Nailing and occlusion of the medullary cavity: Flow and mechanical changes in rat femora

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To cite this article: Oliver Grundnes & Olav Reikeras (1994) Nailing and occlusion of the medullary cavity: Flow and mechanical changes in rat femora, Acta Orthopaedica Scandinavica, 65:2, 175-178, DOI: 10.3109/17453679408995429

To link to this article: https://doi.org/10.3109/17453679408995429

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Published online: 08 Jul 2009.

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Nailing and occlusion of the medullary cavity
Flow and mechanical changes in rat femora

Oliver Grundnes and Olav Reikerås

25 rats were bilaterally operated on and the femoral canal nailed, nailed and plugged with silicone or only plugged with silicone after intramedullary nailing. A fourth group was intramedullarily reamed without any other intervention. The bones were evaluated after 12 weeks, including flow measurements, mechanical properties and bone dimensions.

There were no differences between the groups in total bone or cortical bone blood flow. There were only marginal changes in outer and inner anteroposterior diameters and the area moment of inertia. The maximum bending stress in bones that had been both nailed and silicone-plugged was decreased compared to the other groups, except the nailed bones. In the silicone/nail group, energy absorption was less than in the other groups, except the nailed group.

We conclude that modest intramedullary reaming, nailing or plugging of the femoral canal do not change the mechanical properties of the bone, nor do they induce chronic vascular changes in bone. However, when the medullary cavity is filled with both a nail and silicone, mechanical as well as structural changes may ensue.

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Submitted 93-02-16. Accepted 93-10-31

Intramedullary reaming and nailing have theoretical disadvantages. Reaming destroys the medullary circulation and causes cortical bone loss, while nailing causes some stress-strain shielding of the bone (Rhinelander 1974, Husby et al. 1989b). Furthermore, nails have a space-occupying effect on the medullary canal. These factors may all influence the characteristics of cortical bone. We have studied mechanical and circulatory effects of reaming, nailing, and plugging of the femoral canal in rats.

Material and methods

25 male Wistar rats (Møllegård Avlslaboratorium, Eiby, Denmark) weighing 404 (341–455) g were used in this study. Under intraperitoneal anesthesia (pentobarbitol 5 mg/100g body weight), the trochanteric areas were exposed on both sides and the bones were randomly assigned to be operated on according to 5 different modalities: (1) from the trochanteric groove the medullary cavity was penetrated by an awl, and by steel burrs mounted on an electrical drill gradually reamed to a diameter of 1.6 mm. A 1.6-mm steel pin, with a bending rigidity of 2.71 Nm/rad, was then inserted into the medullary cavity, (2) reaming was done as for those in Group 1, and the medullary cavity was filled with a silicone composition (Xantopren light body, thin flowing, silicone, Bayer Dental, Germany) added hardener (Elastomer activator RZ, Bayer Dental, Germany). The composite had no mechanical characteristics, (3) reaming to 1.6 mm as in Group 1, and the femoral canal was filled with silicone whereupon a 1.6 mm steel pin was inserted, (4) reaming of the medullary cavity to a diameter of 1.6 mm only, and (5) a sham operation. All wounds were closed in 2 layers. The randomization was done according to a randomization table with 5 chores. However, the second operation in one rat was not done in the same way as the first. All rats were allowed normal cage activity post-operatively. A further 8 animals were used to determine bending rigidity and bone dimensions of intact rat femora. Bending rigidity was 2.98 Nm/rad, the inner anteroposterior diameter was 1.98 (1.81–2.12) mm and the transverse diameter 2.57 (2.30–2.73) mm.

The bones were evaluated after 12 weeks. For blood flow measurements, radioactive microspheres (New England Nuclear, Boston, MA, U.S.A.) labeled with 141-Cerium of 15.5 ± 0.1 μm diameter were used, and each injection consisted of 500,000 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. The microspheres were injected over a period of 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 195 μL/min. Withdrawal started 15 sec prior to injection of the microspheres and continued for 30 sec after the injection was finished.

After the animals were killed in a CO₂ chamber, both hind limbs were dissected and soft tissues removed from the femurs. Nails and silicone were removed from the medullary cavity, the bones were then wiped dry and weighed. For mechanical testing, the fracture site was determined as the mid-point between the top of the femoral head and the medial condyle. The bones were mechanically tested in a cantilever bending test with dorsal deflection of the distal end of the femurs (Engeseth et al. 1978). The hydraulic testing machine was run at a constant rate of 0.04 rad/s. The load values were transferred to a chart recorder displaying the load-angular deformation curve. The strength was calculated as the bending rigidity between the groups. In the silicone group, we noted an insignificant decrease in bending rigidity compared to normal bones, and a marginally greater bending rigidity in the same group. Since energy absorption is a function of both bending moment and rigidity, median energy absorption in the silicone/nail group was only half of that in control bones, and was decreased compared to the other groups, except the nailed group (Table 1).

Table 1. Bending moment (Nm × 10⁻¹), bending rigidity (Nm/rad) and energy absorption (Nm × rad × 10⁻¹) in the different groups 12 weeks after intramedullary intervention. Median (25-75 percentiles)

<table>
<thead>
<tr>
<th></th>
<th>Silicone</th>
<th>Silicone nail</th>
<th>Nail</th>
<th>Reaming</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bending moment</strong></td>
<td>13 (9.9–14)</td>
<td>9.4 (8.6–13)</td>
<td>13 (11–15)</td>
<td>13 (10–15)</td>
<td>13 (12–14)</td>
</tr>
<tr>
<td><strong>Bending rigidity</strong></td>
<td>1.7 (1.3–1.7)</td>
<td>1.8 (1.7–2.1)</td>
<td>1.5 (1.4–2.0)</td>
<td>1.7 (1.4–1.9)</td>
<td>1.6 (1.4–2.0)</td>
</tr>
<tr>
<td><strong>Energy absorption</strong></td>
<td>5.8 (4.4–6.7)</td>
<td>3.2 (2.5–3.9)</td>
<td>4.6 (2.8–7.8)</td>
<td>4.5 (4.3–6.0)</td>
<td>6.3 (5.1–6.9)</td>
</tr>
<tr>
<td><strong>P-value</strong></td>
<td>0.3</td>
<td>0.9</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For blood flow estimations, 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 blood flow was calculated, a diaphyseal segment which constituted about one third of the total bone weight, was separated. The medullary cavity was rinsed out from the segment, and the bone segments were weighed and counted together with their reference samples for cortical flow estimations.

Data are presented with medians and 25-75 percentiles. For statistical evaluation of differences between the groups we used the Kruskal-Wallis test. The non-paired Wilcoxon rank-sum test was used when statistical differences were found. \( P \leq 0.05 \) was considered significant.

Results

All rats tolerated the operation well and resumed normal weight-bearing after recovery from the anesthesia. 2 bones in the nailed group were excluded because of eccentric reaming and placement of the nail in the anterior cortex. New bone formation was observed around all implants in the nail group; in the silicone and silicone/nail groups, complete filling of the medullary cavity was observed.

There were no differences in bending moment or in bending rigidity between the groups. In the silicone/nail group, we noted an insignificant decrease in bending moment of nearly 30 percent compared to normal bones, and a marginally greater bending rigidity in the same group. Since energy absorption is a function of both bending moment and rigidity, median energy absorption in the silicone/nail group was only half of that in control bones, and was decreased compared to the other groups, except the nailed group (Table 1).

Internal and external diameters did not differ between the 5 groups. There were no differences between the groups in the calculated area moment of inertia. However, compared to control bones, a slight
Table 2. External and internal anteroposterior diameters (mm), net cross-sectional area (mm²), area moment of inertia (mm⁴) and maximum bending stress (MPa \(\times 10^2\)) 12 weeks after different intramedullary interventions. Median (25–75 percentiles)

<table>
<thead>
<tr>
<th></th>
<th>Silicone n 10</th>
<th>Silicone nail n 10</th>
<th>Nail n 8</th>
<th>Reaming n 10</th>
<th>Control n 10</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diam.</td>
<td>4.1 (3.9–4.3)</td>
<td>4.4 (4.0–4.7)</td>
<td>4.2 (3.6–4.4)</td>
<td>4.0 (3.6–4.2)</td>
<td>4.0 (3.8–4.1)</td>
<td>0.1</td>
</tr>
<tr>
<td>Inner diam.</td>
<td>2.2 (2.0–2.7)</td>
<td>2.3 (2.1–2.6)</td>
<td>2.3 (2.1–2.4)</td>
<td>2.1 (1.9–2.2)</td>
<td>2.2 (2.0–2.4)</td>
<td>0.4</td>
</tr>
<tr>
<td>Net area</td>
<td>5.9 (4.3–6.4)</td>
<td>6.0 (5.9–7.4)</td>
<td>6.0 (4.7–6.2)</td>
<td>5.7 (5.4–6.3)</td>
<td>5.3 (4.9–5.9)</td>
<td>0.2</td>
</tr>
<tr>
<td>Area moment inertia</td>
<td>16 (13–21)</td>
<td>20 (16–28)</td>
<td>17 (11–18)</td>
<td>14 (12–17)</td>
<td>15 (13–16)</td>
<td>0.3</td>
</tr>
<tr>
<td>Bending stress</td>
<td>1.6 (1.4–1.8)</td>
<td>1.1 (1.0–1.6)</td>
<td>1.5 (1.2–2.0)</td>
<td>1.5 (1.4–1.9)</td>
<td>1.7 (1.7–1.9)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 3. Total bone flow (mL/min \(\times 100\text{g}^{-1}\)) and cortical bone blood flow (mL/min \(\times 100\text{g}^{-1}\)) 12 weeks after different intramedullary interventions. Median (25–75 percentiles)

<table>
<thead>
<tr>
<th></th>
<th>Silicone n 10</th>
<th>Silicone nail n 10</th>
<th>Nail n 8</th>
<th>Reaming n 10</th>
<th>Control n 10</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total flow</td>
<td>18 (7.9–24)</td>
<td>13 (7.3–27)</td>
<td>18 (9.9–30)</td>
<td>19 (11–27)</td>
<td>16 (11–29)</td>
<td>0.5</td>
</tr>
<tr>
<td>Cortical flow</td>
<td>6.3 (5.3–16)</td>
<td>13 (5.9–23)</td>
<td>9.5 (7.9–13)</td>
<td>8.2 (6.9–17)</td>
<td>6.2 (4.4–18)</td>
<td>0.4</td>
</tr>
</tbody>
</table>

increase in median values of more than 30 percent was noted for the silicone/nail bones in this group. In the silicone/nail treated bones, maximum bending stress was less than in the silicone, the reamed and the control bones (Table 2).

There were no differences in either total bone or in cortical bone blood flow between the groups (Table 3).

Discussion

In this study the possible consequences of reaming, nailing and plugging of the femoral canal in long bones were investigated after 12 weeks in rats. It has been shown that intramedullary procedures may cause circulatory deprivation of the bone. Following intramedullary reaming, a reduction in cortical flow by one half to two thirds has been reported (Rhinelander 1974, Pfitzer et al. 1979). However, in intact reamed rat femora, circulation seems to be fully restored within the first week (Indrekvam et al. 1992). The femoral canal in rats is formed as an ellipse, and also in clinical practice it has been found that nails do not occupy the medullary cavity completely (Kessler et al. 1986). On this basis it has been assumed that the size of the nail may influence revascularization and, thereby, remodeling after reaming. In the present study, the medullary cavity of some femoral bones was completely plugged by silicone to evaluate the consequences of total obstruction of the femoral canal. We found that the vascularity of the bones was not impaired, either by silicone alone or combined with nailing. On the other hand, median cortical blood flow in the silicone/nail group was twice that in the control bones. The lack of statistical significance may be caused by a wide range in our results due to a small number of microspheres in the specimens (Buckberg et al. 1971, Li et al. 1989). We injected 500,000 microspheres, and since each femur receives about 0.35 percent of cardiac output, each femur then contained about 1750 microspheres (Tothill and MacPherson 1986). The segments used for cortical flow analysis had a weight of about one third of the entire bone. Since medullary flow is approximately 50 percent of cortical flow in the diaphysis (Grundnes and Reikerås 1992), the diaphyseal segment we used contained about 380 microspheres. This is usually considered a sufficient number of spheres to obtain accurate results within a 10 percent error at a 95 percent confidence level (Buckberg et al. 1971, Li et al. 1989).

A cantilever bending test was used to evaluate mechanical properties of the bones, although a torsional test might have been better, as this takes the whole bone into account. However, a bending test at the mid-diaphysis gives information about the cortical bone at the site where bone dimensions were measured, thus the bending test was preferred. We found slight effects of reaming, reaming combined with nailing or silicone-plugging of the femoral canal on mechanical characteristics of the cortical bone. There was, however, a tendency against reduced bending moment and increased rigidity of the bones which had been plugged and nailed and, as energy absorption is a result of these factors, there was a significant reduction in energy absorption in these bones.

In previous studies there were differences as to the degree of impairment in bone strength and stiffness after intramedullary reaming and nailing (Kaartinen et
al. 1985, Mølster 1986, Indrekvam et al. 1991). Weakening of cortical bone depends on the degree of reaming and removal of cortical mass. Bone loss due to reaming causes a thinner corticalis and, thereby, acute reductions in the mechanical characteristics (Husby et al. 1989a). As the degree of reaming may have differed in previous experiments, differences in results should be interpreted from this point of view. With the development of modern nails with interlocking capabilities, reaming of cortical bone to secure adequate stability should be less necessary. In the present study, only modest reaming of the femoral canal was performed (1.6 mm) and without significant interference with the endosteal cortex.

Reaming, then, did not influence either the mechanical characteristics or the bone dimensions to any significant degree. These observations are in conflict with some other studies where increases in outer and inner bone diameters, as well as in the area moment of inertia, have been observed after reaming (Indrekvam et al. 1991). Again, however, such differences may be due to the degree of reaming and, consequently, the degree of cortical damage.

Intramedullary nails cause load-sharing with a minimum of stress-shielding. Husby et al. (1989b) have shown that reaming and nailing with a steel nail of higher stiffness than of femoral bone cause strain-shielding, whereas no such changes were found in the polyacetal-nailed group. Removal of the medullary nail restored, however, the loading configuration immediately. Bending rigidity of the steel nail in our study was approximately equal to intact bone, thus load-sharing due to the implant would be minimal.

The mechanical characteristics of bone depend on structural and mechanical properties of the material. In this study, energy absorption and maximum bending stress were significantly less in the bones that had been silicone-plugged and nailed. The differences were small, but these observations indicate some structural differences in these bones, as compared to the others. This may be a consequence of the plugging of the femoral canal. On the other hand, it does not seem logical that this effect was less in the bones that had only been plugged. However, silicone plugging of the femoral canal, followed by introduction of a nail, may squeeze the silicone into pores of the bone in a manner which occurs during cementation of a femoral stem prosthesis. Thus, the effect of silicone and nailing should be more effective than silicone plugging alone. We are, however, aware that our method for determining bone resorption/apposition is not very sensitive. However, as only the inner and outer zones of cortical bone participate in remodeling (Ream et al. 1983, Danielsen et al. 1986), we consider our method to be accurate for evaluation of significant changes in this respect.

References


