Effects of intramedullary reaming and nailing of rat femur

A mechanical and chemical study

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This study was undertaken to explore the association between mechanical and chemical effects of intramedullary reaming and nailing. The right femora of 80 rats were reamed and nailed with steel nails. Forty rats were evaluated from 3 days to 24 weeks postoperatively. The other 40 rats had the nail removed after 12 weeks, and they were then followed from 3 days to 24 weeks after nail extraction. Evaluation consisted of in vivo strain recording, geometric measurements, mechanical three-point bending test, and chemical analyses of hydroxyproline and calcium contents.

Reaming and nailing caused immediate weakening of the bone as measured by in vitro mechanical tests, but within 3 weeks the mechanical properties were fully restored, whereas in vivo strain remained reduced throughout the experimental period in rats with nails. Removing the nail increased in vivo strain to a level close to that of the intact femur. Remodeling of the bone resulted in greater external anteroposterior diameter, cross-sectional area, area moment of inertia, and amount of hydroxyproline and calcium in the operated on femur as compared with the intact side. This indicates that the repair processes resulted in greater bone mass of the operated on femur than of the intact femur. Thus, there is evidence that nailing techniques effectively assist tissues by repair and remodeling.

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Intramedullary nailing impairs stiffness and strength of bone (Wang et al. 1981, 1985, Kaartinen et al. 1985, Mølster et al. 1986). We have reported reduced in vivo strain immediately after nailing and reversal to normal values at nail removal 12 weeks postoperatively (Husby et al. 1989a, b). On this basis, it would be of interest to study the possible restoration of mechanical properties after the nail has been removed and to relate mechanical findings to chemistry of the bones.

We have explored the immediate and long-term effects of intramedullary reaming and nailing of the unfractured rat femur with the nail in situ and after nail removal.

Materials and methods

Eighty male Wistar rats (Mol: WIST, Møllegaard Breeding Center, Ejby, Denmark), 10 groups of 8 animals, were used (Figure 1). Half of the animals were followed from 3 days to 24 weeks after reaming and nailing. In the remaining 40 rats, the nail was extracted 12 weeks after implantation, and the animals were evaluated for the following 24 weeks. To minimize the influence of age, adult rats (20 weeks old) were selected for this study, as the mechanical and chemical properties of rat femur differ with age (Indrekvam et al. 1991a, b). The median body weight was 412

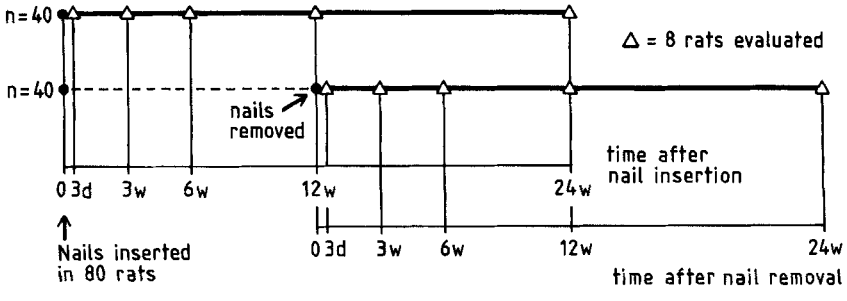

Figure 1. Experimental design. Operation procedures, numbers of animals in each group, and the times of mechanical and chemical evaluation.

(404–424) g at the start of the experiment. The animals were given a standard maintenance rat diet (RM1 Expanded, Special Diets Services, Witham, England) and water ad libitum.

The animals were operated on under inhalation anesthesia. Postoperative analgesia was managed by buprenorphine-hydrochloride injected subcutaneously whenever needed. Nails were made of Kirchner wires (Medicon, Tuttlingen, Germany). The nail diameter was 1.8 mm, length 30 mm, and the stiffness was about 1.4 times that of intact femur in the rats of the actual age as measured by the three-point bending test.

The proximal end of both femora was exposed, and the top of the greater trochanter was excised with a rongeur. The right medullary cavity was entered and reamed with cylindric cutting reamers of diameters increasing to 1.82 mm. The nail was inserted intramedullary with about 2-mm proximal protrusion. The marrow of the left femur was kept intact. The fascia and skin were closed with polyamide sutures. Radiographs were taken to ensure correct position of the nails. Unprotected weight bearing was allowed. The nails were extracted with a pair of pliers after a similar approach to the proximal end of the femur. A sham operation was performed on the left side this time as well.

Three days before killing the animals, a single element strain gauge (0.6/120 LY 11, Hottinger Baldwin Messtechnik, Darmstadt, Germany) was implanted on the anterior surface of both femoral diaphyses of each rat in the 3 days', 6 weeks', and 24 weeks' evaluation groups of nailed rats and in the corresponding three groups after removing the nails. Construction of the strain-gauge units, implantation, and recording of strain have been described in details previously (Husby et al. 1988). Strain in the axial direction was recorded on the second and third postoperative days while the rats were running on a treadmill at a speed of 10 m/min. Peak values of strain (maximum deformation) of 30 walking cycles were measured, and the mean value was calculated. Also the stride frequency was measured. The animals tolerated the operation procedures well. The function of the limbs appeared normal during strain-gauge recordings. Nine of 96 gauges had to be excluded because of electrical malfunction; however, the gauges were uniformly distributed among the groups. The rats were killed on the last day of strain recording by exposure to carbon dioxide gas.

Excised femora were mechanically cleansed of soft tissue, and the femur length and diameters were measured with a sliding caliper. Cross-sectional area and the area moment of inertia at the location of the strain gauge were estimated assuming the femoral diaphysis as having the shape of a hollow ellipse as described previously (Indrekvam et al. 1991a). The femora were kept moist, and three-point bending tests with a span of 14 mm were performed within 3 hours with an Instron® 1193 machine (Husby et al. 1988). Each femur was deflected at a speed of 10 mm/min until fracture occurred. Stiffness was calculated from the initial, linear portion of the load/deflection curve. Ultimate load was recorded.

The collagen content was measured by analyzing the hydrolyzed bone for hydroxyproline in an amino acid analyzer (Biotronik Aminoacid Analyzer LC 7000, Wissenschaftliche Geräte GmbH, Frankfurt, Germany) with an integrator (Spectra Physics SP 4200 Computing Integrator, San Jose, CA, U.S.A.; Indrekvam et al. 1991b). To measure collagen synthesis, ^{14}C-proline (15 μCi/100 g body weight) was injected intraperitoneally 24 h before killing the rats. The specific activity of ^{14}C-hydroxyproline was calculated as the ratio between labeled and total hydroxyproline. Radioactive emission from hydroxyproline was measured in a beta-counter (Wallac 1217 Rackbeta Liquid Scintillation Counter, Turku, Finland). Calcium analyses were carried out by means of continuous-flow spectrophotometry (Technicon SMAC System, New York, N.Y., U.S.A.). Mineralization was expressed as the calcium/hydroxyproline ratio.

Statistics

All the variables are presented as absolute values for operated on femur and as the ratio between the operated on and the intact femur. Median values with 0.25 and 0.75 fractiles were used to express the average and the dispersion of the measurements. The Wilcoxon signed rank test was applied to test for differences of medians from 1.00, and was considered significant when $P < 0.05$ (Minitab, Ryan et al. 1985).

Results

No nails had migrated or were loose at the time of extraction. Further, there was no difference in growth in length between the two femora during the experimental period. The median length was 37.5 (36.9–37.9) mm at the beginning of the study and 40.8 (39.7–42.0) mm at the end. At the 3 weeks' evaluation, a thin fibrous and bony layer was visible around the nails in four of the right femora; and from 6 weeks on, such a thin layer was observed around all the nails.

The internal diameters naturally increased after reaming the femur ($P = 0.02$); but from 12 weeks postoperatively, there was no difference between the

Table 1. External and internal anteroposterior diameter, cross-sectional area, and area moment of inertia of intramedullary nailed rat femora. Ratio of intact femur and absolute values are given. Median and 0.25–0.75 fractiles

	Time after operation				
	3 days	3 weeks	6 weeks	12 weeks	24 weeks
After nail insertion					
External diameter					
(ratio)	0.99 (0.98–1.00)	1.01 (1.01–1.03)*	1.00 (0.99–1.01)	1.03 (0.99–1.04)*	1.04 (1.02–1.06)*
(mm)	3.2 (3.2–3.3)	3.5 (3.4–3.6)	3.6 (3.3–3.6)	3.6 (3.6–3.7)	3.9 (3.7–4.1)
Internal diameter					
(ratio)	1.05 (1.02–1.09)*	1.11 (1.05–1.13)*	1.02 (1.00–1.10)*	1.04 (1.01–1.07)	1.03 (0.99–1.11)
(mm)	1.9 (1.8–1.9)	1.9 (1.9–1.9)	1.8 (1.8–1.8)	1.8 (1.8–1.8)	1.8 (1.8–1.8)
Cross-sectional area					
(ratio)	0.94 (0.93–0.97)*	1.00 (0.97–1.02)	0.98 (0.96–1.00)	1.04 (1.02–1.09)	1.03 (0.93–1.09)
(mm^2)	1.8 (1.7–1.9)	2.2 (2.1–2.2)	2.2 (2.0–2.2)	2.4 (2.3–2.5)	2.7 (2.6–2.8)
Area moment of inertia					
(ratio)	0.93 (0.92–0.96)*	1.04 (1.00–1.07)	0.99 (0.98–1.04)	1.09 (0.96–1.14)	1.08 (1.04–1.12)*
(mm^4)	6.2 (6.0–6.7)	8.6 (8.3–9.9)	9.1 (7.2–10.2)	10.3 (9.5–10.4)	13.1 (11.5–14.7)
After nail removal					
External diameter					
(ratio)	1.02 (1.00–1.03)*	1.01 (0.99–1.02)*	1.04 (1.02–1.06)*	1.01 (1.00–1.02)*	1.01 (1.00–1.02)*
(mm)	3.6 (3.6–3.8)	3.8 (3.6–3.9)	3.9 (3.7–3.9)	3.8 (3.7–3.9)	4.1 (3.9–4.1)
Internal diameter					
(ratio)	1.03 (1.02–1.04)	1.02 (1.00–1.06)	1.02 (1.00–1.08)	1.00 (0.98–1.04)	0.97 (0.94–1.00)
(mm)	1.8 (1.8–1.8)	1.8 (1.8–1.8)	1.8 (1.8–1.8)	1.8 (1.8–1.8)	1.8 (1.8–1.8)
Cross-sectional area					
(ratio)	1.03 (0.97–1.05)	1.01 (0.99–1.03)	1.05 (1.01–1.09)*	1.05 (1.01–1.08)*	1.05 (1.01–1.07)*
(mm^2)	2.4 (2.2–2.5)	2.5 (2.4–2.8)	2.4 (2.4–2.8)	2.7 (2.5–2.9)	3.0 (2.8–3.2)
Area moment of inertia					
(ratio)	1.06 (1.01–1.11)	1.04 (0.97–1.07)	1.13 (1.02–1.10)*	1.06 (1.02–1.10)*	1.05 (1.00–1.09)*
(mm^4)	10.0 (9.2–12.0)	11.9 (10.0–13.5)	11.5 (10.1–13.6)	12.4 (11.3–13.5)	16.1 (13.2–16.5)

* Ratio statistically different from 1.00.

two femora (Table 1). From 3 weeks postoperatively, a larger external anteroposterior diameter was measured in the operated on femur compared with the intact one ($P = 0.04$), although there was no significant difference at 6 weeks (Table 1). There were no differences between the two femora with respect to the external mediolateral diameter.

Cross-sectional area and the area moment of inertia followed similar trends during the experimental period. Initially, there were reduced cross-sectional area ($P = 0.01$) and area moment of inertia ($P = 0.02$) in the reamed femur (Table 1). Normal values were regained within 3 weeks. At the 24 weeks' evaluation, the nailed group had greater geometric values, and thus a higher area moment of inertia than the controls ($P = 0.04$; Table 1). From 6 weeks after nail removal (18 weeks postoperatively), the cross-sectional area and the area moment of inertia were higher in the operated on femur than in the intact one ($P = 0.04$; Table 1).

Peak strain of nailed femora was reduced as compared with the intact ones ($P = 0.04$ to 0.02), but any difference with time elapsed since nail insertion could not be documented. Removing the nail caused an immediate increase in strain to a level close to that of the intact femur. The median stride frequency when running at the treadmill was 1.8 (1.7–1.9) stride/s, and there were no differences between the groups in this respect.

Three days postoperatively, stiffness and ultimate load (structural strength) were reduced in the operated on femur compared with the intact femur ($P = 0.02$ and $P = 0.01$). Within 3 weeks, both variables had reached the level of the nonoperated on femur, and followed the natural slow increase with age during the rest of the experimental period (Indrekvam et al. 1991a).

Hydroxyproline in the operated on femur was reduced 3 days after reaming and nailing ($P = 0.04$), but within 3 weeks normal levels were regained. From 6 weeks after removal of the nails (18 weeks postoperatively), hydroxyproline and calcium contents were higher in operated on femora than in intact ones ($P = 0.04$), although there were no significant differences at 12 weeks. We did not identify any difference between the right and left femur as to mineralization of the bone. Specific activity of ^{14}C-hydroxyproline was 3 days postoperatively 0.82 of the intact femur ($P = 0.04$). Three weeks later, the specific activity of the operated on femur was 1.4 times that of the intact one

($P = 0.02$), indicating a higher rate of collagen synthesis. From 6 weeks postoperatively and throughout the rest of the experimental period, the specific activity of ^{14}C-hydroxyproline was not increased in the nailed group. After removing the nail, an initial high rate of collagen synthesis occurred in the operated on femur ($P = 0.02$). Within 3 weeks, the specific activity stabilized at the same level in the two femora.

Discussion

Implants for osteosynthesis will, together with the bone, form one composite mechanical system. Because the elastic modulus of steel is higher than that of bone, the pattern of stress and strain will change. The immediate strain reduction of about 45 percent after reaming and nailing in our present study was less than we found in a previous study (Husby et al. 1989a), probably because the animals in our present study were older. Thus, stiffness of the bone was closer to that of the nail, and consequently less unloading of the bone occurred. In vivo strain reduction during plate fixation (Manley et al. 1982) and external fixation (Matushek et al. 1989) of canine hindlimbs have demonstrated higher unloading of the bone than intramedullary nailing produced in rats. Conclusions should not, however, be drawn from comparison of experiments on different species.

Bone loss due to reaming resulted in a thinner corticalis and smaller amount of collagen in operated on than in intact femora 3 days after nail insertion. These changes explain reduced mechanical properties expressed as stiffness and strength of the bone, which accord with the findings of Mølster (1986).

The low collagen synthesis rate in the operated on femur 3 days after nail insertion may be due to the vascular damage caused by reaming. Three weeks after reaming and nailing, however, the collagen synthesis was 1.4 times that of the intact femur, and the amount of hydroxyproline apparently had then become normal. The mechanical properties were not reduced compared with the nonoperated on femur, which in addition to the restored bone mass may be explained by an increased external anteroposterior diameter. Restored mechanical properties support the findings of Kaartinen et al. (1985), but is at variance with reduced strength found by Mølster (1986). In the latter study the rats were younger, but a nail diameter identical with that of the present study was used. Consequently, the relative importance of initial damage from reaming and nail stiffness may be different from our study. Further, differences in bone metabolism and composition between animals at different ages may have influenced the results.

Six weeks postoperatively, in vivo strain on the surface of the anterior mid-diaphyseal femur was still reduced despite remodeling processes. Apparently, bone remodels to maintain a physiologic strain pattern that differs from that of femora without implants (Cook et al. 1982).

Reduced mechanical properties have been reported after implantation of steel nails in both osteotomized and nonosteotomized bone (Wang et al. 1981, 1985, Kaartinen et al. 1985, Mølster 1986). This has been ascribed to osteoporosis as a consequence of stress protection by the implant, as well as to revascularization. Intramedullary nails are considered load-sharing devices, and associated stress-shielding should theoretically be minimal. In our study, mechanical properties were of the same magnitude as those of the nonoperated on femur 24 weeks after nail insertion. This accords with a comparable study in rats by Mølster (1986), but differs from Kaartinen et al. (1985), who reported reduced strength after 24 weeks in nonosteotomized rabbit tibia. The difference between the latter study and our results may be related to different species, bone tested, load-sharing effect of the nail, or testing procedures.

Increased amounts of nonmineralized collagen during 2–7 months of immobilization of a nontraumatized bone and reversal after reambulating the limb have been reported (Mechanic et al. 1986). In our study, no reduction in minerals or mineralization (calcium/hydroxyproline ratio) was found during the period when nails were implanted, indicating that stabilization with an intramedullary nail allows sufficient load bearing to prevent osteoporosis.

In vivo strain was of the same magnitude as that of the intact femur when nails were removed 12 weeks postoperatively in this and in a previous study (Husby et al. 1989b). This corresponds to normal calcium and hydroxyproline values, and indicates that no significant osteoporosis had developed.

Load-induced dynamic deformation is assumed to produce equilibrium between resorption and formation; but in the case of healing of an osteosynthesized bone, either may dominate. Apparently, bone formation outweighed resorption in our rats. Neither the contents of collagen and calcium nor the mechanical properties differed between the operated on and intact femur at the time of nail removal.

From 6 weeks after removal of the nail, cross-sectional area and the area moment of inertia were higher than in the intact femur. The amounts of hydroxyproline and calcium also indicated increased bone mass. The increase in ultimate load was not statistically significant. Thus, it seemed as if the result of stimulation to repair and remodeling of bone mass in the operated

on femur overcompensated the geometry of the intact femur.

Intramedullary reaming and nailing of the unfractured rat femur immediately caused weakening of the bone and reduced in vivo deformation. New bone formation restored mechanical properties within 3 weeks. The strain-gauge recordings revealed reduced deformation throughout the period of nailing; but after extraction of the nail, no decrease in the mechanical properties could be demonstrated. Thus, nailing techniques seem to promote a natural sequence of repair and remodeling without major bone loss.

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