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Effects of rotational instability on healing of femoral osteotomies in the rat

Three different degrees of rotational instability were induced in transversally osteotomized rat femora by means of intramedullary steel nails with various degrees of interlocking. Union was delayed in osteotomies with the greatest rotational instability. The strength, stiffness and energy absorption of the osteotomies at 4, 8 and 16 weeks were also lower in this group. At 25 weeks, the end-point of the experiment, there were no differences in incidence of union or in the mechanical properties between the experimental groups. We conclude that a high degree of rotational instability caused delayed fracture healing.

Anders O. Mølster

Surgical Research Laboratory, Department of Surgery and Department for Dental Materials, University of Bergen, Norway

In a previous experiment, we found that increased bending instability of a diaphyseal osteotomy gave more callus and greater strength (Mølster et al. 1982). On the other hand, rotational instability, though stimulating new bone formation, has been found detrimental to bony union (Cameron 1966, Mølster & Gjerdet 1984). Bending and rotational instability may thus have different effects on the healing process. The present study was undertaken to study fracture healing in different degrees of rotational instability.

Material and methods

One hundred and forty-four male Wistar rats with a median weight of 325 g (upper and lower quartile 337 and 309 g) were used. One rat was excluded because of technical error, leaving 143 rats in the series. They were kept four in each cage, and fed on standard maintenance pellets and water *ad libitum*. The animals were anaesthetized with fentanyl-fluanixone (Hypnorm Vet., Leo, Sweden) 0.10 ml subcutaneously. Reaming, transverse osteotomy and introduction of intramedullary nails into the left femur were then performed as described previously (Mølster & Gjerdet 1984).

The nails were 30 mm long and the diameter of 1.8 mm equalled that of the reamer. The bending stiffness was 801 ± 32 N/mm as measured by our bending test (Mølster & Gjerdet 1984). For comparison, the stiffness of intact femora in rats with the same weight preoperatively as in the present experiment was 357 ± 65 N/mm, and the stiffness of the contralateral unoperated femur of the rats in the present study 25 weeks after the start of the experiment 814 ± 147 N/mm.

The rats were randomly allocated to three groups which were given different degrees of rotational instability.

Group A. The most unstable situation was produced by means of electrolytically polished nails without rotatory locking devices (Figure 1). Retrograde sliding of the nail was prevented by a stainless steel 0.04 mm wire encircling the proximal femur through a notch in the nail. The mean stiffness in rotation was 28 per cent of the stiffness of intact femur, and the strength 5 per cent of intact femur.

Group B. An intermediate degree of instability was produced by locking the distal nail end. For this purpose, the nails were flattened at the distal end (Figure 1). A hole was drilled with a 1.2 mm dental bur through the lateral cortex of the distal metaphysis into the reamed medullary cavity. When the nail was 2–3 mm from the distal end of the reamed intramedullary cavity, a small amount of dental composite (Isopast, Vivadent, Schaan, Lichtenstein) was injected through the hole into the distal femur. The nail was thereafter carefully driven home, and the bone kept immobile during the 3 min hardening time of the composite. The proximal end was provided with a cerclage as in Group A. The mean stiffness in rotation of this osteosynthesis was 37 per cent of intact femur and the strength 18 per cent.

Group C. The most rigid osteosynthesis was made by locking both nail ends. Distal locking was performed as in Group B. For proximal locking, three longitudinal grooves, 4–5 mm long and 0.3–0.5 mm deep, were cut in the nails. Corresponding grooves were made in the bone using a pointed dental bur with the nails *in situ*, and dental composite was injected (Figure 1). Because of the shape of the greater trochanter, only two of the grooves could usually be used for cementing. To ensure an equal circulatory situation

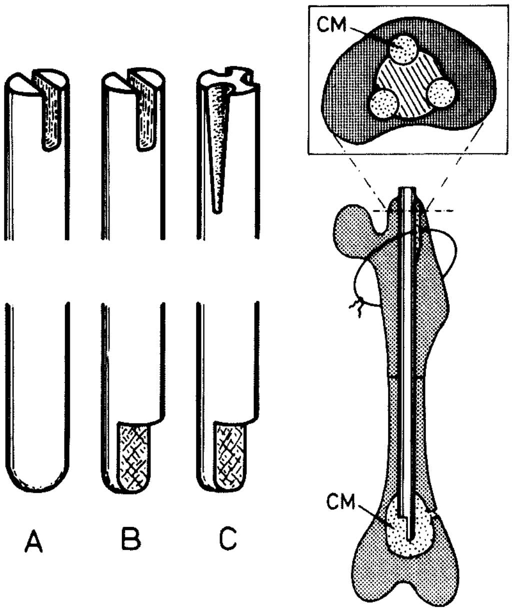

Figure 1. Nail design for different degrees of rotational instability.
A: Round nail for unlimited rotation.
B: Flattened distal end for locking with dental composite.
C: Additional proximal grooves for locking at both ends.
The notch in the proximal end of types A and B allowed passage of the cerclage. The principle for locking nails at both ends by means of dental composite (CM) is shown on the right.

in the proximal femur in the three groups, a proximal cerclage wire was placed around the femur also in Group C, but without passing through the nails. The mean stiffness in rotation was 38 per cent and the strength 34 per cent of intact bone values.

The wound was irrigated with saline, sprinkled with penicillin powder, and closed with Dexon sutures in fascia and skin. The right femur was left untouched.

Unprotected weight bearing was allowed as soon as the animals recovered from anaesthesia. Recovery was uneventful and no signs of suffering were observed during the experimental period, even when delayed union occurred. Macroscopic rotation was seen in some animals during the first few days, but the function of the operated limb was regained without observable delay. There were no infections.

Antero-posterior and lateral radiographs were taken in brief general anaesthesia at 2–7-week intervals and at sacrifice. A selection of groups was made at different time intervals to reduce the number of anaesthesias in each animal. The osteotomized femora were classified as healed or not healed from the radiographs according to the presence of bridging callus (Mølster & Gjerdet 1984).

Twelve animals in each group were sacrificed at 4, 8, 16, or 25 weeks after osteotomy (11 in Group B at 25 weeks). Both femora were dissected free from soft tissues, and the frontal and transverse diameters of the callus and of unoperated contralateral femur at corresponding levels were measured with a sliding caliper. The nails were removed, and the bone specimens were kept in a moist saline chamber until mechanical testing was performed at room temperature within 5 h.

Three-point bending tests were performed, and strength, stiffness, deflection, and energy absorption were determined as previously described (Mølster & Gjerdet 1984).

After mechanical testing, the fragments were repositioned, and longitudinal paraffin sections were prepared for histologic examination after hematoxylin/eosin or toluidin staining.

Statistics

Each osteotomy was classified by time to union, or by time to sacrifice without union; the Lee-Desu survival test was used for comparison of the experimental groups (Hie, N. H. & Hull, H., SPSS update 1981).

The mechanical measurements were expressed as per cent of the corresponding values of the intact contralateral femur. The three groups were then compared by means of the Kruskal-Wallis test for independent samples (Dixon, W. J. (ed.). BMDP Statistical Software 1981) (three-sample test). Each group was then tested against each of the others by the Wilcoxon two-tail test for independent samples (two-sample test).

Results

Group A with the highest rotational instability had a longer time to union compared with the other two groups ($p < 0.0001$). No significant difference in time to union was found between Groups B and C (Figure 2).

Most osteotomies which united during the experiment reached this stage before 12 weeks. However, 5 of 71 osteotomies united after more than 12 weeks, and 2 of 35 osteotomies between 18 and 25 weeks. At 25 weeks, 2/12 osteotomies in Group A and 1/11 in Group B were still ununited (Figure 2).

At 4 weeks all groups had only about 15 per cent of normal *strength* (Figure 3). After this time, strength increased to approximately 75 per cent at 25 weeks. The gain in strength was, however, dissimilar in the three groups. The median strength was lowest in Group A at all intermediate time intervals, with significant group differences at 8 and 16 weeks. At 8 weeks, Group A differed from both the other groups; at 16 weeks the two-sample test revealed differences only between Groups A and B ($p < 0.0005$). There was no difference between the groups at 25 weeks.

A similar development was found for *stiffness* (Table 1), which was lowest in Group A at 4, 8 and 16 weeks. Two sample testing revealed significant differences between Groups A and C at 4 weeks ($p < 0.01$), and between A and B at 8 weeks ($p < 0.005$). There was no significant group difference at 16 and 25 weeks.

The corresponding values for *deflection* differed between the groups at 4 weeks (Table 1).

At 8 and 16 weeks, the energy absorption

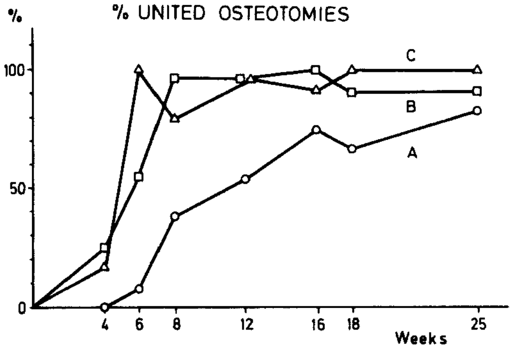

Figure 2. Union as estimated from radiographs. Per cent united of examined animals in each group. To spare the animals from too many anaesthesias, the groups comprising the long-term part of the study were examined at longer intervals. Thus different animals were examined at different points of time, and this explains the apparent increase in ununited osteotomies. Progressing union never regressed to a lower state of consolidation. At all time intervals the numbers of examined animals from each group are identical, giving valid comparison between Groups A–C. At 4, 8 and 12 weeks n = 24, at 6, 16, 18 and 25 weeks n = 12.

Table 1. Mechanical properties and cross-sectional callus area (25, 50 (median) and 75 percentiles) in percent of unoperated contralateral femur. p denotes significance levels obtained by the Kruskal-Wallis test. Groups A, B and C represent different degrees of rotational instability (see text)

	Weeks after osteotomy											
		4			8			16			25	
Stiffness												
A	5.0	*6.1*	9.5	3.4	*12.6*	47.0	43.1	*78.0*	89.2	49.1	*67.4*	96.5
B	6.3	*10.0*	14.0	56.4	*76.4*	100.6	68.3	*97.6*	112.6	55.1	*66.0*	76.9
C	8.2	*16.0*	24.1	32.0	*48.3*	77.1	77.9	*94.5*	111.7	65.3	*81.7*	90.1
p		<0.02			<0.01			n.s.			n.s.	
Deflection												
A	157.5	*230.0*	340.0	56.9	*120.4*	264.6	60.2	*73.4*	91.6	68.2	*84.6*	103.7
B	123.9	*173.6*	200.7	64.5	*76.1*	105.9	65.7	*88.2*	106.3	64.1	*80.7*	105.2
C	76.7	*93.3*	110.9	56.9	*76.2*	97.0	69.5	*76.1*	91.6	69.1	*81.1*	114.6
p		<0.005			n.s.			n.s.			n.s.	
Toughness												
A	17.1	*28.0*	38.8	9.5	*12.2*	16.6	29.2	*38.5*	56.5	34.3	*47.8*	69.0
B	16.4	*26.1*	27.5	33.5	*52.4*	64.1	62.5	*77.0*	87.5	35.2	*51.9*	81.2
C	9.4	*13.6*	36.9	14.0	*30.8*	52.3	36.0	*52.8*	59.6	37.1	*44.6*	70.1
p		n.s.			<0.005			<0.005			n.s.	
Resilience												
A	18.4	*27.6*	37.8	9.9	*12.7*	18.0	35.5	*46.2*	56.7	48.0	*62.2*	81.4
B	12.5	*19.9*	34.9	33.8	*53.1*	72.1	70.1	*87.2*	104.9	50.1	*60.1*	78.3
C	13.8	*18.4*	36.3	17.8	*35.7*	68.8	42.6	*53.5*	74.6	37.8	*54.5*	66.3
p		n.s.			<0.005			<0.005			n.s.	
Area												
A	349.2	*377.1*	461.2	244.9	*290.8*	321.7	134.4	*144.9*	259.0	122.0	*178.8*	197.5
B	336.6	*394.7*	452.7	159.3	*190.7*	239.8	137.3	*149.4*	160.8	122.0	*140.6*	160.5
C	295.0	*323.4*	351.7	169.5	*213.3*	251.7	136.6	*148.6*	164.1	115.5	*126.5*	139.6
p		<0.05			<0.01			n.s.			n.s.	

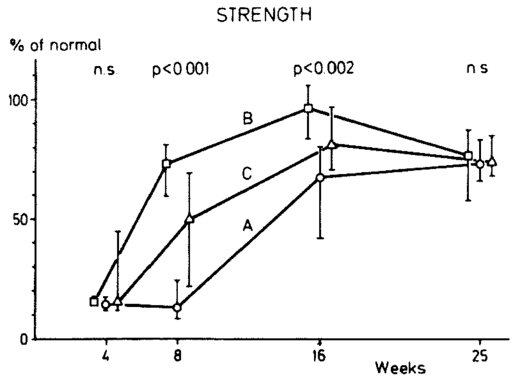

Figure 3. Strength of healing osteotomies at different time intervals expressed as per cent of the values of the unoperated control side. Vertical bars represent interquartile range. *P*-values denote group differences (Kruskal-Wallis).

(*toughness and resilience*) was highest in Group B, intermediate in Group C and lowest in Group A (Table 1). Differences between Groups A and B were significant at both time intervals for both energy absorption parameters. At 16 weeks, the difference between Groups B and C concerning toughness was significant as well ($p < 0.05$). However, the values for all groups merged to a common value at 25 weeks.

The median values for *cross-sectional* callus area were highest at 4 weeks, but declined gradually thereafter (Table 1). In individual osteotomies ununited at later stages, however, high callus area values persisted.

By histologic examination, healed osteotomies showed woven bone in continuity from one fragment to the other. A few osteotomies in Group C had healed by 4 weeks, showing a modified "gap healing" with a transverse arrangement of fibres parallel to the osteotomy line, with none or scarce external callus formation. A more longitudinal arrangement of trabeculae was seen at the latest time intervals.

In ununited osteotomies, signs of a high anabolic activity were seen in the callus tissues in the early phases of healing, characterized by rows of large osteoblasts lining the woven bone trabeculae, large and multiplying chondroblasts with abundant mitoses in the central callus zone, and a high vascularity. Less active bone formation and a more organized lamellar structure was seen even in the ununited osteotomies later than 8 weeks after osteotomy.

Discussion

The detrimental effect of rotational or shearing movements on bony union has been demonstrated experimentally in a few previous reports (Yamagishi & Yoshimura 1955, Anderson et al. 1962, Cameron 1966, Mølster & Gjerdet 1984). Our observation that rotational instability caused delayed union is in accordance with Cameron's (1966) studies on canine femora. He performed oblique osteotomies to stabilize for rotation, which we also did in previous experiments on the rat tibia (Mølster et al. 1982, 1983). The effect of an oblique osteotomy appears to be equivalent to locking the ends of the nail in a transverse osteotomy, as we did. The latter alternative allows, however, a more controlled application and measurement of resistance to rotation, and permits comparison of identical osteotomies with different rotational instability.

The differences in mechanical properties of the healing osteotomies mainly reflected delayed union in Group A. Congregation into almost identical values at 25 weeks indicates that when healing is accomplished, even osteotomies with a late union reach the same level of mechanical properties as those which healed at a normal rate. Strength values at the end of the experiment of about 70–75 per cent of normal are in good accordance with an earlier study with rigid nailing of the tibia. The reduced strength at that time is interpreted as the result of stress shielding (Mølster et al. 1983). Group B, with locking only distally, corresponds to the "dynamic locking" described by Klemm & Schellmann (1972). The high incidence of union at 6 weeks indicates that the friction between the nail and the narrow proximal part of the medullary cavity was sufficient to prevent significant rotation in the osteotomy without proximal locking. The better mechanical properties during the healing process may be due to less axial stress protection (Woo et al. 1983).

It was noted that the median callus area was greatest in the earliest observations, indicating that the callus has a maximal diameter from the time of origin. This gives a maximal area moment of inertia when the callus is soft (Latta et al. 1980, Sarmiento et al. 1980). Delayed reduction of callus diameter in the unstable Group A fits with earlier findings that remodelling is only obtained after bridging of the defect by stable tissue, and reduction in area moment of inertia is correlated with increments in the mechanical qualities of healing tissues (Mølster et al. 1983, Mølster & Gjerdet 1984). The ununited osteotomies in all groups maintained a high cross-sectional area, with a histologic picture of a relatively low rate of new bone formation in the later stages. These observations may be taken as a further support for the theory of delayed remodelling, as well as for the suggestion of McKibbin (1978) that attempts to bridge the fracture gap do not go on indefinitely.

Although most unions occurred within the first 4 months, even in the group with the highest rotational instability, a few osteotomies showed initial signs of union as late as between 18 and 25 weeks. A distinct time limit for identification of a definite non-union could thus not be found in this experiment. Further experiments seem warranted to establish criteria for the identification of a "true non-union".

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