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Stress shielding by rigid fixation studied in osteotomized rabbit tibiae

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In 48 rabbits the bone-formation rates and strength in the tibial shaft, osteotomized and treated with rigid internal plate fixation, were compared with contralateral bones, which were treated with plate fixation without osteotomy. The plate fixation alone induced a 35 percent decrease in torsional strength after 12 weeks. The healing of the osteotomy counteracted the decrease in strength induced by stress protection of the rigid plate at 6 weeks, but this effect subsided within 12 weeks. The osteotomy also induced a 2–3-fold increase in the synthesis of bone matrix and mineral accretion of the bone underlying the plate at 6 and 9 weeks when compared with the contralateral side, which was plated but not osteotomized. The bone-formation levels returned to normal within 12 weeks; and the bone underlying the plate became subject to atrophy, resulting in decreased mechanical strength.

Rigid internal fixation of diaphyseal bone has been shown to cause porosis and reduced mechanical strength of the bone in patients (Terjesen et al. 1985), as well as in experimental animals (Tonino et al. 1976, Slätis et al. 1978). The reduced strength is caused by protection of bone from normal stress, and is proportional to the rigidity of the fixation and the time of exposure (Paavolainen et al. 1978, Woo et al. 1984). However, in clinical practice, the internal fixation device is applied to stabilize a fracture or an osteotomy, and thus a healing process takes place at the same time as the bone becomes protected from stress. We have studied the effects of a tibial osteotomy on the metabolism and strength of diaphyseal bone underlying a rigid internal fixation plate.

Materials and methods

Fifty healthy adult rabbits (Swedish land breed) of both sexes weighing 3.6–5.0 kilograms, and all approximately 1 years old, were used. The rabbits were anesthetized with Mebumal Vet (ACO, Solna, Sweden; 0.5 mL/kg). The animals were randomized into six groups each containing 7 or 8 rabbits, which were operated on sequentially, 1 from each group.

Experimental design

Four experimental groups were used to compare a tibial osteotomy under a rigid internal fixation plate with a plate without osteotomy at different time intervals. In these groups, metal plates were attached to the medial aspect of the mid-diaphysis of both tibiae using four cortical screws without compression. On one side, chosen at random, an osteotomy of the bone underlying the center of the plate was made using an oscillating saw. The animals were killed at 3, 6, 9, and 12 weeks after surgery. The two remaining control groups were used to compare a tibial osteotomy with rigid fixation with a contralateral sham operation and a rigid plate with a contralateral sham operation. The sham operation consisted of fixation of a rigid plate with four screws, after which the plate was removed and the screws reinserted into their holes. The animals of the two control groups were killed 12 weeks after the operation.

The stainless-steel plates (ISI 316) were designed in accordance with the AO standard and measured 35 x 5 x 2 mm. The screws were AO cortical screws

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(Strauman HC, Waldenburg, Switzerland), 2 mm wide and 10–15 mm long.

Postoperatively, the animals were allowed to move freely. Two rabbits died from anesthetic complications, and 6 fractured one tibia (4 with osteotomy and 2 with plate fixation).

Two days prior to death, each rabbit was given an intramuscular injection of 10 μCi ^{45}calcium and 24 μ Ci ^{3}H-L-proline (specific activity 100 Ci/mmol; Amersham, England). The animals were killed with Mebumal Vet. Both tibiae and one humerus were collected. The plates were removed and the screws were reinserted in their holes. The bones were radiographed in two projections using high-resolution film.

Torsional tests

The tibiae were tested with the screws in place (Strömberg and Dalén 1976). Torsional strength was measured as the maximal torque capacity on inward twist at 6°/s. Stiffness was measured as the inclination of the load/deformation curve during the linear phase.

Isotope incorporation

Following mechanical testing, the cortical bone underlying the plates or located between the screws was collected and divided into two approximately equal parts. Cortical bone from the mid-diaphysis of the right humerus was also collected and divided into two portions. The wet weight of the bone samples was determined after submerging in water and blotting. One sample of diaphyseal bone from each tibia and one humerus was then ashed in a muffle furnace at 600 °C for 24 h and weighed. The samples weighing 100–250 mg were then dissolved in 5 mL 1N HCl; next, a 1 mL aliquot was added to 10 mL of scintillation fluid (Aquasol, New England Nuclear) and counted in a Beckman LS 1701 liquid scintillation counter. The other sample from each bone was demineralized in 20 mL 0.6 N HCl at 4 °C for 24 h. The pieces of bone matrix were then lyophilized and weighed. The ^{3}H activity was quantified by hydrolyzing the organic residues in a mixture of 0.4 mL perchloric acid and 0.8 mL hydrogen peroxide at 70° for 1 h, followed by the addition of 15 mL of a scintillation fluid containing 2:1 toluol/cellusol and 6 mg PPO (2.5-diphenyloxazole)/L toluol before counting (Mahin and Lofberg 1966). For each animal the ratio of specific activity between each tibia and the humerus was calculated for ^{45}Ca (percentage of dose ^{45}Ca/g ash) and ^{3}H-proline (percentage of dose ^{3}H/g dry weight).

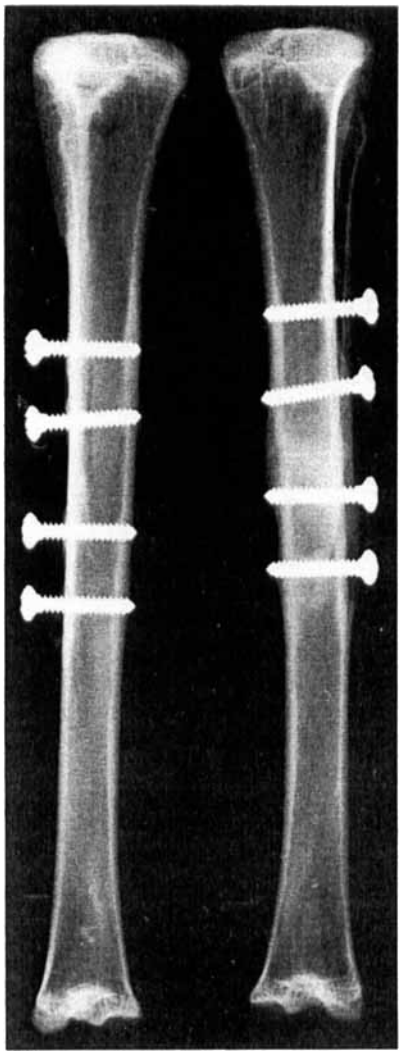

Figure 1. One pair of tibiae in the experimental group at 6 weeks. The left tibia had been operated with a rigid plate, while the right tibia also had been osteotomized. The plates were removed and the screws reinserted.

Statistics

For the mechanical parameters the difference was calculated, and the Wilcoxon signed rank test for paired samples was used to analyze the difference between the two tibiae. For the isotope study the ratio of specific activity for each tibia compared with the humerus was calculated, and the values were compared by the means of the Wilcoxon signed rank test.

Table 1 Maximal torque capacity, and stiffness of tibiae at different times from rigid internal fixation (F), rigid internal fixation and osteotomy (OF) or sham operation (S). Seven or eight pair of bones were tested in each group

	Experimental groups								Control groups			
Time (wk)	3		6		9		12		12		12	
	F	OF	F	OF	F	OF	S	OF	S	OF	S	F
Torque (Nm)												
Mean	1.70	1.56	2.20	2.84	1.83	2.06	2.31	2.47	2.97	1.94	2.83	1.88
SD	0.76	0.56	0.45	0.51	0.50	0.36	0.33	0.51	0.79	0.52	0.83	0.48
Stiffness (Nm/degree)												
Mean	0.19	0.16	0.22	0.24	0.17	0.20	0.19	0.21	0.20	0.18	0.19	0.16
SD	0.04	0.04	0.07	0.05	0.03	0.02	0.05	0.03	0.07	0.05	0.07	0.05

Results

Radiographically, the osteotomies were still visible at 3 weeks in the experimental group. During longer periods after surgery, the osteotomies exhibited solid healing. There were signs of osteopenia and altered bone structure under the rigid plate of both osteotomized and nonosteotomized tibiae (Figure 1). The osteotomized tibiae also showed evidence of callus formation.

Torsional strength

In the experimental groups the maximal torque capacity of osteotomized and internally fixated tibiae as compared with the contralateral plated side showed great variability at 3 weeks, with some of the bones fracturing through the osteotomy at a low torque while others had a spiral fracture across the osteotomy site (Table 1). At 6 weeks, the osteotomized bones showed a 30 percent increase in strength as compared with the plated side ($P < 0.05$). All the tibiae showed solid union at this time and fractured with a spiral fracture. At 9 and 12 weeks following surgery, the difference between the two sides gradually decreased. In the control groups the plated tibiae were 35 percent weaker than the sham-operated on tibiae ($P < 0.01$). The osteotomized and plated tibiae were also about 30 percent weaker than the sham-operated on bones 12 weeks

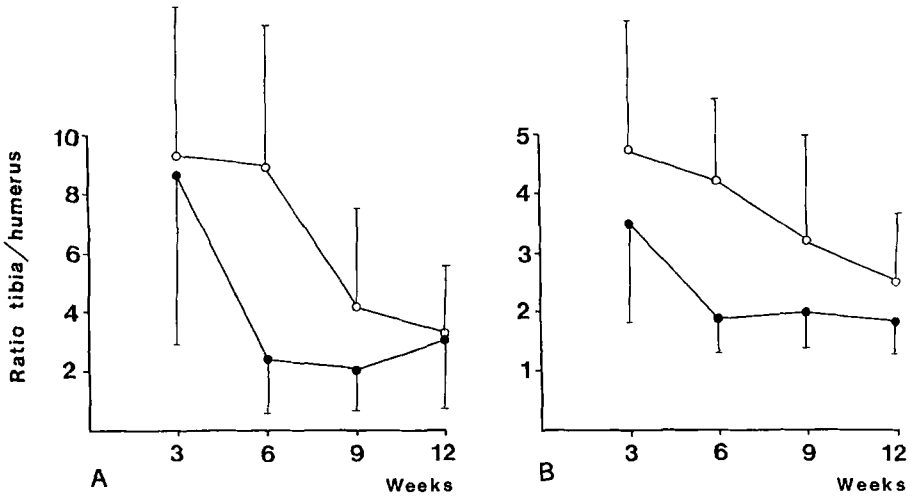

Figure 2. Ratios (tibiae/humerus) of specific activities of the isotopes in the experimental groups. There were 7 to 8 animals in each group. A. Incorporation of ^{3}H-proline. B. Incorporation of ^{45}Ca.
- ○ Osteotomy/Plate
- ● Plate

after surgery ($P < 0.05$). The plated and the sham-operated on tibiae fractured with a spiral fracture, generally through one or two screw holes. There were no differences in stiffness between the tibiae in the experimental groups except in the 3 weeks' group, where the osteotomized tibiae were less stiff ($P < 0.05$).

Isotope incorporation

In the experimental groups, the activity of ^{3}H in both tibiae was about nine times higher than in the diaphysis of the corresponding humeri at 3 weeks (Figure 2). On the plated side, the ^{3}H activity decreased to about twice that of humerus at 6 weeks, and remained at this level at 9 and 12 weeks, while the ^{3}H activity of the osteotomized and plated tibiae remained 9-fold that of humerus at 6 weeks ($P < 0.05$), and they decreased to a index value of four at 9 and 12 weeks. The ratios of both tibiae to the corresponding humeri in the two control groups were between two and four, and did not differ from those of the experimental group at 12 weeks.

The ratios of specific activities of ^{45}Ca in the experimental groups exhibited a similar pattern (Figure 2). The ratios of osteotomized and plated tibiae showed a continuous decay from 4.7 at 3 weeks to 2.2 at 12 weeks. In contrast, the index of plated tibiae was 4 at 3 weeks, but decreased more rapidly to values of about 2 at 6 ($P < 0.05$), 9, and 12 weeks. In the two control groups, the ratios of both tibiae to the corresponding humeri were approximately 2, and did not differ from those of the experimental group at 12 weeks.

Discussion

A rigid internal plate fixation induces porosis and reduced mechanical strength of the underlying bone, and the decrease in strength is proportional to the duration of fixation and the stiffness of the plate (Uthoff and Dubuc 1971, Paavolainen et al. 1978, Låftman et al. 1980, 1988, Terjesen and Benum 1983, Woo et al. 1984). The decrease in strength following rigid internal fixation is a complex process, where the effects of the screw holes and the surgical trauma must be taken into account (Eriksson and Frankel 1985). The lag in increase of metabolism following the trauma further complicates this process (Moyen et al. 1978).

In patients, fracture healing will affect the process of adaptation due to stress protection. Thus, two processes with profound, but opposite, effects on bone metabolism and strength will take place simultaneously. At 3 weeks after plate fixation, there was a great variation in fracture pattern and in strength in the osteotomized bones, indicating incomplete healing of some osteotomies; but the mean torsional strength was equal to that of the control bones. At 6 weeks, the osteotomized tibiae were considerably stronger and stiffer. At 9 and 12 weeks, this difference decreased and disappeared. Thus, in the rabbit the healing of an osteotomy counteracts the effects of unloading by rigid fixation during the healing process, but this effect subsides within 2 to 3 months. This is further supported by the finding of one third decrease in the strength of plated tibiae irrespective of osteotomy when compared with the sham-operated on side in the two control groups.

Incorporation of ^{45}Ca may be taken as a measure of mineral accretion if the distribution of the tracer in exchangeable and nonexchangeable compartments of bone are considered (Bauer et al. 1961, Bauer et al. 1984). Proline is hydroxylated and incorporated into collagen as hydroxyproline. Because collagen is the major protein component of bone, ^{3}H-proline may be taken as a measure of matrix formation (LeBlond and Weinstock 1971, Bauer et al. 1986). The bone formation rates studied with these two isotopes give a measure of mineral accretion and matrix formation in the volume of bone underneath the plate; but by using these methods, it is not possible to discern between bone remodeling, periosteal/endosteal bone formation, or callus formation.

In both control groups and in the 12-week experimental group, the specific activities of both isotopes in tibiae, irrespective of treatment, were two to three times that of humeri. Thus, this rate represents the steady-state incorporation of ^{45}Ca in mineral and ^{3}H-proline in collagen. At 3 weeks the incorporation of the isotopes was increased 2–4-fold above steady-state levels in both tibiae, indicating greatly increased turnover of the bone due to the trauma. Similarly, Sudman and Bang (1979) found an increased haversian remodeling of cortical bone following osteotomy of the ulna. Further, in fracture healing greatly increased incorporation rates of proline and calcium occurs (Shtacher and Firschein 1967). In the present experiment, the increased bone formation was thought to be caused by the periosteal reaction to trauma, by callus formation, and by the metabolic changes induced by the altered stress pattern caused by the plate, but the relative contributions of the different processes cannot be determined.

In conclusion, osteotomy of diaphyseal bone in adult rabbits caused increased matrix formation and mineral accretion, and increased bone strength during the healing process, thus counteracting the effects of stress protection by rigid internal fixation. The bone formation rate returned to normal values within 12 weeks, and the bones exhibited decreased strength due to stress protection by the fixation plate.

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