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Graded exchange reaming and nailing of non-unions

Strength and mineralisation in rat femoral bone

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Abstract The effect of graded exchange reaming and intramedullary nailing on a non-union model in the rat femur was studied by clinical, radiological, bone mineralisation and biomechanical methods. A standardised procedure was first developed to create a non-union that did not heal and in which non-union developed consistently. In 30 male Wistar rats a standardised osteotomy was produced in the left femur diaphysis. The fractures were reamed to 1.5 mm and nailed with a soft polyethylene nail for 12 weeks. After 1 week the fractures were manipulated in bending and rotation every 2nd day for 5 weeks. At 12 weeks radiographs demonstrated a hypertrophic non-union in all fractures, and the rats were randomly divided into three groups. In the control group no reoperation was performed (group C). In group 1.6 exchange reaming to 1.6 mm and medullary nailing were performed, and reaming and nailing to 2.0 mm in group 2.0. The effect of extensive versus modest reaming and nailing on bone repair was then assessed 12 weeks later. Physical examination, radiographs, bone mineralisation measurements by dual energy X-ray absorptiometry (DEXA) and biomechanical femures evaluated by a three-point bending test in a Mini Bionix (MTS) testing system were employed. In the control group radiographs revealed a state of non-union in all fractures, and the mechanical strength was significantly reduced compared with both intervention groups. Bone mineral content (BMC) and bone mineral density (BMD) were reduced in the callus region compared with group 2.0. In the intervention groups radiographs showed various degrees of union. Mechanical testing showed that the fracture energy was significantly higher in group 2.0 than in group 1.6. The finding that extensive exchange reaming and nailing seems favourable in non-unions of diaphyseal fractures compared with modest reaming may have clinical implications.

Introduction

Non-union is a relatively common complication in the management of patients with diaphyseal fracture of the long bones [23, 25, 26]. Options for surgical treatment include open cancellous bone grafting and a variety of methods of stabilisation such as external fixation, application of bone plates and intramedullary nailing [1, 2, 21, 27]. The treatment of choice of aseptic non-unions after primary nailing is to perform exchange reaming and nailing [14, 24]. The term describes removal of an intramedullary nail, further reaming of the intramedullary canal, and reintroduction of an appropriate nail. Despite the recent popularity of intramedullary nailing of diaphyseal fractures of the femur and tibia, relatively few studies have dealt with the effectiveness of exchange nailing on healing [23, 26, 28], and no study, to our knowledge, has dealt with the effects of graded exchange reaming on the healing of diaphyseal non-union in the femur or tibia. This may in part be due to the reported good results of exchange reaming and nailing using various degrees of over-reaming [7, 23, 26, 28]. However, knowledge of the effect of modest vs extensive exchange reaming would aid the surgeon in his choice regarding operative treatment, even though most investigators recommend reaming to larger diameter in non-unions than in primary fractures.

The lack of good animal models has unquestionably limited our knowledge about different operative treatments of non-unions. Experimental non-unions are difficult to produce reliably in animals without extraordinary means such as major distraction or large surgical defects [9], as instability at the fracture site tends to heal spontaneously [17]. To our knowledge, no studies have characterised an animal model in rats producing diaphyseal non-unions by interfragmentary manipulation. Our objectives were: (1) to establish a model of diaphyseal fracture in the

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femur such that a non-union would result if the fracture was left untreated, (2) induce healing in the non-union by exchange reaming and nailing, and (3) measure biomechanical properties and mineralisation of the bones in relation to the degree of reaming and nailing.

Materials and methods

Experimental animals

Thirty 16-week-old male Wistar rats (Møllegård Avlslaboratorium, Eiby, Denmark) weighing 316–378 g were used in the experiment. In addition, 10 rats were killed prior to the experiment to obtain dimensional data of the medullary canal. The anteroposterior diameter of the medullary canal at the femoral midshaft was 1.78 (range 1.75–1.82) mm and the transverse diameter 2.20 (range 2.17–2.26) mm (median values with lower and upper quartiles). The anterior cortical thickness was 0.71 (range 0.66–0.74) mm (Fig. 1). The animals were housed two to a cage and received a standard rodent diet (Special Diet Services, UK; R.M. 1) with a calcium content of 0.71% and phosphorous content of 0.5%, and provided with tap water ad libitum. The light cycles were 12 h/12 h. The experiment conformed to the Norwegian Council of Animal Research Code for the Care and Use of Animals for Experimental Purposes.

Treatment regimen

Following intraperitoneal anaesthesia (pentobarbital, 5 mg/100 g body weight, Temgesic 0.3 ml), the left femur was exposed between the lateral vastus and the hamstrings. The muscles were carefully elevated in the lateral part, and an osteotomy engaging the middiaphysis was made with a fine toothed circular saw blade mounted on an electrical drill. The osteotomy was made at the end of the trochanteric ridge approximately 13 mm from the top of the greater trochanter. The medullary canal was successfully reamed from the osteotomy site proximally through the top of the greater trochanter and distally to the level of the condyles to a diameter of 1.5 mm, using steel burrs mounted on the electrical drill. The fracture was reduced, and a soft polyethylene nail with a diameter of 1.5 mm was inserted from the trochanter to the level of the condyles for stabilisation and to keep the medullary canal open. The wounds were closed in two layers. Starting at 1 week the rats were sedated (fentanyl-fluanisone, Hypnorm, 0.1 ml/kg body weight), blindfolded, and the fractures were manipulated every 2nd day for 20 s over 5 weeks. Manipulation consisted of 90° rotation in the medial and lateral directions and anterior and posterior bending of 90°. At 12 weeks radiographs demonstrated hypertrophic non-unions in all fractures (Fig. 2 a). The rats were randomly assigned to three groups with 10 rats in each. In group C (control group) no reoperation was performed to evaluate the potential of spontaneous healing. In group 1.6 a lateral incision was performed over the greater trochanter, and the polyethylene nail was removed. The medullary canal was reamed to 1.6 mm by a closed technique, and a steel pin of 1.6 mm was inserted from the trochanter to the level of the condyles for stabilisation. In group 2.0 the medullary canal was successively reamed to 2.0 mm, and a hollow steel tube of 2.0 mm was installed into the medullary canal. Proper pin placement was confirmed by radiographs taken postoperatively and at the end of the experiment. The wounds were closed in two layers. The steel pin of 1.6 mm and the hollow steel tube of 2.0 mm had a bending rigidity of 757.06 N/mm (757.05–757.18) and 786.86 N/mm (785.61–787.16), respectively (median values with interquartile range of 5 nails of each size).

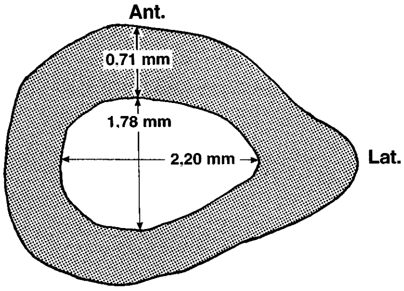

Fig. 1 Cross-section at the midshaft of rat femur with dimensional data

Mechanical testing and DEXA

At 24 weeks after the primary fracture and 12 weeks after the exchange reaming, the rats were killed in a carbon dioxide chamber, and both femurs were dissected free from all soft tissue. The anteroposterior and transverse diameters of the callus region were measured by a sliding caliper (accuracy of 0.01 mm). The callus mass was expressed as total cross-sectional area, assuming it to be elliptical. The bones were subsequently radiographically examined, and the intramedullary devices removed. The bones were stored at –80° C.

Both femurs were examined by dual energy X-ray aborptiometry (DEXA). DEXA was performed on a Lunar DPX (Lunar Corporation, Madison, Wis. USA) equipped with a 4.75 mA X-ray generator and Small Animal software programme. The collimation (size of the X-rax beam at the source) was 0.84 mm, and the sample interval was 1/64 s. The high resolution scan mode had a sam-

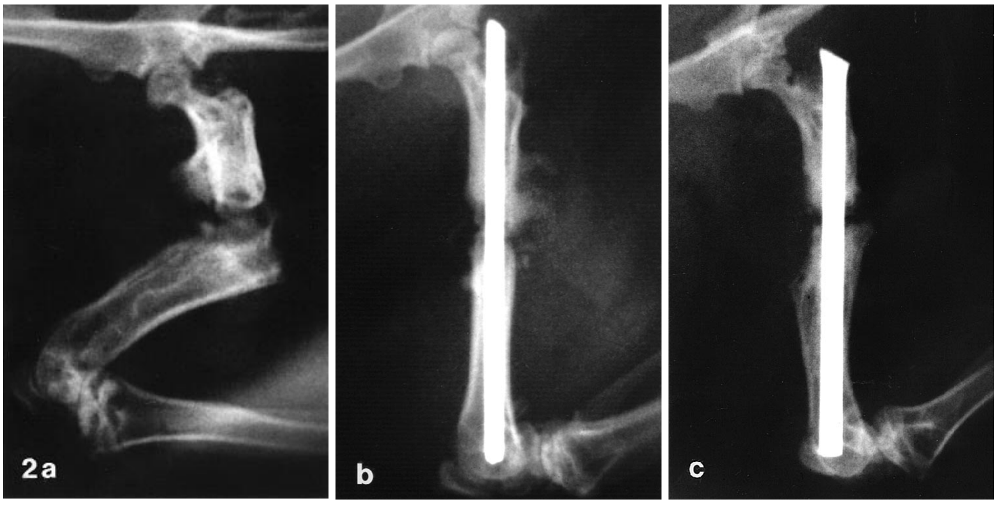

Fig. 2 Radiographs of left femur at 12 weeks in the control group (**a**) and after exchange nailing to 1.6 mm (**b**) and 2.0 mm (**c**)

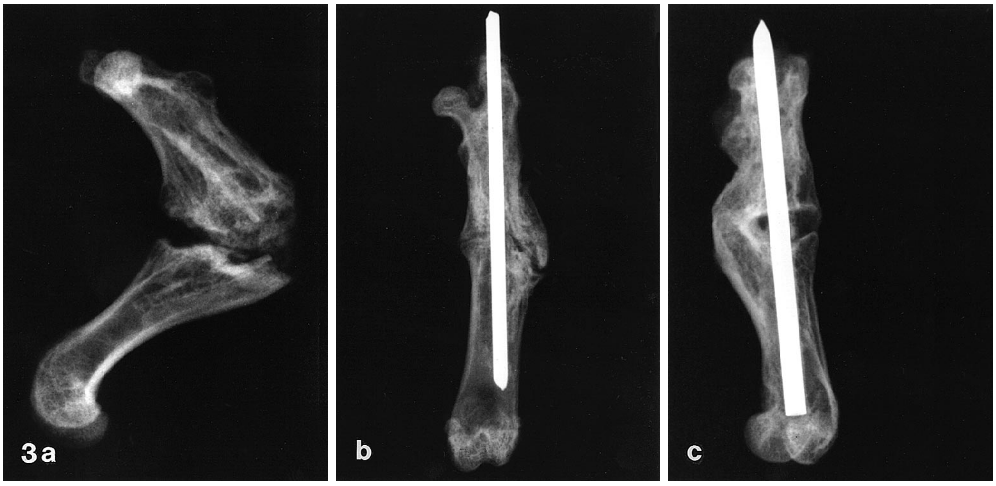

Fig. 3 Radiographs of left femur at 24 weeks in the control group (**a**) and after exchange nailing to 1.6 mm (**b**) and 2.0 mm (**c**)

ple size of 0.15 × 0.3 mm, and a series of transverse scans from the top of the trochanter to the tip of the condyles (scan area of 30 × 40 mm) lasted 7 min for the total femur determination, and giving of 1.92 mrem of radiation. Each femur was placed on a 2 cm lucite off block during scanning. After the scanning procedure a 3 mm region of interest (ROI) was measured between 12 and 15 mm from the top of the greater trochanter, corresponding to the callus region in the left femurs. One right femur in the control group was scanned ten times for the determination of the reproducibility of the method. The coefficient of variation for the mean value of ten DEXA measurements was 3.7% for bone mineral content (BMC) and 1.8% for mid-diaphysis and total femur and 2.4% and 1.2% for bone mineral density (BMD), respectively.

The specimens were placed in a moisture chamber at room temperature prior to mechanical testing. A three-point bending test was performed, applying bending in the plane of natural extension. The bones were placed in a jig with two horizontal bars with a diameter of 3 mm, mounted on roller bearings. The distance between the bar axes was 13 mm. The midpoint was a blunt metal edge moved by the crosshead of a mechanical testing machine (Model 852.02 Mini Bionix Test System, MTS Systems Corporation, Minn., USA). The femur was placed with the lesser trochanter proximal to and in contact with the proximal transverse bar of the jig. This arrangement placed the point of force application over the fracture site at the end of the trochanteric ridge, which corresponds to the narrowest part of the medullary cavity in young rats. However, when the femur had angular or rotational deformities, an approximation of this arrangement was made, as the bone was placed in a stable position to avoid slippage under testing. Bending was applied successively as determined by the degree of strain (ductility) of the femur by Test Star software programme. Observation of stress and strain was recorded for strain values at every 0.05 mm, and stress/strain curves were made as bone strength, structural stiffness (rigidity) and fracture energy were determined. The maximum bending load (Newtons) at the fracture point was interpreted as the strength of the bones. Structural stiffness or rigidity (Newtons per mm deflection) was calculated as the linear slope of the curve between 20% and 70% of maximum load value. Fracture energy (Newton-mm) was calculated as the area under the curve to the fracture point.

The results are presented as median values with lower and upper quartiles. The values in the three experimental groups were compared by the Kruskall-Wallis test for independent samples. When statistically significant differences were found, the group was tested against each of the others by the Mann-Whitney U-test, and the Wilcoxon signed rank test was used to compare the left and right femurs in group C. The level of significance was set at $P < 0.05$.

Results

All rats tolerated the initial operation well and resumed walking during the 1st postoperative day, and partial weight-bearing after 1–2 weeks. Recovery after exchange reaming and nailing at 12 weeks was uneventful. At the end of the experiment, one animal in the control group was excluded due to slippage of the femur during testing and one animal in the 1.6 group, due to proximal migration of the pin.

Radiographs taken at 12 weeks demonstrated hypertrophic non-unions in all fractures with various degrees of angular misalignment (Fig. 2 a). No bridging callus over the fracture gap could be found. At the end of the experiment

Table 1 Cross-sectional area of callus/proximal and distal diaphysis (mm^2); maximum bending load (N), bending rigidity (N/mm) and fracture energy (Nmm); bone mineral density (BMD) and content (BMC) of left (fractured) and right femur in control group at 24 weeks ($n = 9$, median and 0.25 and 0.75 quartiles, *P* value between 6 and 12 weeks)

	Left femur	*P* value	Right femur
Callus/mid-diaphysis area	97.45 76.94–120.31	0.001	21.42 20.37–22.51
Bending load	83.75 64.41–91.33	0.001	298.01 258.96–326.66
Bending rigidity	42.13 40.39–67.08	0.001	874.34 847.59–977.75
Fracture energy	62.72 47.76–67.26	0.01	89.92 74.53–108.24
BMC callus/ mid-diaphysis	0.046 0.033–0.059	0.29	0.056 0.053–0.060
BMC total femur	0.707 0.637–0.886	0.71	0.734 0.682–0.771
BMD callus/ mid-diaphysis	0.261 0.228–0.278	0.004	0.334 0.308–0.343
BMD total femur	0.318 0.254–0.338	0.49	0.289 0.279–0.300

Table 2 Cross-sectional area of callus region and maximum bending load (N), bending rigidity (N/mm) and fracture energy (Nmm) of left (fractured) femur in control group and after exchange nailing to 1.6 and 2.0 mm at 24 weeks (median and 0.25 and 75 quartiles; *boxes P* value between groups)

<table>
<tr><th></th><th>Control
(*n* = 9)</th><th></th><th>1.6 group
(*n* = 9)</th><th></th><th>2.0 group
(*n* = 10)</th></tr>
<tr><td>Callus area</td><td>97.45
76.94–120.31</td><td></td><td>79.34
71.75–93.30</td><td></td><td>87.63
78.94–93.14</td></tr>
<tr><td></td><td colspan="5">0.001</td></tr>
<tr><td></td><td></td><td>0.02</td><td></td><td>0.05</td><td></td></tr>
<tr><td>Bending load</td><td>83.75
64.41–91.33</td><td></td><td>172.15
129.03–207.77</td><td></td><td>217.59
202.98–246.88</td></tr>
<tr><td></td><td colspan="5">0.002</td></tr>
<tr><td></td><td></td><td>0.01</td><td></td><td>0.23</td><td></td></tr>
<tr><td>Bending rigidity</td><td>42.13
40.39–67.08</td><td></td><td>129.04
119.26–140.60</td><td></td><td>185.44
112.48–253.65</td></tr>
<tr><td></td><td colspan="5">0.01</td></tr>
<tr><td></td><td></td><td>0.01</td><td></td><td>0.02</td><td></td></tr>
<tr><td>Fracture energy</td><td>62.72
47.76–67.26</td><td></td><td>118.48
100.77–129.80</td><td></td><td>136.95
124.72–149.73</td></tr>
</table>

Table 3 Bone mineral content (BMC; g/cm^2) and bone mineral density (BMD; g) in the callus region and total left (fractured) femur in control group and after exchange nailing to 1.6 and 2.0 mm at 24 weeks (median and 0.25 and 0.75 quartiles; *boxes P*-value between groups)

<table>
<tr><th></th><th>Control
(*n* = 9)</th><th></th><th>1.6 group
(*n* = 9)</th><th></th><th>2.0 group
(*n* = 10)</th></tr>
<tr><td></td><td colspan="5">0.01</td></tr>
<tr><td></td><td></td><td>0.60</td><td></td><td>0.09</td><td></td></tr>
<tr><td>BMC callus</td><td>0.046
0.033–0.059</td><td></td><td>0.054
0.030–0.077</td><td></td><td>0.079
0.065–0.082</td></tr>
<tr><td>BMC total femur</td><td>0.707
0.637–0.886</td><td></td><td>0.914
0.750–1.150</td><td></td><td>0.759
0.674–0.857</td></tr>
<tr><td></td><td colspan="5">0.003</td></tr>
<tr><td></td><td></td><td>0.16</td><td></td><td>0.19</td><td></td></tr>
<tr><td>BMD callus</td><td>0.261
0.228–0.278</td><td></td><td>0.287
0.258–0.347</td><td></td><td>0.344
0.321–0.357</td></tr>
<tr><td>BMD total femur</td><td>0.318
0.254–0.338</td><td></td><td>0.341
0.302–0.367</td><td></td><td>0.277
0.256–0.339</td></tr>
</table>

at 24 weeks, X-ray revealed a persistent non-union in the control group (Fig. 3 a). The collar of callus tissue was increased peripherally, but still no bridging of the fracture zone was apparent. The interfragmentary area had narrowed, but a radiolucent interfragmentary zone was clearly visible with misalignment of the fracture. In the 1.6 and 2.0 groups closure of the osteotomy gap with different degrees of bridging callus was observed (Fig. 3 b, c).

The calculated callus area in the control group had substantially increased at 24 weeks in the fractured bones, compared with the right (unoperated) femurs (Table 1). All mechanical features were significantly reduced in the fractured bones. Bone mineralisation in the total femur was equivalent on the left and right sides, while BMD in the callus region was significantly reduced in the fractured bones.

Comparing the three groups, we found no differences in calculated callus area ($P = 0.68$), while the mechanical features in the control group were significantly reduced compared with the intervention groups (Table 2). In the 2.0 group fracture energy was significantly higher than in the 1.6 group, while there were no significant differences in bending force and rigidity between the intervention groups.

Bone mineral content and density were significantly reduced in the callus region in the control group compared with the 2.0 group, while no differences were detected between the 1.6 and 2.0 groups (Table 3).

Discussion

The experimental model designed for this study provides a functional method for producing non-union. An osteotomy in the femur diaphysis, reamed and nailed with a soft polyethylene nail prior to manipulation, resulted in non-union in all animals at 12 and 24 weeks. Clinical examination at 12 weeks revealed significant instability between the fracture fragments, and radiologically no bridging callus could be found (Fig. 2 a). Evaluated mechanically at 24 weeks, all bones in the control group had significantly reduced values and a radiolucent interfragmentary zone (Fig. 3 a). Hence these fractures are called “non-unions", as we consider them incapable of spontaneous healing.

Other investigators have addressed the subject of producing an animal model with non-unions. Lindholm et al., using 35-day-old rats of 130 g, noted that tibial fractures always healed when the manipulations were stopped [17]. However, young rats have a better fracture healing potential than mature rats [10, 16], and maturity of cortical bone in Wistar rats occurs late in life, at about 14 weeks, corresponding to a body weight of 350 g [11]. Furthermore, interfragmentary manipulation consisted of manual bending, while we exercised manipulation in both bending and rotation. These differences in experimental set-up may well explain the different results in the experiments. Einhorn et al. [9] described a standardised procedure creating a large diaphyseal defect in rat femur treated with external fixation in which non-union developed consistently as evaluated by clinical, radiological and biomechanical methods. The model seems well suited for experimental studies of non-unions with bone defects. More recently, a model based on open, rotationally unstable, intramedullary nailing of femoral fractures in rats has been described as producing non-unions in nearly 100% of all cases [13].

In the present study the bones were subjected to testing in bending. The angular misalignment of the bones in the control group made exact mounting in the grips impossible for torsional testing of the fractures. The four-point bending test is a preferred method for determining the mechanical characteristics of sharply shaped structures, because it is more accurate than the three-point bending test as the position of maximum moment covers a larger area. However, the fracture callus had an irregular shape, especially in the control group. Therefore, in four-point bending, as the cross head moves down to apply force at two points on the bone, the two wedges do not come into contact with the bone surface simultaneously. In our initial trials we found that the greater theoretical accuracy of the four-point bending method was negated by this error, and that a three-point bending test would be more accurate. The test was performed by applying bending in the plane of natural extension. Placing the bone in a jig with two horizontal bars with a distance of 13 mm between them, the bones were laid firmly with the lesser trochanter proximal to, and in contact with, the proximal bar of the jig. However, for bones in group C certain modifications were made during testing. These bones with angular misalignment were placed on the bars with the angle in the horizontal plane and closely observed during force application by the cross head to avoid slippage. This arrangement makes the exact mechanical values for each bone in group C less certain than for the intervention groups.

One of the early responses of bone to trauma is an increase in the rate of mineral turnover, and many investigators have reported a significant reduction in bone mass after fracture of the long bones in humans, not only at the fracture site, but also at adjacent sites both proximal and distal to it [3]. This persists after union, but there is a wide range in both the amount of loss and the extent of recovery. These differences may, in part, be due to variable accuracies of the measuring techniques [19]. DEXA is an accurate, reproducible and non-invasive technique for measuring mineral density. The potential diagnostic benefits of DEXA include relating normal and abnormal patterns of healing to changes in bone mineralisation, both at the fracture gap and in the proximal and distal segments of diaphyseal bone [3]. Measurements of bending rigidity of newly formed callus correlate closely with the mineral to matrix ratio of the repair tissue [4], and DEXA measurements of both BMC and BMD of bone have a strong correlation with ash weight and the calcium content [6, 18].

Exchange reaming and nailing of non-unions have been studied in both tibial and femoral fractures. Most authors recommend reaming to a larger diameter and installation of a thicker nail than used in the primary operation. However, the exact degree of over-reaming is defined differently, or there is no specific information about the subject. Good or excellent results have been reported [22, 23, 25, 26] with 93%–96% healing followed by weight-bearing and full function within 3-7 months using various degrees of over-reaming and thickness of nails. Court-Brown et al. treated 33 patients with non-unions by reaming 1 mm more than the original reaming, with successful results in closed and open tibial fractures of Gustilo types I, II and IIIa [7]. Taylor also recommends "the next larger nail" [24].

Radiographs at 12 weeks revealed a state of non-union in all control rats with varying degrees of angular misalignment (Fig 2 a). Misalignment was in most cases pronounced (around 60°), and no bones had less than 20° of angulation. Hence, re-nailing at 12 weeks corrected the axis in the bone and provided apposition of the bone ends. Alignment and apposition of the fracture fragments as in the 1.6 and 2.0 groups have beneficial effects on the fracture healing process [2, 15, 21, 27], suggesting both exact positioning of the "non-union" and nailing as factors determining healing in groups 1.6 and 2.0. In questioning the relative influence of each of these two factors, the investigation gives no clear answer, but repositioning and nailing were done identically in the two groups.

In comparing modest over-reaming (equivalent to the anteroposterior diameter of the femoral canal as the medullary canal has an ellipsoid shape) with extensive reaming (corresponding to the lateral diameter of the isthmic region of femur) we used 16-week-old rats. The measured dimensions correspond to the narrowest part of the medullary canal in young rats. However, during aging the outer cortical diameter of bone increases, and the cortical wall becomes thinner. This results from combined effects of increased endosteal resorption and periosteal bone formation [12]. Thus, the dimensions of the medullary canal have probably increased at the time of re-operation (28 weeks old), and therefore the degree of over-reaming in the 1.6 group was relatively modest.

The fracture energy in the 2.0 group was significantly higher than in the 1.6 group, indicating more favourable conditions for healing after extensive reaming. However, the mineralisation values both in the callus segment and in the total femur were similar in the groups. On the other side, both groups 1.6 and 2.0 had increased mechanical characteristics compared with the control group, as well as higher BMC and BMD in the callus segment for the 2.0 group. These results indicate that repositioning of the fracture and exchange reaming to both degrees stimulate healing of the non-union. Increased mineralisation in the callus, at least for extensive reaming, may in part be the mechanism behind this enhanced healing.

There are three possible reasons for the success of exchange reaming and nailing in general and increased healing after extensive reaming in particular. These include increased stability offered by the larger nail, the osteoinductive properties of reaming particles and osteogenetic effect of mechanical reaming. The positive effect of increased stability upon healing in non-unions is well documented [2, 14, 21, 27]. By exchange nailing to 1.6 mm steel nail, a substantial increase in stability is provided, and the larger bone-nail contact area offered by the 2.0 mm nail may further increase this stability. However, whether this represents a net gain in terms of healing is less certain as both axial and bending instability within a certain range tend to be conductive, while rotational instability is detrimental to fracture healing [5, 20].

The osteoinductive effect of reaming particles is an important aspect in fracture treatment, and intense new bone formation can be observed around the reaming dust, if it is surrounded by vital tissue [15]. On the other hand, the reaming dust represents a large amount of necrotic particles and microsequestrae, especially following extensive reaming, if they are deposited in devitalised zones of the medullary canal or non-union. From these considerations, the reaming dust in the 1.6 group may have an osteoinductive effect, but it is uncertain whether further reaming represents a gain in healing. Danckwart-Lilliestrøm [8] documented an important reason for the success of exchange nailing by showing that the reaming of an intact medullary canal caused the formation of periosteal new bone. This accounts for the common finding of increased periosteal new bone formation after exchange nailing.

References

1. Bone LB, Johnson K (1986) Treatment of tibial fractures by reaming and intramedullary nailing. J Bone Joint Surg [Am] 68: 877–887
2. Bøhler J (1982) An approach to non-union of fractures. Surg Annu 14: 299–315
3. Cattermole HC, Cook JE, Fordham JN, Muckle DS, Cunningham JL (1997) Bone mineral changes during tibial fracture healing. Clin Orthop 339: 190–196
4. Chakkalakal DA, Lippiello L, Wilson RF, Shindell R, Conally JF (1990) Mineral to matrix contribution to rigidity in fracture healing. J Biomech 23: 435–439
5. Chao EYS, Aro HT (1992) Biomechanics of fracture repair and fracture fixation. Proc 3rd Conf. Int. Soc. Fracture Repair, pp 16–55
6. Cook JE, Cunningham JL (1995) The assessment of fracture healing using dual x-ray absorptiometry: a feasibility study using phantoms. Phys Med Biol 40: 119–136
7. Court-Brown CM, Keating JF, Chritie J, McQueen MM (1994) Exchange intramedullary nailing. Its use in aseptic nonunion. J Bone Joint Surg [Br] 77: 407–411
8. Danckwart-Lilliestrøm G (1969) Reaming of the medullary cavity and its effect on diaphyseal bone. Acta Orthop Scand Suppl 1, 28: 1–153
9. Einhorn TA, Lane JM, Burstein AH, Kopman CR, Vigorita VJ (1984) The healing of segmental bone defects induced by demineralised bone matrix. J Bone Joint Surg [Am] 66: 274–279
10. Ekeland A, Engasaeter LB, Langeland N (1982) Influence of age on mechanical properties of healing fractures and intact bones in rats. Acta Orthop Scand 53: 527–534
11. Ekeland A, Engasaeter LB, Langeland N (1984) Torsional properties of rat femora. Eur Surg Res 16 [Suppl 2]: 28–33
12. Frost HM (1973) Bone remodelling and its relation to metabolic bone diseases. Charles C Thomas, Springfield
13. Hietaniemi K, Peltonen J, Paavolainen P (1995) An experimental model for non-union in rats. Injury 26: 681–686
14. Kempf I, Grosse A, Rigaut P (1986) The treatment of noninfected pseudarthrosis of the femur and tibia with locked intramedullary nailing. Clin Orthop 212: 142–154
15. Kessler SB, Hallfeldt KKJ, Perren SM, Schveibere L (1986) The effects of reaming and intramedullary nailing on fracture healing. Clin Orthop 212: 18–26
16. Liang CT, Barnes J, Seedor JG, Quartuccio HA, Bolander M, Jeffrey JJ, Rodan GA (1989) Impaired bone activity in aged rats: alternations at the cellular and molecular levels. Bone 13: 435–441
17. Lindholm RV, Lindholm TS, Toikkanen S, Leino R (1970) Effect of forced interfragmental movements on the healing of tibial fractures in rats. Acta Orthop Scand 40: 721–728
18. Lu PW, Briody JN, Howman Giles R, Trube A, Cowell CT (1984) DXA for bone density measurement in small rats weighing 150–250 g. Bone 15: 199–202
19. Markel MD, Chao YS (1993) Noninvasive monitoring techniques for quantitative description of callus mineral content and mechanical properties. Clin Orthop 293: 37–45
20. Moelster AO (1984) Effects of rotational instability on healing of femoral osteotomies in rat. Acta Orthop Scand 55: 632–636
21. Muller ME, Thomas RJ (1979) Treatment of non-union in fractures of long bones. Clin Orthop 138: 141–153
22. Okhotsky VP, Souvalyan AG (1992) The treatment of non-union and pseudarthrosis of the long bones with thick nails. Injury 10: 92–98
23. Sledge SL, Johnson KD, Henley MB, Watson T (1989) Intramedullary nailing with reaming to treat non-union of the tibia. J Bone Joint Surg [Am] 71: 1004–1019
24. Taylor JC (1992) Delayed union and non-union in fractures. In: Crenshaw AH (ed) Campell’s operative orthopedics, 8th edn. Mosby, St Louis, pp 1287–1345
25. Templeman D, Thomas M, Varecka T, Kyle R (1995) Exchange reamed intramedullary nailing for delayed and nonunion of the tibia. Clin Orthop 315: 169–175
26. Webb LX, Winquist RA, Hansen ST (1986) Intramedullary nailing and reaming for delayed union or nonunion of the femoral shaft. Clin Orthop 212: 133–141
27. Weber BG, Brunner C (1981) The treatment of nonunions without electrical stimulation. Clin Orthop 161: 24–32
28. Wiss DA, Stetson WB (1994) Nonunion of the tibia treated with a reamed intramedullary nail. J Orthop Trauma 8: 189–194