Stiffness and compactness of morselized grafts during impaction

An in vitro study with human femoral heads

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ABSTRACT – The mechanical properties of the impacted material is important when using impaction bone grafting in revision arthroplasty. We did an in vitro study to monitor the stiffness and compactness of morsellized bone grafts during impaction.

Using human osteoarthrotic femoral heads as the bone source we prepared 3 types of morselized grafts with the same bone mill: (1) purely cancellous grafts, (2) cortico-cancellous grafts and (3) cortico-cancellous bone with cartilage remnants.

5 g of bone samples were progressively impacted up to 150 times in a contained cavity. All types of grafts became stiffer and stiffer during the first 30 impactions. After 30 impactions, the grafts' compactness continued to increase slowly without concomitant changes in their stiffness. Over-impaction was not useful, but did not jeopardize the implant stability. The presence of cartilage remnants considerably compromised the increase in stiffness. In contrast, the addition of cortical bone from the femoral neck did not affect the impaction and resultant stiffness.

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Impaction bone grafting was popularized by Slooff et al. (1984) for the reconstruction of cavitary acetabular defects in revision hip arthroplasty. It was further modified by Gie et al. (1993b) for femoral revisions. The procedure entails progressive impaction of morsellized cancellous bone grafts in the acetabular cavity or the femoral canal. A standard prosthesis is then cemented directly in contact with the impacted graft layer, which becomes a load-bearing material. The grafts can be remodeled and gradually transformed into normal living bone, restoring the patient's bone stock.

Implant stability is the technical goal of this procedure and a prerequisite for further remodelling of the grafts (Ling 1997). Kärrholm et al. (1999) claimed that hardness (or stiffness) of the impacted grafts is of primary importance.

The practice of impaction bone grafting has led the surgeons to assume that there is a relationship between impaction, compactness and stiffness of the grafts. However, such a relation has not been substantiated in the literature. If it is obvious that impacting the grafts will aggregate the bone morsels, repeated shocks could damage them and a reduce their individual stiffness. Consequently, the first goal of our study was to address the relationship between the number of impactions applied to the graft's layer, its resulting compactness and stiffness.

The composition of the grafting material is another variable that may greatly affect the mechanical properties. The osteoarthrotic femoral head harvested during hip replacement is the commonest source of fresh frozen allografts for impaction bone grafting. It contains three types of tissues: cancellous bone in its bulk, cortical bone (mainly from the neck) and remnants of articular cartilage or synovial lining. Our second goal was to address two questions: Is it really necessary to shave off the residual articular tissues before milling the head?

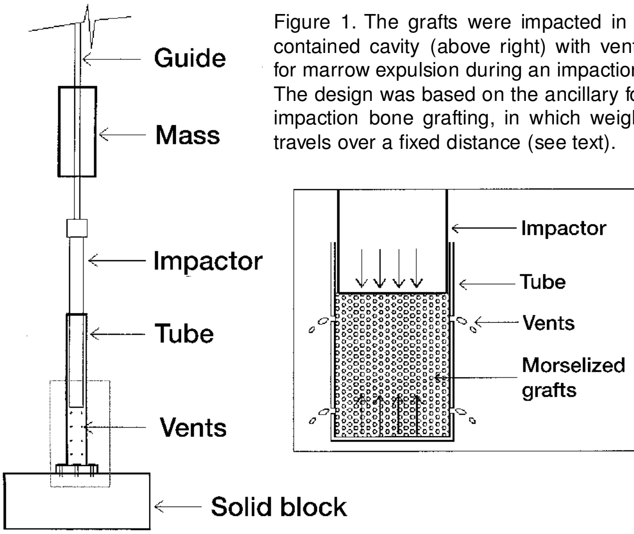

Figure 1. The grafts were impacted in a contained cavity (above right) with vents for marrow expulsion during an impaction. The design was based on the ancillary for impaction bone grafting, in which weight travels over a fixed distance (see text).

Can we leave and use the cortical bone from the femoral neck or is it mandatory to use only cancellous bone?

Material and methods

Preparation of morselized grafts

12 fresh frozen human femoral heads (8 males) were procured at the time of primary hip arthroplasty for osteoarthrosis, and stored at –80 °C. Each femoral head was examined with plain radiography to exclude the presence of severe osteopenia or substantial cystic lesions.

Two separate batches were made of 6 femoral heads each. The median age of the patients was 63 (58–73) years in batch 1 and 72 (51–83) in batch 2. Each batch was processed to produce two types of grafts thus allowing a paired comparison. The femoral heads were cut into two halves in the coronal plane (an anterior and a posterior half) on a band saw using the fovea femora capitis as the reference point. Half-femoral heads were weighed separately before and after processing to estimate the loss of material.

In the first batch, all adherent soft tissue was shaved from one half of each head (alternatively the anterior or the posterior). Articular cartilage and cortical bone from the neck were shaved off with a band saw to obtain pure cancellous grafts. This method minimized the bone loss. The other half of the same head was left intact. These half heads were used to prepare the cortico-cancellous grafts with articular cartilage.

In the second batch, one half of each femoral head was processed to obtain pure cancellous samples, as in the first batch. Preparation of the cortico-cancellous graft samples involved retaining the cortical bone from the femoral neck, but removal of the articular cartilage and adherent soft tissue.

Each batch consisted of pure cancellous bone as control and the other type of graft (cortico-cancellous with or without cartilage) as test groups.

These half-heads were milled separately twice for each type, as done in our surgical practice, with the small rasps of the Noviomagnus bone mill (Spierings, Nijmegen, NL). The size of the morselized particles was a mean 3.3 (SD 1) mm. Each type of morselized grafts was mixed in a bowl and sampled in units of 5 g each. 18 samples of each type were selected randomly for the mechanical testing.

Impaction procedure

The impactions were done with an apparatus which consisted of an aluminum tube (inner diameter 14.6 mm) to contain and confine the grafts (Figure 1). 36 holes (1 mm diameter) had been made in it to facilitate expulsion of bone marrow during an impaction. The tube was fixed to a solid aluminum block. A solid cylindrical aluminum impactor (diameter 14.4 mm) telescoped freely into the cylinder. An iron rod of 1 m was placed on top of the impactor. This served as a guide for a mass (simulating the classical impaction instrumentation) of 455 g.

The 5 g samples of morselized grafts were thawed at room temperature, 2 hours before the mechanical test. One sample was loaded in the cylinder and passed through the testing at a time. Preliminary tests showed that in this model some changes occurred with up to 150 impactions.

Parameters

3 parameters were measured to describe the changes in the material during impaction. 2 of these, the

height of a contained cylinder of morselized grafts and its elastic modulus, were measured at the 1st, 3rd, 5th, and 10th impactions, and there after in multiples of 10, until the 150th impaction. The height (mm) was measured between two points (the top of the cylinder and the top of the impactor) with a digital caliper, after the telescoping of the impactor into the tube. Elastic modulus (or stiffness) was measured by placing the testing device, without its guiding rod and mass, between the plates of a testing machine (Zwik Machine, Zwik GmbH & Co. Ulm, Germany). The upper plate of the machine gently compressed the impacting material at a speed of 0.5 mm/min. The load was measured with a 2 kN load cell and the displacement by an extensometer (Multisens, Zwick) placed across the tube and the impactor. To avoid excessive "compression" of the grafts during measurement of the elastic modulus, the test was limited to a range of 80 N of force (0.5 MPa) or 0.3 mm of displacement. The elastic modulus (MPa) was calculated as the slope of the curve between 60% and 98% of the maximal load (the linear part of the curve). After reaching the measurement limit, the cylinder of the grafts was immediately unloaded.

Knowing the time-dependent mechanical properties of morselized grafts (creep and recoil, Ullmark and Nilsson 1999), we standardized the testing conditions for each sample. The height and elastic modulus measurements were performed at intervals of 1 min between impactions.

The third parameter was the changes in the apparent density of the impacted material. For this analysis, we stopped the procedure at various levels of impaction, gently expressed the impacted cylinders of graft in their original plastic tubes (diameter 15 mm) and rapidly froze the specimens. Consequently, of the 18 samples in each group, 4 were impacted until the 3rd impaction, 4 until the 10th, 4 until the 50th and 6 until the final 150th impaction.

To evaluate the density, the frozen graft samples were subjected to peripheral quantitative computerized tomographic scanning (XCT Research SA pQCT, Germany). Density measurements were taken from 4 different levels of the impacted graft cylinder (slice thickness: 0.7 μm). These levels were selected by dividing the height of the cylinder into 4 equal quarters. The density of a sample was calculated as the mean value of the four slices, as g/cm^3 of bone content, according to the calibrations performed under uniform conditions.

Statistics

The differences in the changes in height and elastic modulus due to the type of grafts were analyzed using repeated measures ANOVA. The within subject (sample) factor was the number of impactions and the between subject factor was the type of graft. Since we analyzed the density in different samples during the impaction, we compared the mean density of each type of graft at the four different levels of impaction with a two-sample t-test. These analyses were performed using SPSS 9.0 (SPSS Inc, USA) separately for batches 1 and 2. The significance level was set at $p < 0.05$.

Results

Material weight loss during preparation of the different grafts

Preparation of the pure cancellous samples from a femoral head induced a mean loss of 36 (SD 6)% of material in batch 1 and 40 (SD 7)% in batch 2. In batch 2, removal of soft tissue and cartilage caused a loss of 25 (SD 2)% of material.

Height

The height showed a steady decline corresponding to the log of the number of impactions (Figure 2). In batch 1, the height of the cortico-cancellous bone with cartilage was higher than that of the pure cancellous bone ($p = 0.02$, ANOVA with repeated measures). In batch 2, the change in height also differed slightly with a faster impaction of the cortico-cancellous bone without cartilage than of the pure cancellous bone grafts ($p = 0.006$).

Elastic modulus

The grafts gradually stiffened until the 30th impaction (Figure 3).

In batch 1, the rise in the elastic modulus for the pure cancellous bone was higher ($p < 0.001$) than that of the cortico-cancellous bone with cartilage. The mean final modulus of the pure cancellous impacted grafts was about 48 MPa, while

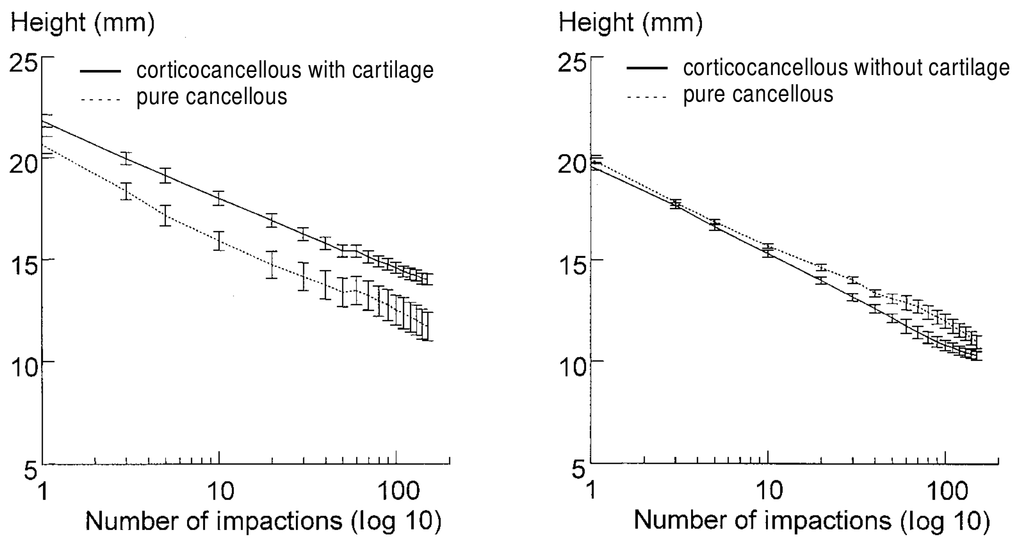

Figure 2. The evolution of the height during the impaction, for batch 1 and batch 2. Note that the number of impactions is presented as a log scale. The line represents the mean value and the bars the standard error of this mean value. Up to 3 impactions n 18 (number of measurements performed), up to 10 impactions n 14, up to 50 impactions n 10, up to 150 impactions, n 6 for each type of graft.

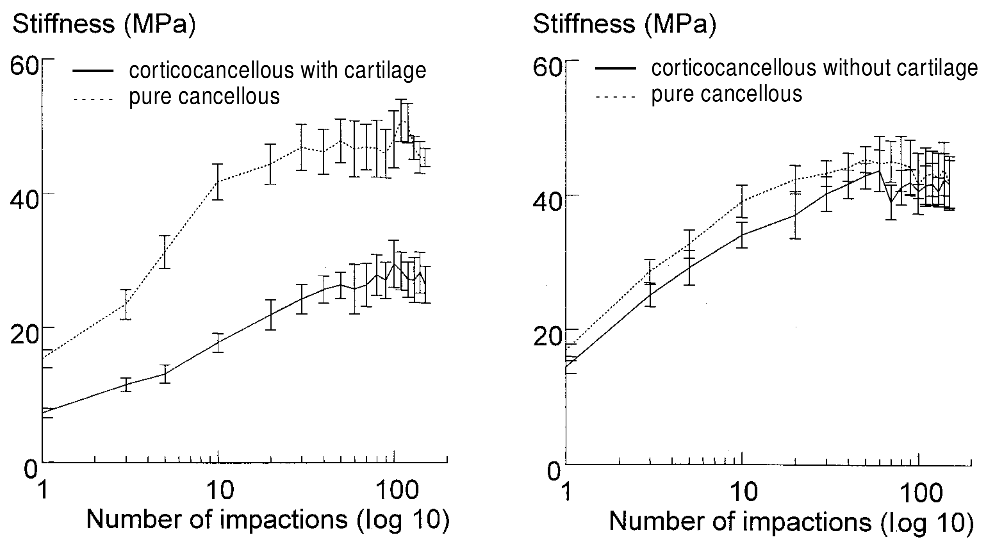

Figure 3. The evolution of the stiffness (Emod) of the material grafts with progressive impaction. Same number of data as in Figure 2 are used for mean and stardard error of the mean (bars) calculations. In batch 1, note the difference in the modulus values reached between the pure cancellous and cortico-cancellous with cartilage while, in batch 2, such a difference is not observed.

it was 26 MPa for cortico-cancellous grafts with articular cartilage. Furthermore, the cortico-cancellous bone with cartilage reached the same elastic modulus value after 150 impactions as did the pure cancellous bone after 5 impactions.

In batch 2, rise in the elastic modulus was similar to that of the pure cancellous and cortico-cancellous bone without cartilage (p = 0.6) and the mean final elastic modulus was the same, 42 MPa.

Mean density

Mean density showed a steady increase with further impactions (Figure 4).

In batch 1, the pure cancellous grafts showed

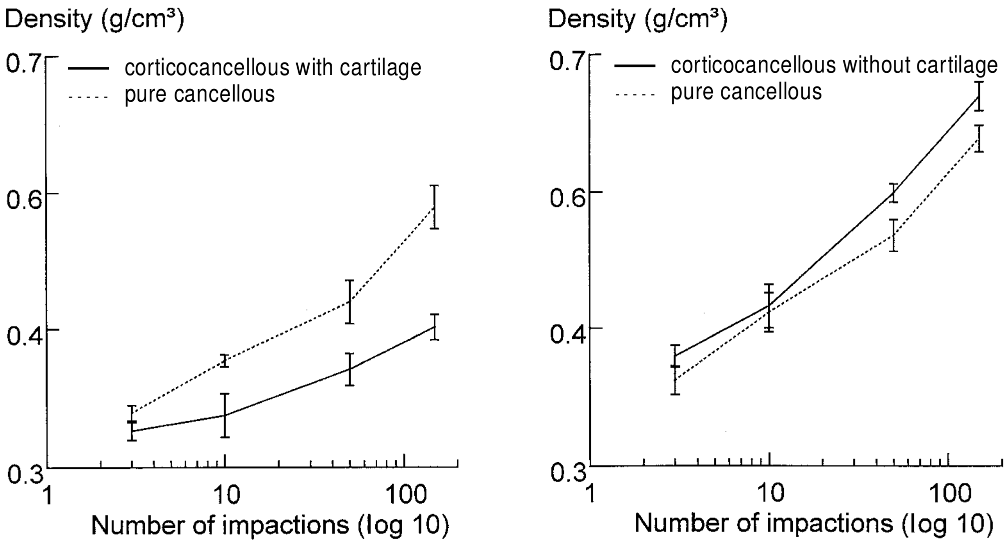

Figure 4. The evolution of density (g/cm^3) in batches 1 and 2 on successive impactions. At 3, 10 and 50 impactions, density measurements were carried out on 4 samples of each type of grafts. At 150 impactions, 6 measurements were done. Note the significant difference in the rise in densities after 50th impaction unto the 150th impaction.

higher densities values than the cortico-cancellous with cartilage at 10 ($p = 0.01$), 50 ($p = 0.05$) and 150 impactions ($p < 0.001$).

Mean density values of the impacted cylinders in batch 2 differed between the pure cancellous and cortico-cancellous grafts at 50 ($p = 0.03$) and 150 impactions ($p = 0.001$). Cortico-cancellous grafts reached a slightly higher density than its pure cancellous control.

Discussion

We obtained morsellized grafts from human femoral heads that were harvested during primary hip arthroplasties. The femoral heads were not treated or defatted (Brewster et al. 1999) before performing the tests with all their normal constituents, especially the marrow. On preparing the material for batches 1 and 2, our goal was to obtain 2 batches of samples as homogeneous as possible and prepared from the same 6 femoral heads. To rule out the presence of regional discrepancies of bone quality and trabecular patterns (Brown and Ferguson 1980), we cut the femoral heads in the coronal plane into two halves. By mixing the morselized grafts, we could reduce the variations between the samples that would reflect the quality of each individual head (Brodt et al. 1998). Therefore the only difference between the groups could be ascribed to the presence or absence of some constituent of the original femoral head (cartilage or cortical bone from the neck).

We made every effort to standardize all parameters related to the impaction procedure. We impacted the grafts by intermittent blows, instead of compressing them slowly, to suit the clinical impaction procedure (Brodt et al. 1998, Ullmark and Nilsson 1999). The drop of the mass was very reproducible, but does not exactly mimic the clinical situation. The characteristics of the shock wave are not the same as the one found in an operating room during surgery. Expulsion of the marrow through small holes in the tube may not be as complete and easily performed in a bleeding diaphysis. Keeping these caveats in mind, it must be clear that the number of impactions in our study does not correspond to the number of impactions that the surgeon would have to perform. Our experimental set-up was meant to simulate the impaction procedure itself, but not the progressive prosthetic migration seen in clinical practice (subsidence). This implant migration is a process going on during thousands of physiological loading cycles while we tested the effects of a few blows.

Studies have been done on the mechanical behavior of morselized grafts considered as a material. Brewster et al. (1999) investigated the shear modulus of impacted grafts, on a few samples, and found a relationship between shear strength and energy of impaction. Brodt et al. (1998) did triaxial tests on unimpacted, but slightly compressed, morsels. Giesen et al. (1999) and Ullmark et al. (1999) studied the time-dependent properties (creep and recoil) of the impacted material. In our study, we followed the graft layers from a loose particulate state towards a well impacted state. Compactness and compressive stiffness of the graft layer were monitored to obtain insight into the changes in the material during the impaction process.

Morselized grafts became consistently more deformed, compact and dense during the impaction. The recduction in height (corresponding to the rise in compactness) is due to the deformation of the grafts and expulsion of the marrow through the vents of the tube. The changes in height or density further fit a decimal log of the number of impactions. This means that the reduction in height was almost the same during the first 10 impactions and from the 10th to the 100th impaction.
For the modulus such a relationship did not exist. After the 30th impaction, the modulus stabilized and reached a plateau. We observed a maximum level of impaction after which, on further impactions, we saw no further rise in the elastic modulus. During that phase, the aggregated particles were probably becoming more damaged. Structurally damaged cancellous bone is known to have a much lower elastic modulus (Keaveny et al. 1994). However, on impacting the graft layer, such damage would be compensated by the ongoing slow rise in compactness of the morselized grafts. On the other hand, in our experiment, no reduction was seen in the modulus of the grafts. So, we have no experimental data to show that overimpaction is dangerous for the mechanical integrity of the graft layer and hence for initial implant stability. The general relationship between the number of impactions and stiffness shows that the quality of the impaction itself is of primary importance for obtaining a sufficiently stiff layer of grafts and a stable implant.

Our experiments were also intended to give the surgeon some basis about the best way to prepare femoral heads before milling. We estimated that the minimal loss of material in preparing a femoral head to obtain pure cancellous bone is 40% of the initial graft mass. In comparison, the minimal loss related to the removal of soft tissues and retaining the neck is 25%. This loss is mainly due to bone debris produced by the saw and the mass of cartilage on an osteoarthrotic head, which is probably less than 10% of the cortico-cancellous morselized grafts with cartilage. Comparing the loss in batches 1 and 2, it can also be calculated that the cortical neck is 15% of the mass of the allograft.

Although Slooff et al. (1996) report the use of cancellous graft alone, other teams in the United Kingdom morselized "the whole femoral head" (Brewster et al. 1999, Gie et al. 1993a). This terminology is somewhat confusing but, obviously, no team has reported leaving the cartilage in place.

The presence of cartilage prevented efficient impaction of the morselized grafts, probably due to its elastic nature. This confirms that cartilage must be removed before milling.

The cortico-cancellous grafts without the articular cartilage had stiffness values as good as in their control group. It seems unlikely that a few cortical bone fragments will significantly change the biological response of the graft. However, our experiment did not concern the biological aspect of the impaction bone grafting technique and more clinical follow-up studies or in-vivo animal studies should tackle this question. Leaving the cortical bone from the neck did not interfere with the impaction of the morselized grafts or the creation of a stiff layer of bone. When there is a limited supply of allografts (Galea et al. 1998) saving 15% of the material is probably worthwhile.

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