Reconstruction of femoral defects in revision hip surgery

RISK OF FRACTURE AND STEM MIGRATION AFTER IMPACTION BONE GRAFTING

The use of impaction bone grafting during revision arthroplasty of the hip in the presence of cortical defects has a high risk of post-operative fracture. Our laboratory study addressed the effect of extramedullary augmentation and length of femoral stem on the initial stability of the prosthesis and the risk of fracture.

Cortical defects in plastic femora were repaired using either surgical mesh without extramedullary augmentation, mesh with a strut graft or mesh with a plate. After bone impaction, standard or long-stem Exeter prostheses were inserted, which were tested by cyclical loading while measuring defect strain and migration of the stem.

Compared with standard stems without extramedullary augmentation, defect strains were 31% lower with longer stems, 43% lower with a plate and 50% lower with a strut graft. Combining extramedullary augmentation with a long stem showed little additional benefit (p = 0.67). The type of repair did not affect the initial stability. Our results support the use of impaction bone grafting and extramedullary augmentation of diaphyseal defects after mesh containment.

Failure of total hip replacement results in more than 40 000 revision procedures being carried out each year in the USA alone. Some, especially younger, patients face multiple revision procedures. Usually, less host bone is available at each revision because of stress shielding, osteolysis, loosening, failure of the implant, or infection. Further bone loss may occur during removal of the failed implants. Uncemented revision is a useful option which gives good mid-term results, but it may lead to proximal stress shielding and further osteolysis. Revision techniques which restore bone stock can help to ensure the presence of sufficient bone at future operations. The use of impacted morsellised bone graft is one such technique.

Intra-operative and post-operative fractures are the most common serious complications associated with the technique. Post-operative diaphyseal fractures occur in 5% to 10% of cases and are associated with cortical windows or perforations. Such diaphyseal defects are present, or created, in 13% to 19% of revision cases. The risk of fracture decreases when a femoral reconstruction method is used which reduces strains around the defect.

In revision surgery, metal meshes, plates, cortical strut allografts or a combination of these have been used to reconstruct diaphyseal defects in the proximal femur, before insertion of a cemented femoral stem. Alternatively, the defect can be bypassed using a long-stemmed prosthesis. In order to minimise the risk of fracture during femoral impaction bone grafting, some authors have used mesh fixed by cerclage wires and have advocated a plate or strut graft in conjunction with a long stem. Others have used long stems for the elderly, but extramedullary augmentation combined with a standard stem for younger patients. It is unknown whether and how much, these reconstruction methods reduce strain when used in conjunction with impacted morsellised bone graft. At present, there are few data on which to base a decision on the repair method to be used.

Given these uncertainties, we undertook this laboratory study to answer the following three questions: 1) do extramedullary augmentation or longer stems reduce defect strain?; 2) if so, does combining extramedullary augmentation with a long stem further reduce the defect strain?; and 3) do cortical defects and their repair methods increase migration of the femoral stem?

Materials and Methods
We prepared 14 large composite femora (3103-2; Sawbones, Malmö, Sweden), in order to simulate American Academy of Orthopaedic
Surgeons (AAOS) type-II cavitary defects, by removing all of the polyurethane foam which represented cancellous bone. The cortices were then reamed to an internal diameter of 18 mm in order to represent the cortical thinning typically encountered during revision surgery. In 12 of the 14 diaphyses, a lateral cortical perforation 18 mm x 40 mm was machined in the region of the tip of a standard primary prosthesis, to simulate an AAOS type-III combined defect.

Four uniaxial strain gauges (FLA-3-23; TML, Tokyo, Japan) were mounted on the anterior and posterior edges of the defect where the strain was maximal and on the corresponding locations of the intact cortices. The 12 perforated diaphyses were reconstructed with either X-Change femoral mesh, mesh and a Dall-Miles plate (both Stryker, Newbury, United Kingdom) or mesh and a strut graft (n = 4 each). The strut grafts were prepared from the cortex of a composite femur. All three types of repair were fixed using four Dall-Miles cables (Stryker).

Bone graft was obtained from the distal part of freshly-frozen porcine femora. Previously, porcine bone has been used for biomechanical testing. This bone was morsellised using a manually-operated bone mill (Noviomagus; SMT, Nijmegen, The Netherlands), producing particles with a mean size of 5 mm (1 to 10).

Operative technique. The cavitary defects were reconstructed by impaction of the morsellised bone graft using the X-Change reconstruction system (Stryker), following a standard technique. A cement plug with a guide wire (Stryker) was first inserted to a level 2 cm below the planned tip of the prospective prosthesis. Morsellised bone was inserted on top of the cement restrictor and compacted using distal impactors, until a layer of tightly packed bone, 2 cm thick, was formed. A new medullary canal was then reconstructed from impacted morsellised bone by inserting bone particles inside the cortical shell, which were then impacted using proximal tampers. These proximal tampers were sized such that the new medullary canal would leave space for a prosthesis plus a cement mantle 2 mm thick. Bone cement (Simplex P; Stryker) was mixed without vacuum in a disposable gun and injected after four minutes in retrograde fashion, with a proximal seal to ensure pressurisation.

In the 12 femora with a reconstructed perforation, either a standard (155 mm) or a long (205 mm) prosthesis (Exeter; Stryker) was implanted. The long implant bypassed the perforation by two cortical diameters, in keeping with evidence from previous laboratory studies. Hence, six combinations of defect repair were created (mesh alone, mesh and plate, or mesh and strut, combined with either a long or a short femoral stem (n = 2) each). Standard Exeter stems were implanted into the two femora with cavitary defects only and served as controls (n = 2). The femora with prostheses were kept at room temperature for a day, in order to allow curing of the cement. They were then stored at -18°C.

Mechanical testing. The femora were defrosted overnight. Then, a length of polyester webbing sling (PS030/50; Load-Lok Int, Oud-Beijerland, The Netherlands), simulating the abductor muscle, was fixed to the greater trochanter using two-part epoxy adhesive and eight self-tapping screws, each 5 mm long. These screws did not protrude through the cortical shell and did not, therefore, provide extra anchoring for the prosthesis. A purpose-built movement transducer, based on six linear potentiometric displacement transducers (S8FLP10A; Sakae, Kawasaki-city, Japan) and with six degrees of freedom, was fixed between the proximal prosthesis and the calcar region (Fig. 1). The femora were then positioned in a jig fixed in a materials testing machine (ESH Testing Ltd, Brierley Hill, United Kingdom). The jig was designed to apply a load through the hip and greater trochanter as described by McLeish and Charnley and was comparable with the jig used by Burke et al. Loading of the prosthetic head was achieved through an acetabular cup, which was fixed on the jig. The proximal femur was orientated at an angle of 12° medially...
and 8° posteriorly, relative to the vertical. This orientation ensured that the force on the femoral head was directed 23° laterally and with 20° of retroversion, in accordance with measurements of in vivo prosthetic loads using telemetrised implants.21,22 The prosthetic head was loaded cyclically at a frequency of 1 Hz. Initial loading cycled between 10 N and 500 N. Every 100 cycles, the peak load was increased in steps of 500 N until it reached 2500 N. This regime was chosen in order to allow comparison of defect strains and migration of the prosthesis for all repair methods, even if some would fail at lower load levels. Strains and migration were digitised with a frequency of eight samples per cycle and stored on a personal computer for further analysis.

**Statistical analysis.** The outcome measures were, 1) the mean amplitude of cyclic anterior and posterior defect strains as predictors of risk of fracture (strain (ε) is expressed as microstrain, με; 1 με = 1 10^-6 ε); 2) permanent subsidence and retroversion of the stem after 100 cycles of loading as predictors of migration of the stem. All statistical analyses were performed by NCSS 2001 (NCSS Statistical Software, Kaysville, Utah) and Systat 11 (Systat Software Inc, Point Richmond, California). Analysis of strains was by one-way analysis of variance (ANOVA) and of migration of the prosthesis by two-way ANOVA, with the reconstruction method and stem length as independent factors. Further analysis of migration was by one-way ANOVA. The Student-Newman-Keuls post-hoc test was used to test for significance, in case the null hypothesis of no difference was rejected. In all cases a p value of 0.05 was assumed to denote significance. The results are given as the mean and SEM.

**Results**
All 14 femora sustained cyclic loading up to 2500 N without fracture or excessive migration of the prosthesis.

**Defect strain.** Strain amplitude at the defect strongly depended on the reconstruction method. On testing a defect without surgical reconstruction, i.e. without a long stem or extramedullary augmentation, strains were three times larger than the cortical strains in the control group (a cavi-tary defect alone).

Compared with the reconstruction method of a standard stem without further augmentation, the strains associated with the defect were a mean of 31% lower (28% to 34%) when using a longer stem, 43% lower (37% to 49%) when using a plate and 50% lower (50% to 51%) when using a strut graft (Table I). All of these differences were significant (Table II). Using a long stem with externally-augmented femora gave a further strain reduction of 2% (-7% to +11%) when using a plate and 5% (-1% to +11%) with a strut graft. This was not significant (Tables I and II).

Only when using extramedullary augmentation were the defect strains close to those of the control.

**Migration of the stem.** After each increment in peak load the stems subsided during the first few load cycles. However, at each subsequent load cycle they subsided at a reduced rate until the next increment. The stems in the perforated femora augmented with a plate subsided about twice as much as those in the non-augmented or strut graft-augmented femora (Table III). Subsidence was influenced by the repair method but not by stem length (two-way ANOVA, p = 0.04 and p = 0.93 respectively). Compared with the control cases, the subsidence of the stems in the plate-augmented femora was similar, but in the non-augmented and strut-augmented femora, was about half that of the control group. Control versus all others p = 0.06 two-way ANOVA.

Retroversion of the stem in the perforated femora was similar for all cases (Table III). The largest retroversion occurred in the control cases (mean 1.1°).

Neither repair method nor stem length influenced retroversion (two-way ANOVA, p > 0.90 for both factors).

**Discussion**
In our study, both extramedullary augmentation and longer stems reduced the strain around a defect by 31% to 50%. We also found that complementing extramedullary aug-
mentation with a long stem further reduced strain by 2% to 5%, an insignificant reduction. Finally, we found that the cortical defects and the repair methods were unlikely to cause increased migration of the stem.

Defect strain for standard stems in perforated femora, repaired with mesh only, were over 5200 microstrain. In comparison, longer stems reduced these strains by 31% to 3600 microstrain and extramedullary augmentation reduced them by 43% to 50% to a maximum of 3000 microstrain.

Such reductions of strain have a large impact on the risk of fracture, which can be illustrated using data from in vitro fatigue tests. These data indicate that strains of 4000 microstrain would cause fatigue fracture of human cortical bone in a year (one million cycles), but strains of 4800 microstrain would cause fracture in a month. Because the quality of bone differs, our results cannot be translated directly, but they do fit the authors’ clinical observation that fracture at diaphyseal defects is likely with a standard stem, but not after augmentation.

Our observation of a defect strain reduction of 31% with a long stem is broadly in line with the reduction of 25% around a drill hole found in an earlier study. In addition, our finding that plates and strut grafts give a larger strain reduction than long stems is in line with a finite-element study of peri-prosthetic fracture fixation, which showed that strut graft fixation gave cortical strains of approximately two-thirds of those around long stems.

Some authors have proposed the combination of extramedullary augmentation and a long stem. Our second question was, therefore, whether complementing extramedullary augmentation with a long stem would further reduce defect strains. Our study showed that a longer stem gave a small but insignificant extra reduction.

Adequate early stability is imperative for the success of impaction grafting. Our final question was whether cortical defects and their repair methods would increase migration of the stem. We found no evidence of this. An important factor is the degree of graft impaction achieved by the surgeon, which could account for 94% of the variation of measurements for early migration of the stem and 90% of the variation in early tibial tray migration. We suspect that coincidental differences in graft impaction may well explain the differences in subsidence of the femoral stem found in our study.

We also found no evidence that longer stems reduce subsidence. This is in contrast with the findings from a finite-element study, which showed that longer stems could substantially reduce subsidence. However, in that study the longer stems extended into the normal femoral canal, whereas in our study a layer of impacted bone surrounded all of the stems. This could account for the different findings.

Our study is experimental and was designed to address specific clinical concerns regarding the selection of extramedullary augmentation and length of stem when dealing with diaphyseal defects in the context of impaction grafting. In keeping with any similar laboratory study, a number of assumptions and simplifications were made. The first concerned the mechanical loading conditions. The reconstructed femora were loaded with a combination of an axial joint load orientated slightly laterally and retroverted and an abductor load. A single orientation for the joint load may simplify the true loading conditions, but is common practice for such studies. Although instrumented hip implants show only small variations in the orientation of joint force, they do show variations in the torsional direction. This could cause torsional toggling of the implant. By ignoring these variations, we may have overestimated torsional stem stability. However, implant retroversion in our study was similar in magnitude to that measured by Ornstein et al., suggesting this simplification had at most, a minor effect.

Representing muscle loading by a single abductor force is also a simplification. It may exaggerate bending of the femur by ignoring, in particular, the iliotibial tract. In reality, however, the iliotibial tract is only one of the many muscles acting on the femur during gait. A recent study by Stolk, Verdonschot and Huiskes compared cement stresses and bone strains around an implant, assuming a joint load combined with the full set of muscle loads and the combination of joint load and abductor force, as used in our study. In the study by Stolk et al., the stresses in the cement and strains in the bone around the implant were very similar in the two cases. Hence, although our study may have overestimated strains around the defects, the degree of overestimation was probably small.

A further limitation is our use of artificial femora and porcine cancellous bone, instead of cadaver femora and human cancellous bone. Artificial bone models have the advantage of minimising the experimental variations in bone geometry and properties, which can be considerable. The mechanical properties of the artificial femora which we used have been validated by comparison with cadaver specimens. The main deviation from the clinical situation was probably the large tensile strength of the artificial cortex, approximately 30% greater than that of human femoral cortical bone (172 vs 131 MPa). This high strength may explain why no fracture occurred in our experiments. When the cortex is weaker and less stiff, strains are larger and failure more likely. Porcine cancellous bone has advantages in terms of availability and laboratory safety. Compared with cancellous bone from the dog, cow and sheep, the fracture strength of porcine cancellous bone is very close to that of man.

Finally, a potential benefit of longer stems which we have not addressed in our study is their ability to reduce the risk of re-revision by being cemented into a newly opened interface. This reduces the risk of re-revision by a factor of 35. Finite-element analysis suggests that a longer stem in this situation could substantially reduce the relative movement between the cement and bone, and thereby reduces
cement stresses. However, when using impaction grafting methods, the advantage of fixation to a previously unused part of the canal is likely to be limited.

In conclusion, the results from our study show that when using impaction bone grafting for revision hip surgery in the presence of a diaphyseal cortical defect, a longer stem or extramedullary augmentation is very advantageous. The choice between a plate or strut graft cannot be made on the basis of this study. In our study, bypassing a cortical defect with a long stem in addition to extramedullary augmentation gave only a small additional reduction in cortical strain. However, this ‘belt-and-braces’ approach may well be justified by clinical experience, since the unacceptable failure rate encountered when a defect was not bypassed with a long stem has led one group to change its practice. The authors would like to acknowledge Stryker Howmedica for the provision of the implants and surgical equipment for this project. The authors also acknowledge that Tomoki Takahashi contributed significantly to the experimental part of this study. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References