Immediate strain shielding after femoral reaming and nailing

An in vivo study in rat femora

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Following intramedullary reaming and nailing of rat femora, in vivo changes in dynamic strain were correlated with in vitro measurements of the bones. Reaming and nailing procedures were performed 2 days after implantation of unidirectional strain gauges at the anterior, mid-diaphyseal level of the femur. Structural stiffness of polyacetal nails were three times as stiff as intact bone. Reaming only decreased the median strain value by 26 percent, and this value was not reduced by insertion of polyacetal nails. Steel nailing reduced the strain by 74 percent. Tested by three-point bending, reaming increased stiffness by 5 percent at the anterior aspect. The presence of nails gave stiffness values that were 9 percent (polyacetal) and 56 percent (steel) higher than the reamed only condition. Our results indicate that steel nailing following reaming causes marked reduction in strain at the anterior, mid-diaphyseal surface, whereas reduction in strain caused by polyacetal nails is negligible.

Contrary to the concentrated stress protection caused by a rigid plate, the central position of intramedullary nails is believed to place less load on the implant and more on the surrounding cortical bone (Fielding et al. 1974). Mølster (1986) reported that rigid intramedullary nails, compared with flexible nails or no nails, were associated with lower values of bone strength and energy absorption (toughness) after 6 months. We report the immediate effect on in vivo strain in rat femora by intramedullary reaming and by flexible and stiff intramedullary nails. Furthermore, corresponding alterations in stiffness were evaluated in vitro.

Table 1. Design of experiment

Group	n	Days after strain-gauge implantation				
		0	1	3	4	5
A	9	G	I	IR	I	I K M
B	9	G	I	IR + P	I	I K M
C	9	G	I	IR + P	I	I K M
D	6					G M R

G Gauge implantation. I In vivo strain recording. R Reaming. P Polyacetal nails. S Steel nails. K Killing. M Mechanical testing.

Materials and methods

Experimental design

Twenty-seven 8-week-old male 229–280 g Wistar rats were used. The rats were caged separately and given water and standard animal pellets ad libitum. Strain-gauge units were implanted in right femora. Two days later, the animals were randomized and operated on in groups of 9 (Table 1): A) reaming of the medullary cavity only; B) reaming and insertion of polyacetal nail; C) reaming and insertion of a steel nail. The immediate effect on stiffness caused by reaming only was measured in an in vitro study (Group D) using untreated left femora from Group A. In addition, structural stiffness was measured on six polyacetal nails, six steel nails, and six intact femora from 8-week-old rats.

Strain gauge

The strain measuring unit consisted of a strain-gauge element, two wires, and a connector. The overall di-

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mension of the gauge was 3.2 x 5.0 mm. The resistance grid measured 0.6 x 1.0 mm. The resistance was 120.5 ohms, and the K-factor was 1.90 (0.6/120 LY11, Hottinger Baldwin Messtechnik, Darmstadt, FRG). The voltage applied to the gauge was 1.5 V. During measurements the strain gauge was included in a full bridge circuit, connected to a DC amplifier (MGT 231, Hottinger Baldwin Messtechnik, Darmstadt, FRG). The output from the amplifier was recorded on a DC tape recorder (Model 3964A, Hewlett-Packard, USA).

Nails

The nails were 30 mm in length with a diameter of 1.8 mm. Stiff nails were made of solid stainless steel and had a median structural stiffness of 817 (743-846) N/mm, as measured by a bending test (Mølster 1986). Flexible nails were made of polyacetal (Zellamid®, Zellmetal, Zell am See, Austria), with a median stiffness of 23 (22-24) N/mm. Intact femora had a median stiffness of approximately 285 (218-322) N/mm.

Strain-gauge implantation

Under anesthesia, the right femoral shaft was subperiosteally exposed through a lateral, longitudinal incision. The bone surface at the implantation site was washed with Ringer solution, dried slightly with argon, and pretreated with an adhesion promotor (Scotchbond, EM, St. Paul, MN 55144, USA). The gauge was glued to the anterior surface of the femoral shaft with a methymethacrylate-based adhesive (X 60, Hottinger Baldwin Messtechnik). The upper lateral corner of the gauge was positioned at the site where the trochanteric edge merges with the shaft. The measuring grid of the gauge was positioned parallel to the long axis of the femur in order to measure the strain component in this direction. The strain gauge and the soldered junctions were coated with a resin (Enamel Bond System, 3M). A 5-mm incision was made in the skin of the rat's neck, just distal to the ears. The connection wires were passed through a subcutaneous tunnel made from the incision to the implantation site. Fascia and skin were closed with polyamide sutures (Dexon, Davis + Geck Inc., Manati, PR 00701, USA). The neck connector was fixed to the skin by suturing.

Reaming and nailing

Under anesthesia the right femoral shaft was approached through the incision made 2 days earlier. The top of the greater trochanter was excised with a rongeur, and the medullary cavity was entered using a spherical 0.8-mm dental bur. The medullary channel was reamed with cylindric cutting reamers with increasing diameters up to 1.8 mm. The nails were introduced from the greater trochanter and driven close to the distal epiphyseal plate. The fascia and skin were closed with polyamide sutures, and unprotected weight bearing was allowed. The animals tolerated the operations well. They regained normal gait on the first day after gauge implantation or reaming and nailing. No limp was observed. Signs of mechanical loosening of the gauges were never observed. All the strain gauges functioned throughout the experiment except five, which showed pronounced electrical disturbance or no signals at all (Table 2).

Preparation of ground sections

Ground sections through the gauge were made from two femora of Groups B and C. The specimens were embedded in PMMA resin, ground on silicon carbide paper, polished with 1-μ alumina paste, and cleaned in an ultrasonic cleaner. Ground sections of nailed femora showed a tight fit between the nail and cortical bone in the region of the strain gauge. A triangular gap was seen between the distal third of the nail and the bone in the posterior region (Figure 1).

Table 2. Median strain values (x 10^{-6}) recorded in vivo days 1, 2, 3, and 4 after implantation of strain gauges (lower-upper quartiles)

		No reaming/nailing		Reamed/nailed	
		Day 1	Day 2	Day 3	Day 4
A		422 (324–473)	375 (317–480)	300 (231–330)	317 (251–370)
	n	9	9	9	9
B		321 (271–376)	316 (260–375)	244 (212–279)	297 (195–314)
	n	9	9	9	9
C		321 (308–336)	322 (298–339)	90 (72–118)	85 (80–104)
	n	9	9	9	7

Group A Reamed. Group B Reamed, polyacetal nail. Group C Reamed, steel nail.

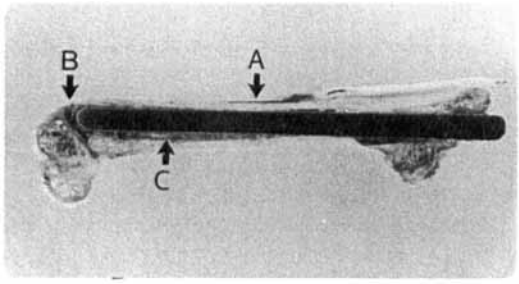

Figure 1. Longitudinal ground section of the femur through center of strain gauge (A). The distal end of the nail is driven close to the distal epiphyseal plate (B). A gap is seen between the distal third of the nail and the bone in the posterior region (C).

Table 3. Median stiffness ($mN/10^{-6}$) values of rat femora tested in vitro (lower-upper quartiles)

Group	n		
A	9	Reamed only 15 (12–20)	
B	9	With nail 19 (17–24)	Nail removed 17 (15–22)
C	9	With nail 27 (21–35)	Nail removed 17 (15–20)
D	6	Intact 16 (13–20)	Reamed 17 (14–21)

Group A Reamed. Group B Reamed, polyacetal nail. Group C Reamed, steel nail. Group D Intact, reamed.

In vivo measurements

In vivo measurements

Strain measurements were made while the rats were walking on a treadmill running at a speed of 10.2 m/min. Measurements were taken for 1 min each day. The peak-to-baseline strain value of 30 walking cycles was measured from each recording, and the arithmetic mean values were calculated. This value represented absolute changes in dynamic strain at the compressive side during walking (Husby et al. 1988).

Mechanical testing

The animals were killed with an overdose of ether 2 days after the reaming-nailing operation. The right femora in Groups B and C, and both femora in Group A were dissected free from soft tissues and placed in a moisture chamber with the implanted strain-gauge unit intact. Bones with the nails in situ were subjected to a three-point bending test within 3 hours. Strain was measured with the same equipment as used during the in vivo measurements. By embedding the distal end of femur in a small amount of methyl methacrylate-based cement, an exact repositioning at retesting was achieved. The supporting bars of the testing jig were 13 mm apart, and the bone was positioned in the jig with the crosshead opposite the grid of the strain gauge. Thus, applied bending induced tensile strain. Bending was applied at a crosshead speed of 0.5 mm/min up to a load of 5 N, which was well within the elastic range of the bone (Mølster 1986). Stiffness was calculated from the linear part of the load/strain curve. Immediately after the first tests in Groups B and C, the nails were removed and the femora were retested. Strain gauges were glued to six of the untreated left femora in Group A, and bending tests were performed. After reaming, testing was repeated. These femora constituted Group D.

Presentation of data

All the results are presented as median values with upper and lower quartiles. The three experimental groups were compared by the Kruskal-Wallis test for independent samples, and each group was tested versus each of the others by the Wilcoxon two-sample test. Further, paired differences between measurement obtained on 2 successive days were tested versus zero by the Wilcoxon one-sample test. A P-value < 0.05 was considered significant.

Results

In vivo

Median strain values obtained at Days 1 and 2 ranged from 316 to 422 x 10^{-6} (Table 2) with no difference between Days 1 and 2. The strain values were reduced by reaming only or reaming followed by nailing, most pronounced for Group C, followed by Groups A and B. With reaming only, there was a median decrease in the strain at Day 3 of 26 percent ($P < 0.01$) compared with the measurements at Day 1. For polyacetal nails, reduction in strain was 25 percent ($P < 0.01$) and for steel nails 74 percent ($P < 0.01$). Strain values for the reamed and the polyacetal groups did not differ.

In vitro

After the nails had been removed in Groups B and C, there were no differences in values of the reamed bones. Reaming only (Group D) increased stiffness by 5 percent compared with intact bones. The presence of nails gave values 9 percent (polyacetal) and 56 percent (steel) higher than the reamed only condition ($P < 0.05$, Group D; $P < 0.01$, Group B; $P < 0.01$, Group C; Table 3).

Discussion

In a previous study, unidirectional strain gauges were implanted in intact rat femora (Husby et al. 1988). Daily strain recordings showed reproducibility for 5 days, indicating that the trauma caused by implanting the gauges did not affect the peak strain values. No influ-

ence on peak strain values was observed when the walking speed of the animals ranged from 6 to 15 m/min. Moreover, strain recordings obtained with replacement gauges agreed within 5 percent of the recordings with gauges implanted for 1 week. The results presented in this study were also based on unidirectional strain-gauge recordings. Strain components parallel to the long axis of the femur at the anterior mid-diaphyseal aspect were recorded. Strain values were recorded from the same gauge before and after reaming and nailing procedures, thus making the strain gauge its own control.

As the nail was driven into the distal epiphyseal plate, and the proximal end protruded outside the bone, the working length of the nail constituted the whole length of the bone (Martens et al. 1972). Further, absence of locking screws implied that axial strain protection depended on the friction between the nail and the remaining endosteal wall of the bone. However, due to the horizontal positioning of the rat femur, the forces acting upon the bone produced compression on the anterior aspect at the mid-diaphyseal level. The slight posterior convexity of the femoral shaft probably contributes to this distribution of forces.

Reduced strain after reaming may be caused by lower walking load due to pain. However, all the animals appeared to regain normal gait on the first day after gauge implantation as well as after the reaming and nailing procedures. Moreover, no differences were observed between recordings at Days 1 and 2 in any group, or between recordings at Days 3 and 4 for the nailed groups. The notion that reduced strain in vivo following reaming may not only be caused by restricted weight bearing is supported by our in vitro results that the stiffness at the anterior cortical wall of the reamed only group was slightly higher than that of intact bone. The in vitro measurements of this group were, however, not contrary to the findings of Mølster (1986), who reported that the femoral structural stiffness decreased about 20 percent following reaming. The elliptical shape of the medullary cavity of the femur at the mid-diaphyseal level caused asymetric removal of bone mass during reaming; the neutral axis of the cross section was altered, and the regions of maximum compressive and tensile strain were displaced. The reduction in in vivo strain values following reaming could therefore be caused by a combination of reduced walking load due to pain and an altered distribution of stress and resulting strain. However, all the femora were reamed in the same manner in this respect. Thus, the differences in strain values between the nailed groups and the reamed only group represent the effect of intramedullary nails of different quality: the steel nails reduced the strain by one half at the gauge site, whereas the polyacetal nails had no strain protection effect. The immediate change in strain following steel nailing was in the same range as earlier reports on the effect of medullary implants. Lanyon et al. (1981) reported a 58 percent reduction in compressive strain in the calcar femorale after total hip replacement in sheep. However, the stiffness of our nails relative to that of femur was higher than in most clinical situations, as 13-mm Küntscher nails have about the bending rigidity of human femora (Allen et al. 1968, Martens et al. 1972). Our polyacetal nails increased stiffness by 10 percent. Gilbert et al. (1986) reported flexible intramedullary Ender nailing increased femoral stiffness by about 7 percent, whereas human tibial stiffness increased about 10 percent when external Vidal-Adrey fixators were applied (Terjesen and Benum 1983). Thus, the relationship between structural stiffness of polyacetal nails and intact bone appears to be proper for clinical application of such nails.

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Acknowledgements

We thank E. J. Angelskår Barth for typing the manuscript and Egil S. Erichsen for technical assistance during the mechanical testing. This work was supported by the Norwegian Research Council for Science and Humanities, Grant 13.31.36–067.