 12.5%, 5 mg/kg b.w., i.v., was given 10 min prior to euthanasia. Dye staining thus indicates an intact blood supply. The tibiae and femora were removed and frozen over 30 min. The plate was removed and a color photograph taken of the plate bed. A transverse saw cut was made at the midpoint of the plate bed and the cut surfaces were photographed. The bone was then lyophilized and embedded in polymethylmethacrylate. Three consecutive transverse slices of 0.1 mm thickness were obtained from the midpoint of the plate bed for histological evaluation. The histological sections were examined under a Wild M1 stereo microscope at 6–25 × magnification. Sketches were made with a drawing attachment to indicate which portions of the cortical bone were avascular. Impaired blood supply was indicated by empty or thrombotic vessels as compared to blue-stained, vascular bone. General lamellae do not usually contain blood vessels and therefore were not considered to be avascular zones.

Data analysis

IMKO[1] image analysis was used to quantify the fraction of the area of cortical bone with disrupted blood supply based on a pixel count. D = DBS (area of damaged blood supply)/mm (total cross section cortical area). The graphs were made and the statistical analysis performed using the data analysis program RS/1[2].

Method of statistical data analysis

The basic question addressed by the data analysis is the comparison of the vascular damage between the dynamic compression

[1] IMKO
[2] RS/1(R) release 4: Data analysis software of BBN (Cambridge, Mass.)

plate and the experimental plate for the sheep, or between the round-hole plate, the round-hole plate with silicone undersurface, and the experimental plate for the beagles. The statistical methods are nonparametric (rank test analysis). This analysis should first detect the influence of different bones (tibia or femur) and different ages of bone (old and young animals); if no difference is established, the results of different aged bones are pooled in order to compare the different plates. Since a dog is obviously not a sheep, the statistical differences in vascular damage observed between the two animal species are left open to discussion!

Results

One dog was excluded from the study due to technical problems in Disulfin blue delivery, as noted previously (see Table 1).

Sheep

Impairment in cortical blood supply was seen deep to the plates. This is shown in Fig. 1, which includes plate bed photographs and cut section photographs for both the conventional and the experimental plate. The area of disrupted blood supply on transverse sections is shown in Fig. 2, which includes both of the plates and both of the bones examined. The relative area of damaged blood supply on cross section is seen in Fig. 3 and analyzed statistically as shown in Fig. 4. The cortical vascular disruption due to the conventional plate exceeds that of the experimental plate, with median percentage areas disrupted by 8.9% and 0.78%, respectively. Qualitatively this corresponds to the plate-bone contact areas of the different plates. No significant difference was noted between sheep of different ages or between the tibia and femur.

Dog

Impairment in cortical blood supply was also seen deep to the plates in the dogs. Figure 5 shows plate bed photographs and cut section photographs for the plates used. The cross-section areas of cortical blood supply damage are seen in Fig. 6, with relative areas shown in Fig. 7 and statistical evaluation in Fig. 8. The median percentage areas of disrupted cortical blood supply for the conventional plate, the silicone-undersurface plate, and the experimental plate are 3.92%, 5.09%, and 1.03%, respectively. No significant difference in the degree of vascular damage can be observed in comparing the conventional plate with and the conventional plate without the silicone layer. Although comparably high scatter was observed in the areas of blood supply impairment with the experimental plate, this plate did produce a significantly lower absolute and relative area of damage compared to the others. As in the sheep, the percentage area of vascular impairment corresponds qualitatively to the different bone-plate contact areas. No significant difference was noticed between dogs of different ages or between the tibia and femur.

No significant difference could be established between results for any of the plates used, nor between the reactions of different bones to these plates.

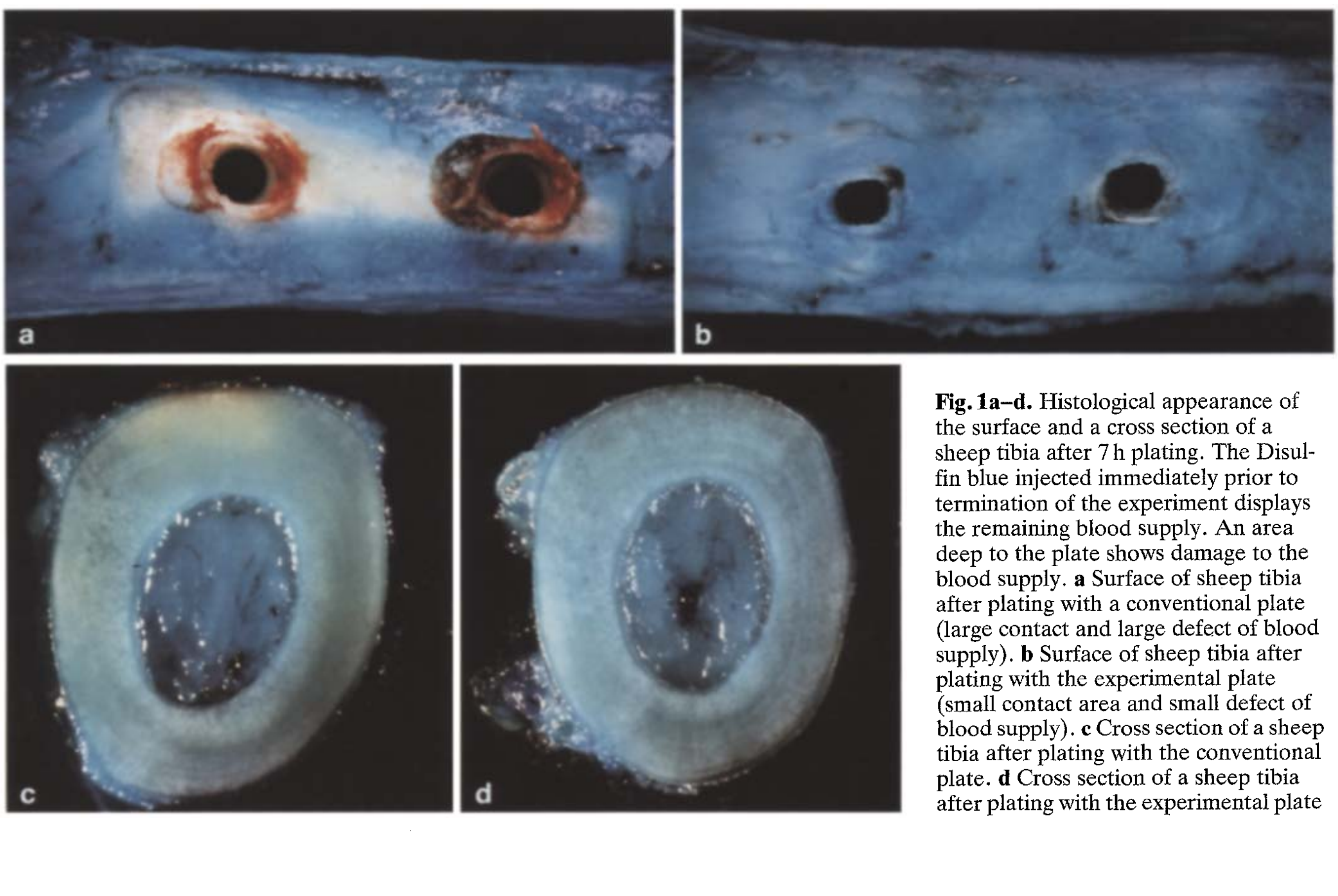

Fig. 1a–d. Histological appearance of the surface and a cross section of a sheep tibia after 7 h plating. The Disulfin blue injected immediately prior to termination of the experiment displays the remaining blood supply. An area deep to the plate shows damage to the blood supply. **a** Surface of sheep tibia after plating with a conventional plate (large contact and large defect of blood supply). **b** Surface of sheep tibia after plating with the experimental plate (small contact area and small defect of blood supply). **c** Cross section of a sheep tibia after plating with the conventional plate. **d** Cross section of a sheep tibia after plating with the experimental plate

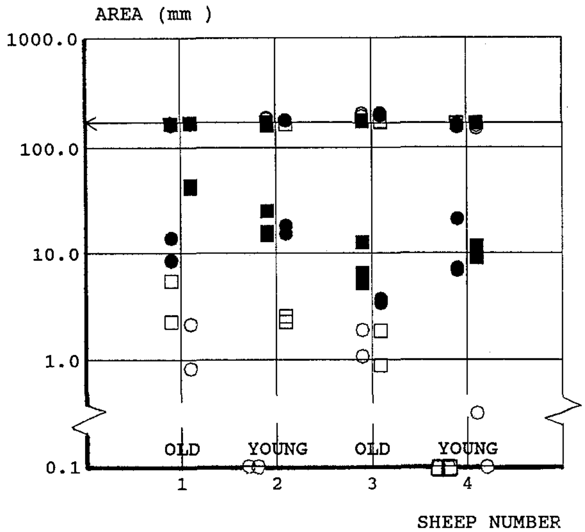

Fig. 2. Area of damaged blood supply measured on the cross section of sheep bones. For each sheep, both tibial and both femoral values were evaluated and plotted on a logarithmic scale. The total bone area is of the same order of magnitude for all the bones. The vascular damage due to the conventional plate (DCP) by far outweighs that observed under the experimental plate. This is more pronounced in young animals. ← Total bone area; ■ tibia, DCP; □ tibia, exp. plate; ● femur, DCP; ○ femur exp. plate; young sheep: 3 years; old sheep: 11 years

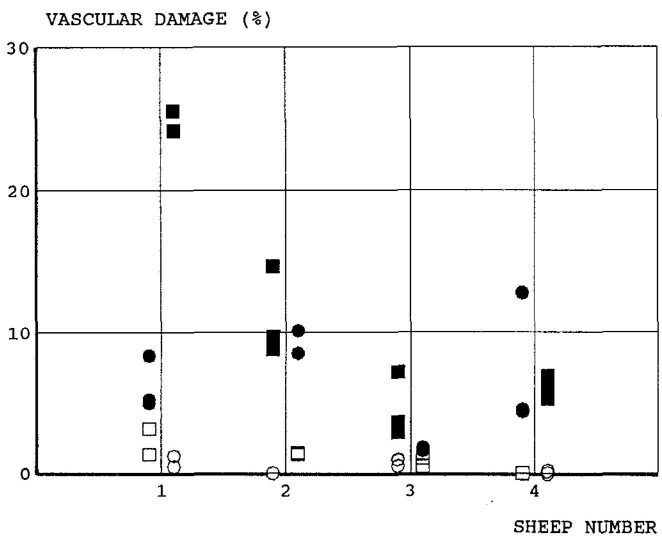

Fig. 3. Relative value of vascular damage in sheep bones. Each point represents the percentage value of damaged area compared to the total of cross-sectional area minus the area occupied by the general lamellae. Here again, the experimental plate with its smaller contact surface to bone is superior when compared to the conventional DCP with smooth undersurface and therefore larger contact area. ■ Tibia, DCP; □ tibia, exp. plate; ● femur, DCP; ○ femur, exp. plate

Statistical analysis (W. J. Ziegler)

Dog

1. As a general observation, no significant difference was revealed between the conventional plate and experimental plate groups, between the different ages, with the exception of the experimental plate used on femora (about 2.5% in the young compared with 1% in the old beagles).

2. No significant difference in the vascularization effect was observed between tibiae and femora, with the exception of experimental plates used on tibiae of young animals (about 1% for the tibiae versus about 2.5% for the femora).

3. The silicone layer revealed nothing but a tendency to increase the effect of the conventional plate on the underlying vascularization.

4. The case is different for the experimental plate: less significant vascular damage was found under it (1%) than under either of the conventional plates (without silicone 4%, with silicone 5%) in either tibiae and femora in older beagles or in tibiae in young beagles; however, no difference was found in the femora in young beagles.

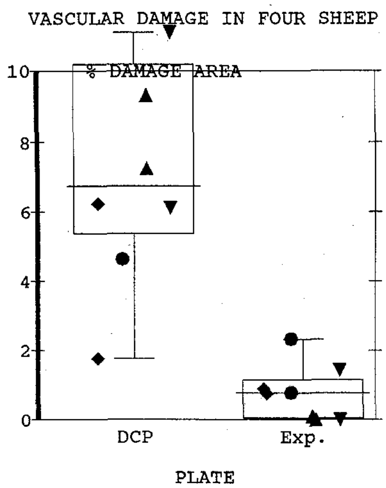

Fig. 4. Statistical representation of the relative amount of vascular damage in the sheep bones. As no normal distribution of the values could be assumed, the data are displayed on box plots, giving the median and the two quartiles as well as the individual data. The medians of the two groups were: conventional plate 8.9%, experimental plate 0.78%. 1 outlier, high value (24.9%) for DCP, old/tibia, age/bone; ◆ old/femur, ● old/tibia, ▲ young/femur, ▼ young/tibia

Sheep

The differences in vascular damage under the conventional and the experimental plate behaved similarly in young and old animals: the differences between the young and the old animals were small and not reproducible when compared to the differences between the conventional plate (8.9%) and the experimental plate (0.8%).

Discussion

Although bone would initially appear to be a uniform material, significant differences do exist between and

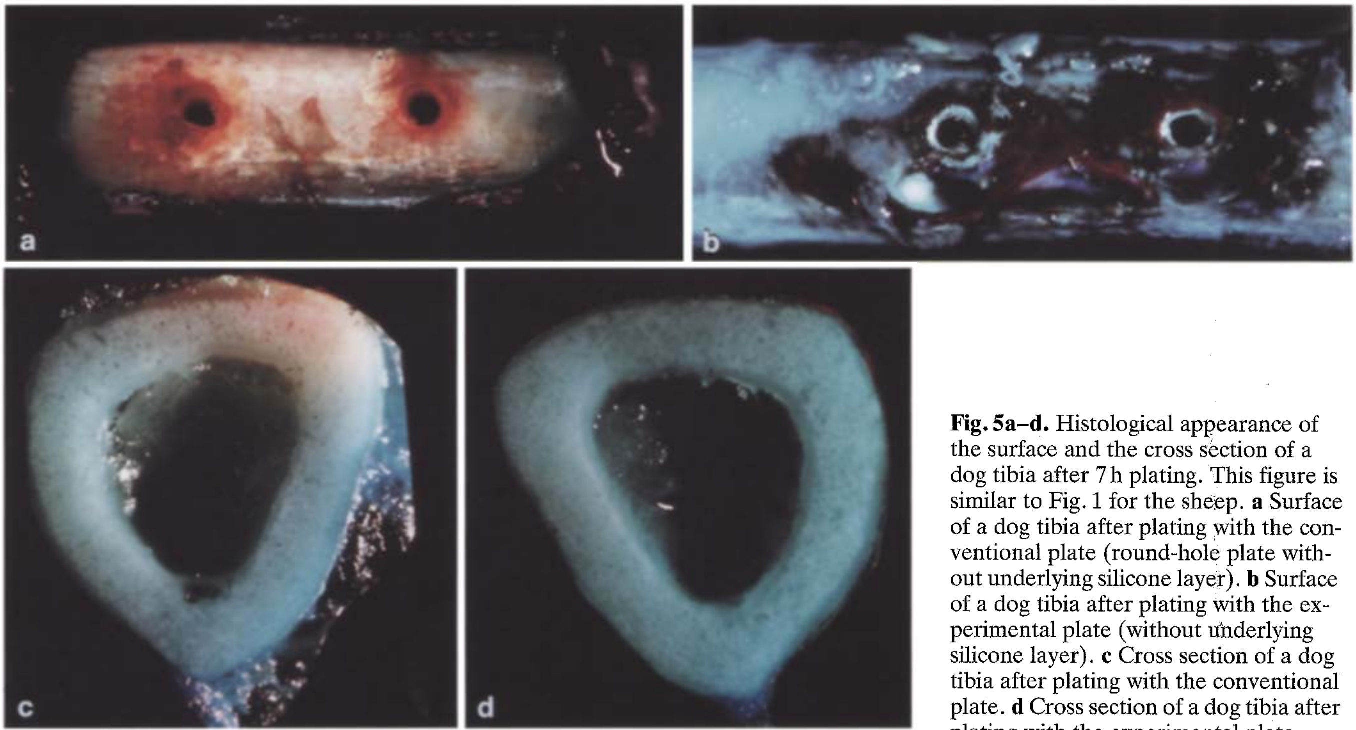

Fig. 5a–d. Histological appearance of the surface and the cross section of a dog tibia after 7 h plating. This figure is similar to Fig. 1 for the sheep. **a** Surface of a dog tibia after plating with the conventional plate (round-hole plate without underlying silicone layer). **b** Surface of a dog tibia after plating with the experimental plate (without underlying silicone layer). **c** Cross section of a dog tibia after plating with the conventional plate. **d** Cross section of a dog tibia after plating with the experimental plate

within species. These include physical dimension and shape, relative importance of endosteal and periosteal contributions to cortical blood supply, and the proportions of primary and secondary Haversian system cortical microanatomy. This latter difference can be further increased by remodeling induced by fracture or by fracture treatment.

In reference to the clinical problem of bone refracture following open reduction and plating, animal experiments which point to cortical osteoporosis secondary to impairment in blood supply have been used to evaluate the human situation. However, some authors have objected to such extrapolation, citing interspecies differences.

For this reason, we carried out a two-species study of the effect of plating on cortical blood supply, using the sheep and the dog. The sheep tibia was used as the standard model of cortical porosity deep to the plates. We decided to include different bones (tibia and femur), animals of different ages, and different plate designs. A simple evaluation of cortical blood supply was attained with the use of Disulfin blue which stains tissue elements perfused by the blood stream and within the immediate diffusion volume. Vascular assessment at 7 h after plating was selected because Göz et al. [6] demonstrated that 5–7 h are required for full thrombosis after pressure-generated deperfusion.

We used smaller implants in the dog than in the sheep. This selection was based on the animal bone-implant relation of Cordey [2], on which [17] have commented.

Our results show no appreciable difference in subplate cortical vascular damage for comparable plates between the dog and the sheep. We conclude that the ani-

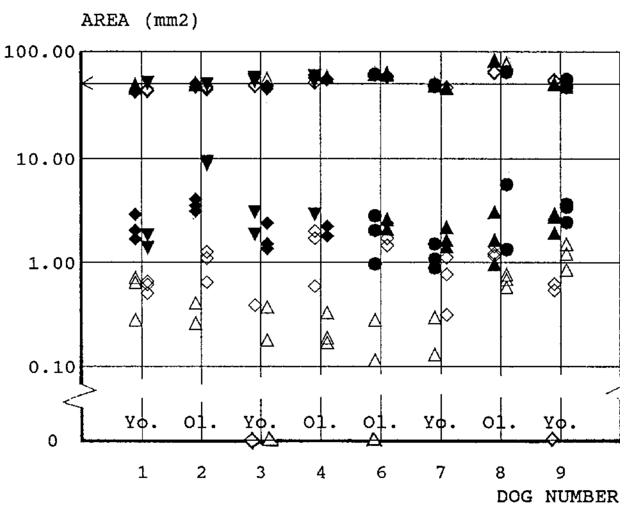

Fig. 6. Area of damaged blood supply measured on the cross section of dog bones. For each dog, both tibial and both femoral values were evaluated and plotted on a logarithmic scale. The total bone area is (as for the sheep, Fig. 2) of the same order of magnitude for all the bones. The round-hole plate was applied without a silicone layer to the first four dogs (nos. 1–4) and with a silicone layer to the last four dogs (nos. 6–9); the experimental plate was applied to the contralateral bone in all the dogs. For each dog, both tibiae and femora were evaluated and plotted on a logarithmic scale. The vascular damage due to the experimental plate shows a comparably high scatter. The damage with the conventional plate did not differ significantly whether a silicone layer was applied or not; the difference between conventional and experimental plates is significant. ← Total bone area; ▲ tibia R. H. + silicone; ▼ tibia, round-hole plate; △ tibia, expl. plate; ● femur, R.H. + silicone; ◆ femur, round-hole plate; ◇ femur, expl. plate; young dogs: 3–4 years; old dogs: 6–8 years

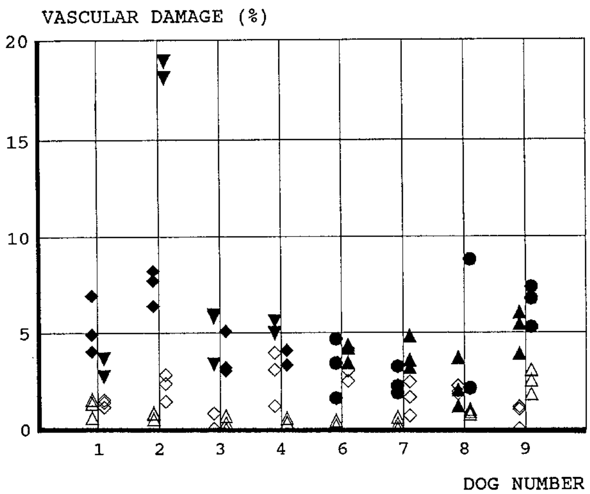

Fig. 7. Relative value of vascular damage in dog bones. The groups are the same as in Fig. 6. Each point shows the percentage of damaged area compared to the total cross-sectional area. Here again, the experimental plate shows less relative damage than the conventional one; the additional silicone layer did not contribute significantly to the degree of blood supply damage. ▲ Tibia, round-hole plate; ▼ tibia, R.H. + silicone; △ tibia, exp. plate; ● femur, round-hole plate; ◆ femur, R.H. + silicone; ◇ femur, exp. plate

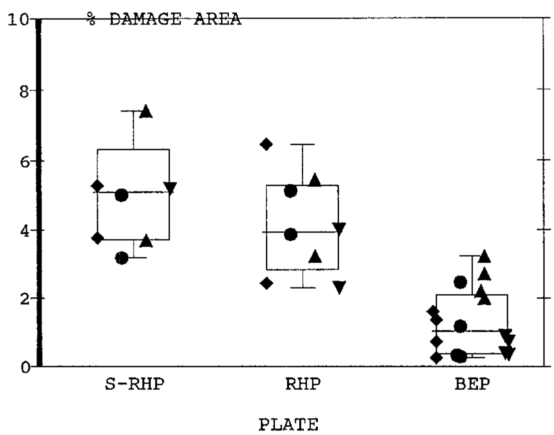

Fig. 8. Statistical representation of the relative vascular damage in the dogs. This figure may be compared to Fig. 4 obtained for sheep. The medians for the three groups (conventional plate with and without silicone and the experimental plate) were 5.09%, 3.92% and 1.03%, respectively. 1 outlier, high value (18.5%) for S-RHP, young/tibia, age/bone; ◆ old/femur, ● old/tibia, ▲ young/femur, ▼ young/tibia

mal experiments reported here and previously are comparable and the results are applicable to the human situation.

We have observed that plates presenting a smaller bone surface contact area qualitatively are associated with less cortical necrosis deep to the plate. This observation suggests the need for a reevaluation of plate design, to minimize the reduction in bone strength after plating and to reduce the incidence of refracture. We note that our experimental plate design appears superior to modifications of the DCP including longitudinal and/or transverse grooves [8] (Fig. 9). We have further noted

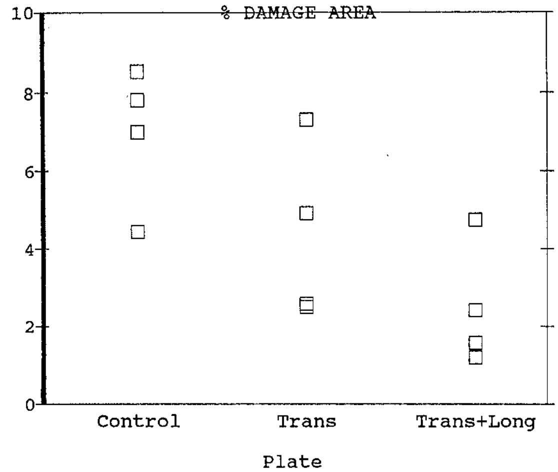

Fig. 9. Relative vascular damage caused in sheep by Jörger (1987) using the conventional stainless steel DCP, a modified DCP with transverse grooves at the undersurface between the screw holes, and a modified DCP with transverse and longitudinal grooves. These results are consistent with those presented in Fig. 4

no significant differences in subplate cortical necrosis between animals of different ages or between the tibia and the femur. The intraosseous microvascular anatomy and the contribution to cortical bone blood supply from the adjacent soft tissues may be less important than previously suspected.

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