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Effects of instability on fracture healing in the rat

The effect of bending and rotational instability on the healing of a femoral osteotomy was studied in rats using intramedullary fixation with nails made of either steel or flexible polyacetal. All osteotomies were made rotationally unstable by reaming the medullary cavity to a diameter wider than the nails. At 16 weeks, four osteotomies had healed, and 17 had not healed. However, bending tests gave higher values for strength and energy absorption in non-unions with flexible as compared to Stiff nails. Rotational instability thus caused a high rate of non-union in the present model, which has given safe healing when the osteotomy has been stabilized for rotation. Flexible nailing increased strength and energy absorption in bones with non-union, but did not affect the incidence of healing.

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Shearing movements are believed to be detrimental to bony union (Pauwels 1935, Küntscher 1950, Seligson et al. 1982, Mølster et al. 1983), although few authors have provided strong experimental evidence for this assumption (Yamagishi & Yoshimura 1955, Mindell et al. 1971). Flexibility is believed to stimulate new bone formation and thus improve healing of fractures (Braden et al. 1973, Brown & Mayor 1978, Greiff 1981, Wang et al. 1981, Sarmiento et al. 1977, Sarmiento et al. 1980, Latta et al. 1980, Mølster et al. 1982). Experiments were therefore undertaken to evaluate the effect of rotational instability, with and without additional bending instability.

Material and methods

Animal preparation

Twenty-one male Wistar rats (median body weight 382 g) were anesthetized with fentanyl-fluanixone. After shaving, the middle portion of the left femur was approached through a lateral incision between the lateral vastus and hamstring muscles. The top of the greater trochanter was excised with a rongeur and the medullary cavity was entered from this site with a 0.8 mm spherical dental bur. The medullary cavity was then reamed with cylindrical cutting reamers up to 1.7 mm, and an osteotomy was made with a fine-toothed circular saw under saline irrigation. The saw was 0.1 mm thick, had a diameter of 19 mm, and rotated at 800 rev/min. The osteotomy was made transversally and placed immediately distal to the third trochanter. An intramedullary nail was introduced from the greater trochanter to the osteotomy level, the osteotomy was reduced and the nail was driven into the distal fragment. The nail was prevented from sliding upwards by a 0.4 mm stainless steel cerclage through its upper end and around the femur. There was virtually free rotation at the osteotomy site in all animals. The wound was irrigated with saline, sprinkled with penicillin powder and closed with dexon sutures in fascia and skin.

Unprotected weight bearing was allowed as soon as the animal recovered from anesthesia. Recovery was uneventful and no signs of suffering were observed during the experimental period, even when non-union occurred. Function of the operated limb was regained within a few days. There was no infection.

Nails

Two types of nails were used and the rats were allocated into two corresponding groups. Both types were 30 mm long with a diameter of 1.6 mm. One type was made of solid stainless steel with a stiffness of approximately 600 N/mm as measured by our bending test. The other type was made of polyacetal (Zellamid 900, Zellmetall, Austria) with a stiffness of 19 N/mm. Intact femora had a stiffness ranging from approximately 600 N/mm to approximately 770 N/mm All nails were sanded (1000 grit) to give a uniform surface roughness.

Radiographs were obtained in the anteroposterior and lateral projections at 2-week intervals with the animals in brief general anesthesia The largest callus diameter was measured in both projections of the osteotomized femur. The unoperated femur was measured at the corresponding site. The cross-sectional area was calculated, assuming it to be an ellipse (Mølster et al. 1982). The two callus diameters at the osteotomy site were also measured directly on the dissected specimen, using a caliper. The per cent increase in the operated as compared to the unoperated contralateral side was taken as an expression of callus size.

Mechanical testing

At 16 weeks, the animals were killed with an overdose of ether. Both femora were excised and the nails were removed. The femora were placed in a moisture chamber at room temperature and mechanical testing was performed within 5 h. A three-point bending test was performed, applying bending to the femur in the plane of natural extension. The bones were placed in a jig with two cylindrical, horizontal bars with a diameter of 3 mm, mounted in roller bearings. The distance between the bar axes was 13 mm. The midpoint was a blunt metal edge with an indentation to fit the specimen, moved by the crosshead of a mechanical testing machine (Instron 1193, High Wycombe, England). The femur was placed with the lesser trochanter proximal to, and in contact with, the proximal transverse bar of the jig; this arrangement uniformly placed the point of force application at the level of the osteotomy. Bending was applied at a speed of 10 mm/min until fracture occurred. When a definite fracture could not be recognized, the loading was continued well beyond the point of maximum load.

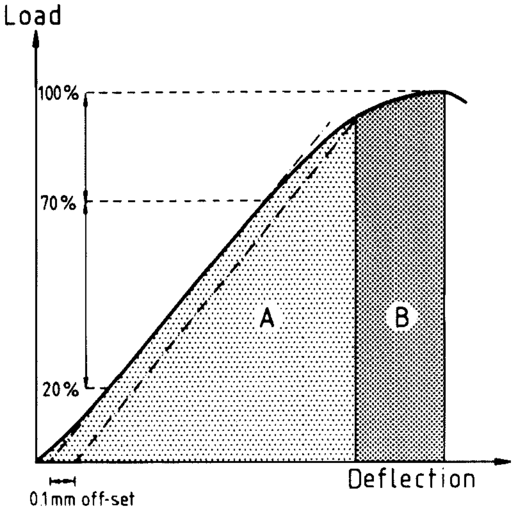

Figure 1. Schematic load-deflection curve. Area A = resilience. A + B = toughness. Stiffness was calculated as the slope between 20 and 70 per cent of maximum load.

Load/deflection curves were recorded and the strength, stiffness and deflection were determined (Figure 1). The maximum load was interpreted as the strength of the bone at the fracture site. Stiffness was calculated as the slope of the curve between 20 and 70 per cent of maximum load value. In testing of nails, the stiffness was measured in the elastic part of the curves. Because of poorly defined fracture points in bones with non-union, deflection was measured to the point of maximum load. Energy absorption was calculated as the area below the curve to the same point (toughness), and also within the apparent elastic range (resilience). The end of the elastic area was defined as the point of 0.1 mm off-set from the first linear part of the curve (Figure 1). Resilience can be interpreted as the maximum energy absorption before permanent structural damage occurs.

Histology

After mechanical testing, the fragments were repositioned, fixed in formaldehyde, decalcified in formic acid for 72 h, dehydrated and embedded in paraffin. Longitudinal 6 μm sections were stained with hematoxylin and eosin or with toluidin blue.

Non-union

Non-union was defined as gross instability of the osteotomy after removal of the nail, no signs of bridging callus on X-rays, and no bone tissue in continuity from one fragment to the other on histological examination.

Statistics

The mechanical parameters were expressed as percentages of the corresponding values of the intact femur. The two experimental groups were then compared using the Wilcoxon two-tailed test for independent samples.

Results

Sixteen weeks after the operation, two of 11 osteotomies in the polyacetal group and two of 10 in the stainless steel group were healed (Figure 2); the remainder were classified as non-unions (Figure 3). Of the four healed os-

Figure 2. Healed osteotomies at 16 weeks after intramedullary nailing with polyacetal (left) and steel (right) nails.

teotomies, three showed radiographic signs of healing after 8 weeks and one after 12 weeks. In all femurs there was full accordance between radiographic examination, histological appearance and manual testing concerning classification as healed or not healed. Strength and energy absorption (toughness and resilience) were higher in the non-unions with flexible than in those with rigid nails (Figure 4, Table 1).

The cross-sectional areas of calcified callus in femora with non-union were highest in the polyacetal nailed femora (Figure 5, Table 1).

Figure 3. Non-unions at 16 weeks after intramedullar nailing with polyacetal (left) and steel (right) nails.

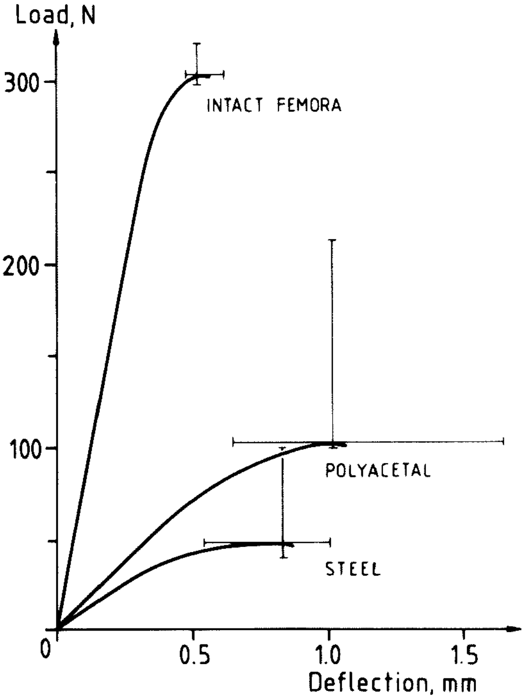

Figure 4. Load-deflection curves representing the median values of non-unions with the two types of intramedullary nailing, and the contralateral intact femur. Vertical and horizontal bars represent interquartile ranges.

Histological examination revealed a distinct zone of new bone surrounding the nail both proximally and distally to the osteotomy site. The healed osteotomies showed bony healing with woven bone and with only a slight tendency to longitudinal orientation of bone trabeculae and lamellae. The non-unions, however, showed an apparently ceased healing process with longitudinal orientation in the periphery of the callus and a random arrangement of trabeculae toward the center.

Discussion

As flexible nailing gave healing with higher values for mechanical properties at 8 weeks in earlier experiments (Mølster et al. 1982), we assumed that flexibility added to rotational instability would produce a higher incidence of healing. The greater callus area in osteotomies with flexible nails suggested an increased stimulus to new bone formation in the present

Table 1. Mechanical properties of osteotomies at 16 weeks. Values are in per cent of unoperated, contralateral femur. Cross-sectional area calculated from measurements directly on specimens. Median value and interquartile range.

	United osteotomies		Significance of difference	Non-united osteotomies	
	Steel group	Polyacetal group		Steel group	Polyacetal group
Number of animals	8	9		2	2
Stiffness	7.6 (4.5–19.2)	18.1 10.7–23.9)	n.s.	54, 101	97, 49
Strength	14.6 (9.7–20)	35.1 (30.9–49.3)	p<0.002	66, 101	92, 78
Deflection	153 (118–230)	211 (172–309)	n.s.	79, 109	127, 83
Toughness	21.8 (8.7–29.2)	83.2 (48.7–106)	p<0.02	48, 86	73, 48
Resilience	29.4 (8.3–37.2)	84.5 (48–91.6)	p<0.002	56, 126	76, 77
Cross-sectional area	253 (228–342)	350 (285–411)	p<0.05	156, 227	247,119

study, but the number of unions was unaffected by the flexibility of the implant. However, the histological appearance of scant new bone formation at 16 weeks postoperatively cannot safely exclude union at a later stage. It is not known whether there is a decisive time limit after which spontaneous healing cannot be achieved.

Even with a rigid nail, some minor movements may have occurred because of the slightly greater diameter of the reamed medullary cavity relative to the nail and the wider distal part of the medullary cavity. Furthermore, the nails were shorter than the femur. However, the contact area in the narrowest part of the medullary cavity was shorter than the nail, so that maximal cortical contact was ensured. Any flexural or *ad latus* instability tends to diminish during the experiment, since a zone of dense bone in contact with the nail is found at histological examination (Kaartinen et al. 1982). A smooth osteotomy line, like the one produced in this study, will enhance the tendency for rotation compared to fractures, due to the lower friction between fragments (Seligson et al. 1982). Furthermore, it appears that healing, even in a stable situation, may show less tendency to periosteal bone production in osteotomies compared to fractures (Jacobs et al. 1982).

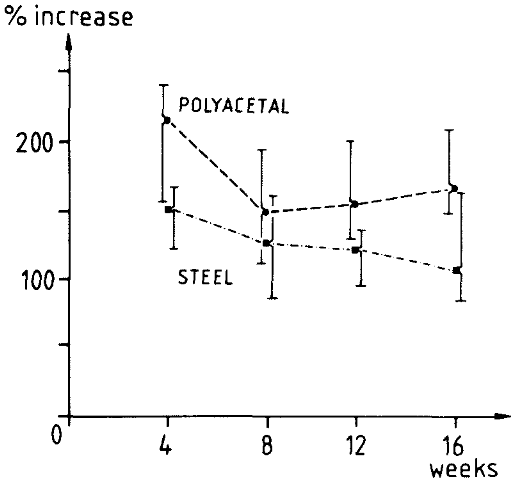

Figure 5. Callus area in non-unions expressed as per cent increase in the operated as compared with the contralateral intact femur.

The relation between rotational instability and delay of union is supported by other experiments which showed safe union in a similar model when stabilized for rotation (Mølster et al. 1984).

The denuding of bone ends and reaming of the medullary cavity may have caused devascularization associated with delay of union (Olerud & Danckwardt-Lilliestrøm 1971, Albrektsson 1982). However, at 16 weeks abundant vascularization was observed adjacent to the osteotomy gap.

The finding that the mechanical properties of non-unions varied with different stiffnesses of the intramedullary nails indicates that even the soft tissues in the non-unions adapt to the mechanical environment.

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