Effects of graded reaming on fracture healing

Blood flow and healing studied in rat femurs

Oliver Grundnes[1], Stein Erik Utvåg[1] and Olav Reikerås[2]

In 30 rats, closed bilateral fractures of the femur were produced. On the left side intramedullary reaming was performed to 1.6 mm, and the fracture fixed with a steel pin with a diameter of 1.6 mm. On the right side the femoral canal was reamed to 2.0 mm and a hollow steel tube with a diameter of 2.0 mm was used for fixation. An additional 8 rats were used to obtain mechanical, dimensional and flow data on intact femurs, and another 10 rats were used to study the acute flow changes caused by fracture and different degrees of reaming and fracture.

Fracture and reaming reduced total bone and cortical bone blood flows to about one third of normal flow, with no differences between the 1.6-mm and the 2.0-mm reamed bones. At 4 weeks, total bone flow was about double and cortical bone flow about 4 times increased in the 1.6-mm group. In the 2.0-mm reamed bones increases of approximately 5 times in total bone flow and of about 7 times in cortical flow were found. Callus flow was about twice the size of the respective cortical flow in both groups. Both total and cortical flows gradually subsided, without differences between the 2 groups.

At 12 weeks, the callus area in the 2.0-mm group was greater than in the 1.6-mm group, while bone dimensions were greater in the 2.0-mm group at 4 and 12 weeks. Bending moment and rigidity were greater in the 1.6-mm group than in the 2.0-mm one at every time interval; no differences were found in fracture energy.

We conclude that, in terms of healing, modest reaming is preferable to extensive reaming. The adverse effect of extensive reaming is not due to excessive flow derangement at the acute stage or to impaired vascularity at the phase of remodeling.

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[1]Department of Orthopedics, Institute of Clinical Medicine, University Hospital, N-9012 Tromsø, Norway, and [2]Sophies Minde Orthopedic Hospital, N-0570 Oslo, Norway. Correspondence: Dr. Oliver Grundnes, Department of Surgery, Harstad Hospital, N-9400 Harstad, Norway. Tel. +47-82 15000. Fax -82 15126

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The modern approach to intramedullary nailing of fractures favors minimal reaming with the use of a small-diameter nailing system, which involves less operative trauma (Bucholz and Jones 1991). In a previous study we found a positive correlation between the degree of reaming and the reduction in bone blood flow of intact bone (Grundnes and Reikerås 1993). The present study raises the question whether different degrees of reaming might influence blood supply to the fractured bone and, hence, healing.

Material and methods

48 male Wistar rats (Møllegård Avlslaboratorium, Eiby, Denmark) weighing 356 (330–377) g were used. 10 rats were used in the acute study, and 8 rats were used to obtain mechanical characteristics, data on bone dimensions and for blood flow measurements of intact femurs. The remaining 30 rats were randomly divided into 3 groups, with 10 in each, which were tested after 4, 8, and 12 weeks. Under intraperitoneal anesthesia (pentobarbital 5 mg/100 g body weight), bilateral fractures were produced by first driving an awl percutaneously through the bone at the midshaft of the femur to weaken it and to avoid comminution of the fracture. Both bones were then manually broken. The fracture areas were then exposed by a small lateral incision. On the left side the medullary cavity was gradually reamed from the fracture site in proximal and distal fragments to a diameter of 1.6 mm, using steel burrs mounted on an electrical drill. The reamings were left in place and not rinsed out. The fracture was then stabilized by pinning. A steel pin with a diameter of 1.6 mm was introduced from the fracture site and, by use of the electrical drill, it was driven through the proximal fragment. On the right side, medullary reaming was done to a diameter of 2.0 mm, and the fracture

stabilized with a hollow steel tube with a diameter of 2.0 mm. All wounds were closed in 2 layers. The 1.6 mm steel pin had a bending rigidity of 2.69 Nm/rad and the hollow steel tube a bending rigidity of 2.85 Nm/rad.

In the 8 other rats used for estimation of mechanical parameters, bone dimensions and bone blood flow in intact bone, the left femur was used. After flow measurements, the bones were fractured in a cantilever bending machine. The fractures were standardized to the distal end of the trochanteric rim, median bending rigidity was 2.91 Nm/rad. Furthermore, the internal anteroposterior diameter of the medullary cavity at the fracture site was 1.8 (1.6–2.0) mm and the external anteroposterior diameter of the bone was 3.3 (3.2–3.4) mm.

For blood flow measurements, 85-Strontium radioactive microspheres (New England Nuclear, Boston, MA, U.S.A.) of 15.5 ± 0.1 µm diameter were used. Each injection consisted of 750,000 spheres homogeneously suspended in 0.9 percent saline. The spheres were vortexed on a whirl mixer for 2 min prior to injection. A heparinized polyethylene catheter (PE-50) was introduced via the carotid artery and placed in the aortic root for injection of microspheres during 30 sec, and the catheter was then flushed with 0.5 mL saline. The caudal artery was cannulated with a heparinized polyethylene catheter (PE-10) and connected to a Harvard infusion-withdrawal pump for reference sampling. The flow rate in the reference organ was set at a rate of 195 µL/min. Withdrawal started 15 sec prior to injection of the microspheres and continued for 30 sec after the injection was finished.

To study the acute effects of fracture and different degrees of reaming on bone blood flow, a separate group of 10 rats was used. In this group blood flow measurements started at 30 min following fracture. The left femur was fractured first in every other rat. Otherwise, the bones were evaluated at 4, 8, and 12 weeks following fracture.

All rats tolerated the operation well and resumed full weight-bearing after a few days. There was one failure in the 12-week group. Radiographically all fractures healed by production of external callus; proper pin placement was confirmed in all rats.

After the animals were killed in a CO_2 chamber, both hind limbs were dissected, soft tissues removed from the femurs, and the bones were wiped dry and weighed. The anteroposterior and transverse diameters of the callus mass and the corresponding diaphyseal dimensions were measured by use of a sliding caliper, and the cross-sectional areas were calculated assuming an elliptical shape. The diaphyseal dimensions were measured 12 mm proximal to the tip of the femoral condyle. Thereafter, the bones were radiographed and the fixation devices removed.

For blood flow measurements, the bones were placed in counting vials and, together with the reference samples, counted in a Packard Auto Gamma Scintillation Spectrometer. Specimens were counted for 5 min, which gave a counting error less than 1 percent. After the total bone flow was calculated, the bones were subjected to mechanical testing. Thereafter, a diaphyseal segment proximal and distal to the fracture and the callus area was separated. The medullary cavity was rinsed out, and the bone segments were weighed and counted together with their reference samples for cortical and callus flow estimations. In the acute study, only a mid-diaphyseal segment which included the fracture area was used for cortical blood flow analysis.

The bones were mechanically tested in a cantilever bending test with dorsal deflection of the distal end of the femurs (Engesæther et al. 1978). The hydraulic testing machine was run at a constant rate of 0.08 rad/s. The load values were transferred to a chart recorder displaying the load-deformation curve. The strength was calculated as the bending moment necessary to produce a fracture. The bending rigidity was determined from the slope of the linear elastic part of the curve. Fracture energy was defined as the energy absorbed during loading to fracture.

Data are presented as medians and 25–75 percentiles. For statistical evaluation we used the paired Wilcoxon signed rank test for comparisons between limbs. When comparisons between the time intervals were made, the Kruskal-Wallis test was used. The Mann Whitney U test was used when differences were found. $P < 0.05$ was considered significant.

Results

The radiographs generally revealed narrow fracture gaps and relatively dense callus masses in the 1.6-mm reamed bones. In the 2.0-mm group, the fracture gaps were generally wider, the callus masses were abundant, but at all time intervals they appeared more translucent than the contralateral bones, which had been modestly reamed and fixed with a 1.6-mm nail (Figure 1).

Fracture and reaming reduced total bone and cortical bone blood flows by about 65–75 percent in the 2 groups. There were no differences in total bone or in cortical bone flows between the 1.6-mm and the 2.0-mm reamed bones (Table 1). At 4 weeks, a 5-fold increase in median total bone flow was found in the 2.0-mm group, and a 2-fold increase in the 1.6-mm

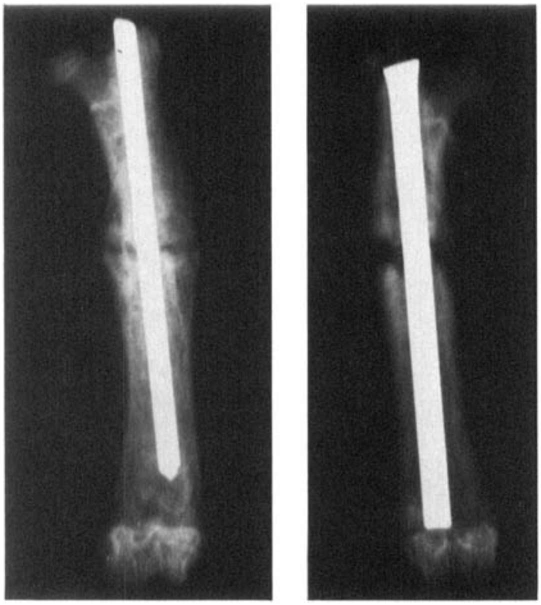

Figure 1. Anteroposterior radiographs of nailed femoral fractures at 4 weeks. 1.6-mm solid steel pin left, 2.0-mm hollow steel tube right.

Table 2. Total bone, cortical bone and callus blood flows with different reaming at 4, 8, and 12 weeks following fracture. Median (25–75 percentiles)

Weeks	1.6 mm	*P*	2.0 mm
Total bone blood flow			
4	45 (36–103)	0.2	90 (36–113)
8	32 (22–33)	0.6	30 (22–36)
12	21 (18–23)	0.5	27 (19–27)
Cortical bone blood flow			
4	34 (22–72)	0.1	57 (32–105)
8	20 (13–31)	0.4	25 (15–35)
12	12 (8.4–17)	0.08	16 (13–18)
Callus blood flow			
4	72 (57–134)	0.2	118 (49–146)
8	55 (42–64)	0.2	63 (34–119)
12	31 (24–33)	0.3	37 (20–43)

Decreases in total bone flow were seen between each time interval in the 1.6-mm group (*P* 0.002 and *P* 0.03), and between 4 and 8 weeks in the 2.0-mm group (*P* 0.002). Cortical blood flow declined between 4 and 8 weeks in the 2.0-mm group (*P* 0.009), but not in the 1.6-mm group (*P* 0.06). There was a significant reduction in callus flow between 4 and 8 weeks in the 1.6-mm group (*P* 0.04) and between 8 and 12 weeks in the 2.0-mm group (*P* 0.01).

Table 1. Acute effects of fracture and different degrees of reaming on total bone and cortical bone blood flows (mL/min × 100 g^{-1}) in rat femora. Median (25–75 percentiles)

Group	Total bone flow	Cortical bone flow
Fracture + 1.6-mm ream	7.1 (3.5–11)	2.8 (1.5–5.1)
P	0.01	0.008
Control	19 (14–30)	8.1 (4.8–15)
P	0.01	0.008
Fracture + 2.0-mm ream	5.5 (3.1–9.8)	2.0 (1.4–4.1)

No differences in total bone (*P* 0.4) or in cortical bone (*P* 0.4) flow between the 1.6-mm and 2.0-mm reamed bones.

Table 3. Cross-sectional callus area (mm^2) and diaphyseal area (mm^2) with different reaming at 4, 8, and 12 weeks after fracture. Median (25–75 percentiles)

Weeks	1.6 mm	*P*	2.0 mm
Callus area			
4	58 (48–72)	0.3	61 (48–100)
8	50 (39–61)	0.07	63 (51–88)
12	37 (31–53)	0.04	52 (46–102)
Diaphyseal area			
4	23 (20–28)	0.04	30 (23–41)
8	22 (18–27)	0.1	27 (19–34)
12	20 (19–21)	0.01	30 (24–35)

group (Table 2) when compared to the respective flow values in the control group at Day 0. Callus flow was approximately twice that of the respective cortical flows in the 2 groups. As the fractures healed, total bone, cortical bone and callus flows all gradually subsided. Throughout the experiment there were marginal increases in total bone, cortical bone and callus blood flows in the 2.0-mm group compared to the 1.6-mm group.

The cross-sectional callus area in the 2.0-mm group was marginally increased at 4 and 8 weeks compared to the 1.6-mm group, with a 40 percent increase at 12 weeks. When the 2 groups were compared, the outer diaphyseal area was increased by 30 percent at 4 weeks and by 46 percent at 12 weeks in the 2.0-mm group (Table 3).

At 4 weeks the median bending moment was increased by about 70 percent in the 1.6 mm group, compared to the 2.0-mm reamed bones and, throughout the experiment, a more than 2-fold increase in bending moment was seen in the 1.6-mm group. When comparisons in bending rigidity were made, an increase of about 80 percent was found in the 1.6-mm group at 4 weeks, and of approximately 70 and 50 percent in the same group at 8 and 12 weeks, respectively. There were no differences in fracture energy (Table 4).

Table 4. Mechanical parameters of femoral fractures after 4, 8, and 12 weeks in 1.6-mm and 2.0-mm reamed bones. Values are medians and 25–75 percentiles

Weeks	1.6 mm	*P*	2.0 mm
Bending moment (Nm x 10^{-1})			
4	2.13 (1.51–3.00)	0.04	1.26 (0.99–2.08)
8	5.08 (4.52–8.03)	0.03	2.52 (1.86–4.14)
12	8.03 (6.14–9.35)	0.03	3.57 (2.47–7.64)
Bending rigidity (Nm/rad)			
4	1.95 (1.60–3.33)	0.03	1.09 (0.83–1.47)
8	3.19 (2.78–4.18)	0.008	1.86 (1.57–3.04)
12	3.34 (3.19–3.71)	0.008	2.23 (1.95–2.78)
Fracture energy (Nm x rad x 10^{-2})			
4	2.16 (1.36–4.72)	0.2	2.14 (1.04–3.64)
8	7.68 (5.46–18.6)	0.1	3.22 (1.76–8.26)
12	15.8 (11.9–26.8)	0.4	6.12 (3.34–23.4)

Discussion

The influence of intramedullary reaming on fracture healing has been discussed by many authors, and conflicting results have been obtained. Reikerås et al. (1989) found no differences in reamed and unreamed femoral osteotomies in rats, while Bråthen et al. (1990) found delayed healing of tibial osteotomies in rabbits when intramedullary reaming was performed. However, in previous studies on this topic there have been either various degrees of stability or various degrees of rigidity in the fixation devices. In the present study, both fixation devices had about the same bending rigidity as intact bone.

The anteroposterior diameter of the medullary cavity was about 1.8 mm in the rats in this study. Thus, a 1.6-mm steel nail would provide a rather rotational unstable fixation, while the 2.0-mm nail would increase the stability due to a larger bone-nail contact area. Some bending and axial instability seem to be conductive, while rotational instability is detrimental to fracture healing (Mølster et al. 1982, Mølster 1984, Goodship and Kenwright 1985). In the present study, bending rigidity was about the same in both groups. However, the loose-fit nail would allow some interfragmentary movements at the fracture site. The diminished rotational instability in the 2.0-mm group seems better for healing than in the 1.6-mm group, while axial instability should favor healing in the 1.6-mm group.

A full-sized intramedullary nail requires so much reaming that the inner one third to two thirds of the diaphyseal cortex is deprived of its blood supply and thereby causes damage to the endosteum (Trueta and Cavadias 1955, Rhinelander 1974, Pfitzer et al. 1979).

Measurements of bone blood flow immediately following reaming and fracture provided information about the circulatory changes at the acute stage. Since blood flow was only a fraction of normal flow, differences following different degrees of reaming were hardly to be expected. The ischemic phase was, however, short due to both reversal of flow and to the rapid regeneration of intramedullary vessels. After severance of the medullary circulatory systems, compensatory periosteal arteries will rapidly contribute to the perfusion of the cortex. The direction of the arterial blood flow after damage to the medullary vessels reverses from a centrifugal to a centripetal mode (Strachan et al. 1990). In a situation following fracture, both Trueta (1974) and Rhinelander (1974) noted that the main number of new vessels arrives from the periosteal side, and that the suppression of intramedullary flow increases the vascularity of the periosteum. Thus, the impact of extensive reaming on healing has been questioned, especially as there are indications that it may not be long before endosteal flow is re-established and begins to contribute to the cortical blood supply (Rhinelander 1974, Smith et al. 1990). On the other hand, the process of callus formation is finite (Henricson et al. 1987), and the mechanical differences found in the present study may be caused by a delayed revascularization of the fracture area in the critical period when the hematoma becomes organized and inherites its osteoinductive potentials.

Reaming particles and bone marrow cells are considered to be of great importance in fracture healing because of bone-inductive potential (Mizuno et al. 1990); intensive new bone formation can be observed around the reaming dust on histological sections and in roentgenograms, if it is surrounded by vital tissue. On the other hand, the reaming dust represents a large amount of necrotic particles, if they are deposited in devitalized zones of the medullary canal (Kessler et al. 1986). Thus, extensive reaming may, in fact, cause increased phagocytotic activity at the fracture site which, in turn, produces a hypertrophic and immature callus. Similar features are seen in fractures with extensive soft tissue damage (Hulth 1989). Data on callus area in this study give support to this view.

Indrekvam et al. (1991) noted an increased bone mass in reamed intact rat femora and concluded that the nailing technique assists in bone remodeling. Our experiment provides indications of a substantial periosteal reaction in the 2.0-mm group, as evidenced by an increase in the outer diaphyseal area in contrast to the 1.6-mm group. Thus, it seems that either endosteal destruction or blocking of the medullary canal, or both—and not the nailing technique itself—is responsible for the periosteal reaction.

In conclusion, the present study shows that low-graded reaming is superior to extensive reaming in fracture healing. Reaming with endosteal destruction and tight-fit nailing induced a significant periosteal reaction, and indications of a hypertrophic and immature callus were found. We were not able to demonstrate any negative effect on bone circulation, either in the acute phase or during healing, due to extensive reaming. However, important phases concerning restoration of bone blood flow following fracture were not studied.

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