Acta Orthop Scand 1988;59(5):548–551

Reduced energy absorption of healed fracture in the rat

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Mechanical testing of closed tibial fractures in rat fixed with a medullary nail was performed after 10–80 days of healing. In the three-point bending test, the maximum load at fracture and maximum stiffness of the fracture gradually increased, reaching 81 and 118 percent, respectively, of intact bone values after 80 days. The fracture failed immediately after the maximum load had been reached in contrast to intact bone, where further bending resulted in gradually decreasing load values until failure occurred at 73–85 percent of the maximum load values. Therefore, the resulting energy absorption until load at fracture and until failure of the healing bone was only 33 and 13 percent, respectively, of intact values after 80 days of healing, and thus markedly reduced even though the maximum stiffness and the load at fracture (maximum load) approximated the values of intact bone.

Penttinen (1972) and Ekeland et al. (1981) have pointed out that in rat both tibial and femoral fractures regain the mechanical strength of intact bones after 90 days of healing. However, one important property of the healing fracture has received little attention: viz., the ability to absorb energy during loading, which is a function of both load and deflection. Mølster et al. (1987) measured the energy absorption in femoral fractures after reaming of the medullary canal and found reduced values of energy absorption even after 25 weeks of fracture healing.

We have studied the strength of healing tibial fractures and corresponding intact bones with special reference to maximum stiffness, deflection, and energy absorption at fracture, both at maximum load and at failure.

Materials and methods

Fifty-six, 90 day-old, 300-gram male Wistar rats were used. The animals were anesthetized with 50 mg/kg, i.p. pentobarbital. A 1-cm incision was made on the anteromedial aspect of the proximal part of the right tibia. The incision was carried through to the bone, and a 1-mm hole was drilled 4-mm proximal to the distal aspect of the tibial tuberosity and 2-mm medial to the anterior ridge. No reaming of the medullary canal was performed. To insure a tight fit of the medullary nail, a test nail was tried out in the canal. With specially designed adjustable forceps with blunt jaws (modified from Ekeland et al. 1981), a closed fracture was performed in the tibiofibular bone by three-point bending 2 mm above the tibiofibular junction. To minimize soft-tissue damage, care was taken not to displace the fracture. Closed medullary nailing was performed with a 0.8-mm stainless steel tube (maximum load 36 N, deflection at maximum load 2.53 mm, maximum stiffness 61.8 N/mm, tested under the same conditions as the bones). The skin was closed with monofilament nylon sutures. Radiographs of all the fractures were taken immediately after nailing, and animals with fractures outside the specified diaphyseal area or displaced nails were excluded. The remaining animals were randomized into four groups for testing after 10, 20, 40, and 80 days of healing. Unprotected weight bearing was allowed; the animals usually resumed normal activ-

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Figure 1. Fractured tibiae in rat. A Immediately after osteosynthesis, B after 10 days, C 20 days, D 40 days, and E 80 days.

ity immediately after recovering from anesthesia. During the healing period, there was a steady increase in the body weight of the animals.

Before testing, the animals were anesthetized with pentobarbital and killed by exsanguination. Both tibiofibular bones were removed by dissection, and the bones were stored in Ringer's solution (cooled to +4 °C and buffered to pH 7.4) for a maximum of 2 hours until testing. Radiographs of all the fractures were taken (Figure 1). The fibula was resected, and the intramedullary nail was then removed. The bone was placed on two rounded bars with a distance of 15 mm in a materials testing machine (Alwetron 250, Lorentzen and Wettre, Stockholm). The mechanical properties of the bones were analyzed by a destructive three-point bending procedure. The deflection rate of the cross head was constant (2 mm/min). The left unfractured tibia was tested at the same level of the bone as the fracture in the corresponding right tibia using exactly the same procedure, including resection of the fibula. The load and deflection were recorded continuously by transducers coupled to measuring bridges, and the signals were fed to an x-y recorder. The load-deflection curves obtained were read by a digitizer into a calculator, and the following parameters were calculated (Figure 2): maximum stiffness, load at fracture (maximum load), deflection at fracture, energy absorbed at fracture, load at failure, deflection at failure, and energy absorbed at failure (Oxlund and Andreassen 1980).

Of the 56 rats used for the experiment, 23 were excluded; 7 had the fracture outside the specified area, 9 had bending or fracture of the intramedullary nail; 2 had infection around the nail and marked bone resorption; 2 developed pseudoarthrosis; for 3 rats, technical failure in the test set-up destroyed the results.

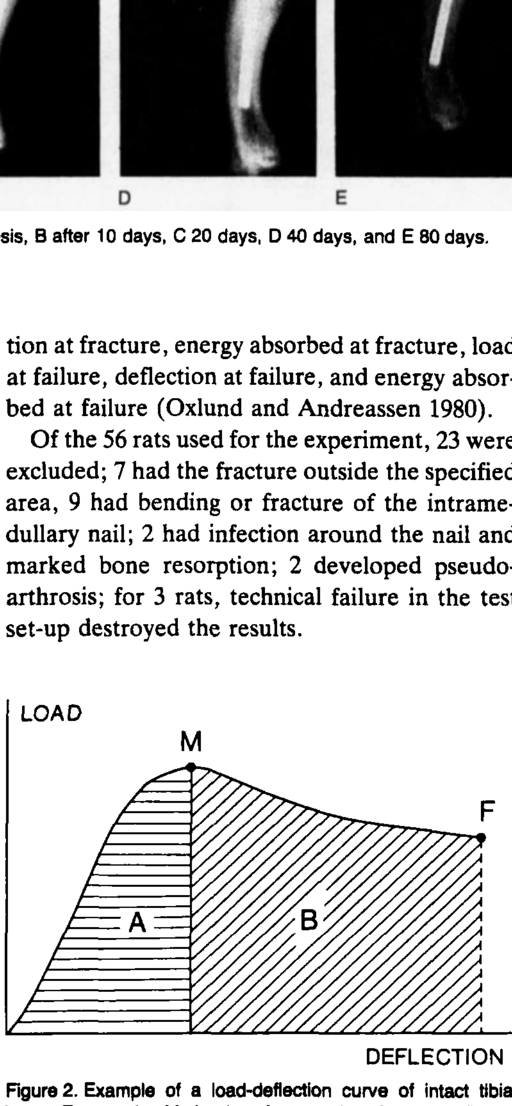

Figure 2. Example of a load-deflection curve of intact tibial bone. From point M, load at fracture (maximum load) and deflection at fracture are calculated. From point F, load at failure and deflection at failure are calculated. Area A represents the energy absorbed at fracture. Area A + area B represent the energy absorbed at failure. Maximum slope of the curve is equal to maximum stiffness.

When achieving normal distribution and homogeneity of variance (G1, G2, Kolmogorov-Smirnov's test and F-test), the fracture groups were tested against the corresponding intact groups with the Student's t-test. In case of inhomogeneity of variances, Wilcoxon's nonpaired two-sample test was used (Sokal and Rohlf 1981); $2\ P < 0.05$ was considered significant.

Results

During bending, the intact bone showed a characteristic load-deflection pattern with steadily increasing load values until fracture (maximum load) was reached. Further bending resulted in a gradual decrease in load values until failure suddenly occurred. Load values at failure ranged from 73–85 percent of load at fracture (Table 1). After 10 and 20 days of healing, bending resulted in increasing load values until fracture, after which the load slowly decreased without any distinct point of failure. The fractures possessed little mechanical strength compared with corresponding values of intact bone, whereas the deflection at fracture increased considerably.

After 40 and 80 days of healing, bending resulted in increasing load values until fracture, and the healing bone failed immediately thereafter (Table 1, Figure 3). Both load at fracture and maximum stiffness had now reached values not different from values of intact bone, whereas the energy absorbed in the healing bone at fracture and at failure was reduced considerably compared with the corresponding values of intact bone. The deflection at fracture and at failure of the healing bone was markedly reduced compared with that of intact bone.

Discussion

Mechanical testing of long bones may be performed by bending, tension, torsion, compression, or shear tests. The first three tests are the most commonly used. Ekeland et al. (1981) showed that these methods reflect the same pattern of strength development during healing with respect to load at fracture and maximum stiffness.

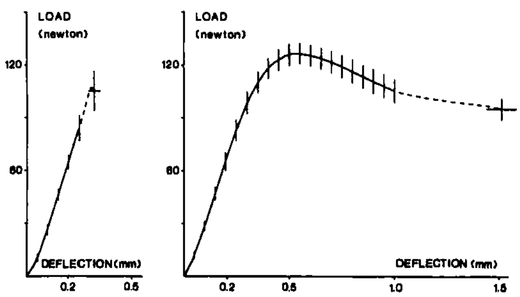

Figure 3. Load-deflection curves for fractured (A) and intact (B) tibiae after 80 days of healing. Mean values ± SEM are shown for load at each deflection increment of 0.05 mm. The dotted part of the curve represents values where failure has taken place in some of the healing or intact bones. The load at failure ± SEM and the deflection at failure ± SEM terminate the curves.

Table 1. Mechanical tests after 10, 20, 40, and 80 days of healing. Mean values (SEM), are given

	Number	Max. stiffness ($N \times mm^{-1}$)	Deflection at fracture (mm)	Load at fracture (max. load) (N)	Energy at fracture ($N \times mm$)	Deflection at failure (mm)	Load at failure (N)	Energy at failure ($N \times mm$)
10 days:								
Intact	8	191 (14)	0.60 (0.05)	75 (4)	30.4 (3.0)	1.26 (0.12)	64 (5)	76 (7)
Fractured	8	5.1 (0,3)**	2.58 (0.13)**	7 (0,5)**	7.8 (0.6)**			
20 days:								
Intact	8	307 (33)	0.60 (0.03)	112 (8)	43.4 (2.7)	1.20 (0.13)	93 (9)	100 (12)
Fractured	8	31.9 (7.3)**	1.02 (0.22)**	16 (2.0)**	8.3 (1.7)**			
40 days:								
Intact	6	369 (71)	0.58 (0.04)	134 (19)	51.2 (7.3)	1.23 (0.13)	110 (16)	119 (14)
Fractured	6	374 (108)	0.37 (0.05)*	92 (27)	16.8 (4.5)**	0.37 (0.05)**	91 (27)	17 (5)**
80 days:								
Intact	11	367 (25)	0.55 (0.02)	128 (6)	48.1 (4.0)	1,51 (0.08)	93 (6)	147 (9)
Fractured	11	435 (22)	0.32 (0.03)**	107 (11)	15.9 (3.1)**	0.32 (0.03)**	105 (11)	19 (3)**

* $2P$ 1.< 0.05, ** $2P < 0.01$ compared to corresponding intact values.

Tibial fractures in rat are usually considered healed in 90 days when strength has reached values of intact bone (Penttinen 1972). Our experiment emphasizes that even after 80 days of healing in the rat tibia, when load at fracture and stiffness have normalized, the ability of the fracture to absorb energy is still markedly reduced compared with intact bone. This is in agreement with Panjabi et al. (1977), who in torsional testing of rabbit long bone found reduced energy absorption until fracture, even though torque capacity was approaching and torsional stiffness had surpassed values of corresponding intact bones after 56 days of healing.

The properties of healing bone thus have a resemblance to skin wound healing (Marangoni et al. 1966, Doillon et al. 1985); even after one half to 1 year of healing, the orientation of collagen fibers in the skin wound is irregular, although the diameter of the fibers are equal to that of intact skin (Levenson et al. 1965, Doillon et al. 1985).

When mineral deposition takes place in bones, the collagen fibers are responsible for the orientation and size of the mineral crystals and thereby for the strength and rigidity of the skeleton (Boskey 1981). Mølster et al. (1987) showed that the fiber direction in the experimental osteotomy gap after 8 weeks differed from intact bone by being mainly in parallel to the osteotomy line. Therefore, one explanation of the different load-deformation patterns of healing fractures and intact bones in our experiment might be a different orientation of the collagen fibers in the fracture zone giving a different orientation of the mineral crystals compared with intact bone.

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