Fibrous tissue armoring increases the mechanical strength of an impacted bone graft

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Submitted 99-11-13. Accepted 00-08-22

ABSTRACT – Impacted, morselized bone allografts are used with good clinical results in revision of hip prostheses with loosening and osteolysis. The impacted bone graft appears radiographically to remodel, but histological analyses have shown a heterogeneous picture with a mixture of living and dead bone. Thus, complete remodeling of the graft may be neither a prerequisite nor a cause of the good clinical results. The present study concerns the mechanical effect of the mere armoring of the bone graft by ingrowing fibrous tissue. We compared the compression strength of freshly-impacted grafts to grafts that had been inserted into a bone chamber and thus were penetrated by fibrous tissue growing in between the graft trabeculae. The compressive strength was doubled after 4 weeks of fibrous ingrowth. We conclude that the mechanical properties of an impacted graft are enhanced by armoring with ingrowing fibrous tissue. Strengthening of the parts of the impacted grafts which have not yet remodeled, would be clinically relevant for the outcome of the operation, since these parts are at high stress during the whole remodeling period. Complete osseous remodeling may not be necessary to obtain a good clinical result with a morselized impacted graft.

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The clinical success of impacted morselized bone grafts (Gie et al. 1993, Ling 1996, Slooff et al. 1996) is not well understood on a biological level. Major parts of the morselized and impacted grafts appear to remodel at least radiographically (Ling 1996). This remodeling would imply that new bone also penetrates further into impacted grafts than into structural ones, into which new bone often penetrates only 2–3 mm (Enneking and Mindell 1991). In a rat chamber model, we found the ingrowth of new bone to be reduced in impacted grafts (Tägil and Aspenberg 1998). Since osseous remodeling was not increased by impaction, another explanation of the clinical success of impacted grafts had to be sought.

Possibly, a firmly impacted bone graft, armored by ingrowing fibrous tissue, could act as a composite material better able to withstand and transfer load during remodeling than a structural graft that may collapse. We designed the present study to see if the ingrowth of fibrous tissue would increase the mechanical stability of an impacted graft.

Animals and methods

Animals

Male outbred Sprague-Dawley rats (353–370 g) were used as recipients and female rats from the same breeding stock as graft donors. They were all obtained from Møllegaard, Køge, Denmark. They were kept in our animal facility for 1 week before being operated on (22 °C; 2 rats in each cage, free access to food pellets and water).

Bone grafts

Grafts were taken from the proximal tibia. The epiphysis and the growth plate were cut off and a cylindrical bone rod was taken from the metaphysis in the axial direction, using a hole-cutter. The grafts were wet-frozen at –30 °C for 24 hours. After thawing, the grafts were packed in a specially designed impactor in which 2 cancellous bone cylinders were longitudinally compressed into about the size of one. The denser proximal portion

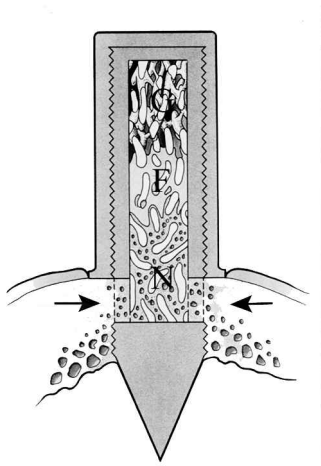


Figure 1. Bone conduction chamber. Arrows point to ingrowth openings situated subcortically. Newly-formed bone (N) grows into the graft (G). Above the new bone is revascularized, but not yet remodeled graft (F).

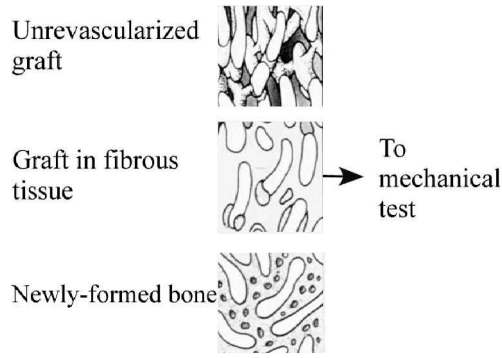


Figure 2. Drawing of graft specimen removed from the chamber. A 2 mm piece from the middle part was taken for mechanical testing. This part consists of unremodeled graft material in vascularized fibrous tissue. The part at the bottom of the chamber with newly-formed bone and the non-revascularized part at the top were discarded.

of the graft was always directed towards the end of the graft, where the ingrowth opening of the chamber would be. The interior of the impactor was cylindrical, having the same diameter as the inside of the bone conduction chamber. A piston could then be inserted into the cylinder to impact the 2 graft cylinders along their longitudinal axes. The piston did not fill the whole inner diameter. A constant force of 80 N was kept on the free end of the piston for 2 minutes while the fat and fluid could escape between the piston and the wall of the cylinder. The pressure applied was calculated as 25 MPa. The impactor was opened opposite the piston and the graft could be removed as one bone pellet and put into the bone conduction chamber or tested directly without being inserted. With this method of impaction, the mean bone volume fraction rises from about one third in the unimpacted grafts to about two thirds in the impacted ones (Tägil and Aspenberg 1998).

Bone conduction chamber

The bone conduction chamber (Figure 1) consists of a threaded titanium cylinder, formed of 2 half cylinders held together by a hexagonal closed screw cap (Aspenberg and Wang 1993). One end of the implant is screwed into the bone. The bone ingrowth space inside the chamber has a diameter of 2 mm, and is 7 mm long. There are 2 bone ingrowth openings at one end of the chamber situated subcortically.

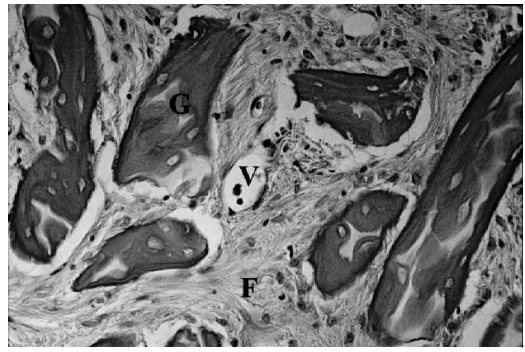
Surgical procedure

5 rats were anesthetized with peritoneal injections (0.6–0.7 mL) of a solution containing pentobarbital (15 mg/mL) and diazepam (2.5 mg/mL). Under aseptic conditions, longitudinal incisions were made bilaterally over the anteromedial aspect of the proximal tibial metaphyses. After incising and raising the periosteum, the medial and posterolateral cortices were pierced with a 1-mm spike just anterior to the insertion of the medial collateral ligament. The hole created in the medial cortex was enlarged manually with a 2.7-mm drill. The chambers were then screwed into position, so that the bone ingrowth holes were placed below the bone surface, and the pointed end of the implant was engaged through the opposite cortical bone. A chamber was placed in each leg so that 10 specimens could be harvested for mechanical testing. The rats were killed after 4 weeks with an overdose of pentobarbital. A further 10 impacted graft pellets were made as above just before the mechanical testing, to produce the unimplanted controls.

Mechanical testing

The harvested grafts were removed from the chambers and immediately put under the dissecting microscope. 3 zones of various heights were seen (Figure 2). Close to the ingrowth openings, we found new ingrown bone with a more whitish color, harder on contact with the edge of the knife.

Figure 3. A. Impacted graft with a marrow cavity (M) at the bottom close to the ingrowth openings and new bone (N) invading the graft from the bottom and upwards. The border of new bone growing into the graft is marked (between arrows). Above the bone ingrowth border, we see unremodeled graft in a vascularized fibrotic stroma (G). The specimen has been cut at the top-edge and the part above this cut was used for mechanical testing.



B. Vascularized part with fibrous tissue in larger magnification (G unremodeled graft, V vessel, F fibrous tissue winding between the graft trabeculae; HE).

Next, a more reddish and softer part was seen, representing the vascularized, but not yet ossified impacted graft. Further up in the specimen, a brownish part was seen which could easily be scraped apart with the knife. This was necrotic graft that had not yet developed vascular and fibrous ingrowth. A 2-mm long segment of the middle piece was manually cut out and mechanically tested. The lower part was taken to histology to verify that the cut had been done at the correct level—i.e., in the vascularized, but not yet ossified, part of the specimen (Figure 3). The unimplanted specimens were cut in the same way to yield a piece of the same height, 2 mm. The specimens were tested within 1 minute to avoid drying of the graft.

A custom made mechanical testing machine was used, which moved at a constant speed of 25 mm/min. A transducer measured the force applied and the failure-point was recorded via a digitalizer (MGC-lab Hottinger Baldwin Messtechnik, Germany) connected to a personal computer (software MGC-lab). The failure-point was determined as the highest value after the initial elastic part of the curve. The mean of the 2 specimens from each animal was calculated and compared to the unimplanted specimens. The data were analyzed with the Mann Whitney U-test.

Results

In 7 of 10 implanted specimens, the cut, as examined histologically, was done as intended in the vascularized, but not ossified part of the specimen. In 2 other specimens, some new bone was found to have reached the cutting border. In one specimen, the whole cut was within new bone and this specimen was excluded. The failure-point occurred at a load almost twice as high in the implanted grafts (2.9, SD 0.8 MPa) as in the unimplanted ones (1.7, SD 0.7 MPa; $p = 0.02$).

Discussion

Structural grafts often collapse during remodeling (Kwong et al. 1993, Shinar and Harris 1997) but impacted morselized grafts seem to maintain their shape and volume. The impacted grafts seem able to withstand the forces acting on them also during revascularization and remodeling. Histological studies show that full replacement of the graft by new bone does not always take place (Heekin et al. 1995, Nelissen et al. 1995). Instead, a mixed pattern of living bone and areas dead of graft in a fibrous tissue stroma is often seen. The addition of ingrowing fibrous tissue, with collagen fibers winding between the graft chips, might lead to a higher resistance to shear and affect the rate of prosthetic migration. Subsidence depends largely on changes in graft volume and is therefore partly

resisted by graft impaction, even without fibrous armoring. However, the largest stresses on a prosthetic femoral stem are not derived from the distally-directed forces that may lead to subsidence. The rotatory forces encountered when rising from a chair or climbing stairs are much greater (Mjöberg et al. 1984, Bergmann et al. 1995). The radius of the femoral canal and of the femoral component is smaller than the moment arm from the femoral axis to the head ("the off-set"). An RSA study of rotational provocation showed that more than a third of the primary femoral stems were unstable in rotation (Mjöberg et al. 1984). While rising from a chair, a rotatory force tends to twist the stem inside the femoral shaft (Bergmann et al. 1995), and in this situation, the tendency of the graft chips to tumble around would be smaller if they are linked together in a fibrotic mesh.

As indicated by the clinical studies, a complete replacement of the graft by new bone might not be necessary to obtain a good clinical result (Heekin et al. 1995, Nelissen et al. 1995). In fact, a full remodeling could in some situations be harmful and lead to reloosening of the prostheses. In a goat study on acetabular components cemented into a morselized and impacted graft, the whole graft remodeled under continuously increasing mechanical strength (Schimmel et al. 1998). However, when the remodeling reached the cement-graft interface, a fibrous membrane developed and the prostheses loosened. Late collapse of morselized and impacted grafts therefore might be expected also in humans, just as with structural grafts, but is only postponed due to slower remodeling. The clinical results, however, with follow-ups now of up to 15 years, show no evidence of this (Schreurs et al. 1998). In some series, a large subsidence is seen (Eldridge et al. 1997, Masterson et al. 1997), indicating the sensitivity of the method to technical differences in the operative procedure. On the other hand, other series using radiostereometry show a migration magnitude (Nivbrant and Kärrholm 1997) and a migration pattern comparable to a primary hip arthroplasty, with a migration stop after 1–1.5 years (Kärrholm et al. 1999, Ornstein et al. 1999, 2000). In these series, the impacted graft must be as resistant to load as the intact endofemoral cancellous bone at a primary hip prosthetic replacement, not only initially but also during remodeling. The graft must have this property regardless of whether it has remodeled entirely or only consists of dead graft in fibrous tissue.

The mechanical properties of an impacted graft have been determined in bench tests, using a triaxial model adapted from engineering soil mechanics (Brodt et al. 1998). In our study, a rather high resistance to compressive load was found, not only in the fiber-armored graft, but also in the unimplanted ones. The failure-point occurred at 10 times the pressure found in the study by Brodt et al. in 1998. This may in part be due to the fact that our grafts were not morselized, but merely impacted to form a pellet. Our model is less exact and was developed to show an effect of the fibrous tissue enhancement of the graft, in a direct comparison, without attempts to characterize detailed mechanical properties. No true breaking point exists that is related to a breakage of bone trabeculae. The failure point presumably corresponds to the first major sliding of the individual graft pieces. This failure point was defined as the first deviation from the direction of the initially straight curve. Since our goal was only to show a principle, we made no attempts to make stress-strain curves or material compliance estimates.

During remodeling, e.g., after a hip revision, various parts of the impacted graft will be at different healing stages, and unremodeled parts are also placed under high stresses. If an increased resistance to graft deformations can be achieved by fibrous tissue ingrowth in parts that have not yet remodeled into new bone, our findings would be clinically relevant. The strengths of impacted grafts increased by fibrous armoring may explain, at least partially, why no collapse of morselized, impacted grafts occurs with time. It seems that the delayed or reduced new bone ingrowth that we have seen in experiments with impaction is therefore of less importance and may even be beneficial, so long as the graft/fibrous tissue composite remains strong enough to withstand the forces acting on it during remodeling.

We thank Inger Mårtensson, Carina Forslund, Ralf Skripitz and Mats Christensson for technical assistance. This study was supported by the Swedish Medical Research Council (project 2031), the Medical Faculty of Lund, the King

Gustav V Jubilee, Alfred Österlund, Greta and Johan Kock and Tore Nilsson foundations.

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