Compacted cancellous bone has a spring-back effect

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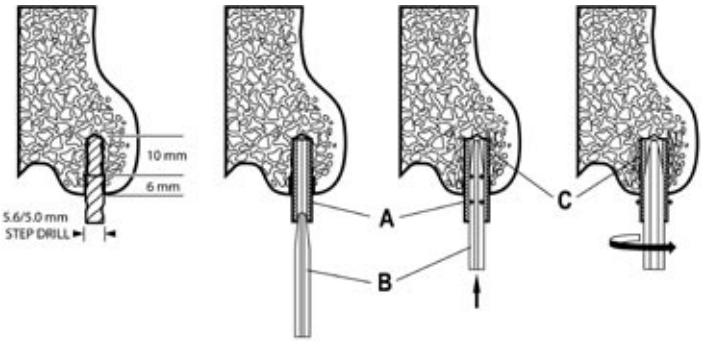
ABSTRACT A new surgical technique, compaction, has been shown to improve implant fixation. It has been speculated that the enhanced implant fixation with compaction could be due to a spring-back effect of compacted bone. However, such an effect has yet to be shown. Therefore we investigated in a canine model whether implant cavities prepared with compaction had spring back. Before killing the animals, we used one of two surgical techniques to make implant cavities of identical dimensions in both lateral femoral condyles of 7 dogs. One side had the implant cavity prepared with compaction, the other side with drilling. The cavities were left empty in vivo for 10 minutes before the dogs were killed. Postoperative micro-CT scanning showed that the diameters of the compacted cavities were significantly smaller than those of the drilled cavities, although they had had identical dimensions initially. Thus we found a spring-back effect of compacted bone, which may be important for increasing implant fixation by reducing initial gaps between the implant and bone.

Clinical studies of cementless implants using radiostereometric analysis have shown that early implant migration is related to late loosening (Ryd et al. 1995, Kärrholm et al. 1997). Moreover, experimental studies have shown that initial implant stability is essential to bone ingrowth (Cameron et al. 1973, Ducheyne et al. 1977, Pilliar et al. 1986, Søballe et al. 1992, Bragdon et al. 1996, Jasty et al. 1997, Heck et al. 1986). It is therefore important to create initial implant stability during surgery so as to ensure the latter stability achieved by bony ingrowth. A new surgical technique that prepares the bone cavity for implantation by compaction of existing cancellous bone has recently been shown to increase initial implant fixation (Channer et al. 1996, Green et al. 1999, Chareancholvanich et al. 2002, Kold et al. 2002a, b). This technique sequentially expands a cavity in existing cancellous bone, unlike conventional rasping/broaching techniques where cancellous bone is removed during preparation of the bone cavity. The increase in implant fixation found with compaction has been ascribed partly to a spring-back effect due to the visco-elastic behavior of cancellous bone (Green et al. 1999, Kold et al. 2002b). A spring back of compacted bone could explain the increase in bone implant contact found with compaction immediately after the insertion of porous-coated implants (Kold et al. 2002a, b). Such implant contact might increase implant fixation both mechanically, by an increase in the frictional forces between bone and implant, and biologically by providing a better bony scaffold for bone ingrowth into the implant. Moreover, the spring-back effect of compacted bone could reduce the initial gaps which are commonly found between the implant and the cancellous bone bed (Schimmel and Huiskes 1988, Paul et al. 1992). On the other hand, compaction may damage the structure of cancellous bone to such an extent that no spring back of compacted bone could occur, and no spring-back effect of compacted bone has yet been shown. Therefore, we determined whether the diameters of circular-shaped compacted cavities



The compaction procedure. We first drilled a 5.0 mm × 10 mm deep cavity and a 5.6 × 6 mm superficial cavity. Then, increasing sizes of split rings (A) were inserted into the hole, and a finned tool (B) was driven into it to compact the cancellous bone in the deep cavity (C). As the split rings were only split apart in one direction, when the finned tool was driven in, the entire tool was turned 360° to compact the cancellous bone around the entire periphery of the deep cavity. Compaction was done until the diameter of the hole measured 5.6 mm.

of the same size would decrease with time when compared with the diameters of drilled cavities.

Animals and methods

Study design

7 skeletally-mature dogs having a median weight of 18 (15–19) kg were used. The protocol was approved by our Institution's Animal Care and Use Committee, and the experiments were performed in an approved animal care facility of the Association for the Assessment and Accreditation of Laboratory Animal Care. The acute procedure was done before killing the animals, which were also being used in a study of implant fixation in the medial femoral condyles. The latter data have not yet been published.

Each dog served as its own control. Thus, compaction was performed on the right femur and drilling on the left femur assuming that there were no preoperative differences in bone quality between the two sides.

Surgical technique

We prepared the implant cavities during general anesthesia with inhalatory isoflurane. The weight-bearing portion of the lateral femoral condyle was exposed via the subvastus approach (Hofmann et al. 1991), and the site of implantation was the central portion of the femoral condyle. We first inserted a 2.1 mm guide wire perpendicularly to the articular surface. All drilling procedures were done at low speed, and the bone was cooled by profuse irrigation to avoid thermal trauma.

Drilling. A cannulated drill created a cavity measuring 5.6 mm in diameter and 16 mm in length.

Compaction. Initially, we drilled a 5.0 mm × 10 mm deep cavity and a 5.6 × 6 mm superficial cavity. Then, by compacting the cancellous bone, the deep cavities were expanded radially in two steps, first to 5.2 mm and then to 5.6 mm (Figure). Thus, we performed compaction until the compacted cavity had exactly the same shape and dimensions (∅ 5.6 mm) as the drilled cavity.

The prepared cavities were cleansed of loosened cancellous bone and irrigated by physiological saline. The cavities were left empty for 10 min before we killed the dogs.

Specimen preparation

The femoral condyles were harvested and stored at –20 °C. The specimens were cut with a water-cooled diamond band saw (Exakt-Cutting Grinding System, Exakt Apparatebau, Norderstedt, Germany), leaving the 10 mm-deep part of the cavities for analysis. Cylindrical specimens, appropriate for micro-CT scanning, with the cavity approximately in the center, were harvested from the cut specimens, using a 14 mm trephine. The 10 mm × 14 mm (length × diameter) specimens were stored at –20 °C before micro-CT scanning.

Micro-CT scanning

We scanned the specimens with a high-resolution microtomographic system (μ-CT 20, Scanco Medical AG, Zurich, Switzerland (Ruegsegger et al. 1996)) in high-resolution mode, with an x-, y-, and z-resolution of about 20 μm. The procedure for scanning each specimen involved a scout view (a two-dimensional side preview of the entire specimen), selection of the area for scanning, scanning, and analysis. A cylindrical section measuring 3 mm in length and 14 mm in diameter at the center

of each specimen was scanned and analyzed. Each section contained 200 microtomographic slices having a slice thickness of 15 μm. For each specimen, 3 random micro-CT slice images, at a distance of 75 μm between them, were used for 2-D evaluation of the prepared holes. The area and the length (longest chord) of the hole was measured and from this, we determined the equivalent circle diameter (D_{Circ}) and roundness of the holes, using the formula: $D_{Circ} = (4 \times Area /\pi)^{1/2}$; Roundness = $(4 \times Area)(\pi \times Length^2)$ (Russ 1990). We also calculated the average value of the 3 micro-CT slices from each specimen. All scannings were evaluated twice, and the intra-individual variation in double measurements was calculated as the coefficient of variation.

Histomorphometry

After micro-CT scanning, the specimens were dehydrated in graded ethanol (70–100%) containing basic fuchsin, and embedded in methyl methacrylate. 3 horizontal sections were made with a microtome (KDG-95, MeProTech, The Netherlands) around the middle of the specimens. The sections, cut at a distance of 1300 μm between them, were 25 μm thick, and counterstained with 4% light-green (Gotfredsen et al. 1989). Blinded histomorphometry was done by using a stereological software program (CAST-Grid, Olympus Denmark A/S). The software places a user-specified grid or counting frame on microscopic fields captured on a monitor attached to a light microscope (objective ×10, ocular ×4). The bone volume fraction (bone volume per total specimen volume) was determined by a point-counting technique in a 2-mm zone immediately adjacent to the cavity. We evaluated 24 random fields (an average of 220 counts) per implant.

Statistics

We used SPSS 10.0 statistical software. Data are presented as medians with interquartile ranges in brackets. The Wilcoxon signed ranks test was used to determine differences between compaction and drilling. Two tailed p-values below 0.05 were considered significant.

Results

Coefficient of variation (CV), expressed in per cent. The CV, determined with double-measurements, was zero for the equivalent circle diameter, and 0.1% for roundness.

The equivalent circle diameter of prepared cavities was 5.1 (5.1–5.2) mm and 5.6 (5.6–5.6) mm for compacted and drilled specimens, respectively ($p = 0.02$).

The roundness of prepared cavities was 0.96 (0.95–0.98) and 0.99 (0.98–0.99) for compacted and drilled specimens, respectively ($p = 0.02$).

The median value (interquartile range) of bone volume fraction for all specimens in a 2 mm zone adjacent to the prepared cavities was 0.29 (0.24–0.35).

Discussion

A spring-back effect of compacted bone has been suggested as an explanation for the increase in fixation of implants inserted with exact-fit or press-fit in vivo (Green et al. 1999, Kold et al. 2002a, b). However, only if the implantation cavities are left empty can one determine whether a spring-back effect of compacted bone occurs. We found that compacted cavities had smaller equivalent circle diameters than drilled cavities although both cavities had originally been made with identical dimensions. Thus, to our knowledge this is the first study providing direct evidence of a spring-back effect of compacted bone.

The reduction in equivalent circle diameter of compacted specimens to 91% of the initially-expanded cavity diameter may be due to the viscoelastic properties of cancellous bone (Linde 1994). The equivalent circle diameter was not reduced completely to the initial 5.0 mm drill hole diameter, and compacted holes were significantly less round than drilled holes. Thus the spring back of compacted bone was neither complete nor symmetrical, which indicates a loss of structural integrity due to breakage of compacted trabeculae. Cancellous bone completely returns to its original dimensions only after nondestructive compression tests, and an upper strain limit of 0.6% during nondestructive compression testing has been suggested in order

to avoid micro-fracture of cancellous bone that will change the architecture of the bone (Linde et al. 1988). Gibson (1985) compared the mechanical behavior of cancellous bone to rigid engineering foams with three distinct regions: the linear, the plateau and the consolidation regions. Initially, the cancellous bone shows an elastic linear behavior until the yield point is reached. Then, a long plateau follows in which the cancellous bone behaves as a perfectly plastic material until it becomes solid, with no remaining porosity. The length of the plateau depends on the apparent density of the bone. The spring back of compacted bone represents the elastic deformation and the nonspring back, the plastic deformation of a stress-strain curve. The lack of a complete and a symmetrical spring back of compacted bone is an important finding for the development of implant designs relying on a spring-back effect of compacted bone. Recoil of impacted morselized corticocancellous bone allograft has previously been shown in vitro where most of the recoil occurred within the first 10 seconds (Ullmark and Nilsson 1999). We did not examine the time frame in which the spring back of compacted bone occurred. However, in our experience from previous implant studies, an implant can be inserted into a compacted bone cavity if it is inserted immediately after the compaction procedure has been performed (Kold et al. 2002a, b).

The mechanical properties of dead bone differ from those of living bone (Linde 1994). We therefore performed this study under in vivo conditions to investigate spring back in bone with unaltered visco-elastic properties. Moreover, we used cancellous bone in canines since it resembles that in humans (Aerssens et al. 1998). The bone volume fraction of 0.29 in our specimens was similar to that found in human arthrotic cancellous bone (Ding et al. 2001)—i.e., 0.24—which is important because the main indication for primary total hip arthroplasty is primary osteoarthrosis (Lucht 2000). However, the magnitude of spring back found in this experimental canine model can not be directly extrapolated to human arthrotic bone, since the mechanical properties of arthrotic cancellous bone have been shown to undergo changes (Ding et al. 2001).

The demonstrated spring back of compacted bone may be the reason for the increase in bone implant contact found at the time of implantation of porous-coated implants inserted with compaction (Kold et al. 2002a, b). An increase in bone implant contact due to spring back of compacted bone may increase implant fixation by mechanical and biological mechanisms. Mechanically, the spring back of compacted bone into the pores of porous-coated implants could result in a mechanical interlock between bone and implant. We have previously shown an immediate postoperative correlation between an increase in bone implant contact and an increase in mechanical fixation of implants inserted with compaction, as compared with implants inserted with drilling (Kold et al. 2002a, b). Moreover, we have previously found an immediate postoperative correlation between increased peri-implant bone volume fraction and an increase in the mechanical fixation of implants inserted with compaction, as compared with implants inserted with drilling (Kold et al. 2002b). Biologically, the increase in bone implant contact due to the spring back of compacted bone may provide a better bony scaffold for the essential bone ingrowth into the implant. It is important to achieve intimate contact between implant and bone, because finite element analysis has shown that gaps of less than 20 μm between bone and implant can substantially change contact stress distribution (Harrigan and Harris 1991). The demonstrated spring back of compacted bone may play an important role in reducing gaps that often exist clinically between the implant and the cancellous bone bed (Schimmel and Huiskes 1988, Paul et al. 1992). The reduction in gaps between implant and bone might also be beneficial because more extensive and better organized bony ingrowth has been observed the closer an implant comes to initial direct apposition to the bone surface (Sandborn et al. 1988).

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