We studied various aspects of graft impaction and penetration of cement in an experimental model. Cancellous bone was removed proximally and local diaphyseal lytic defects were simulated in six human cadaver femora. After impaction grafting the specimens were sectioned and prepared for histomorphometric analysis.

The porosity of the graft was lowest in Gruen zone 4 (52%) and highest in Gruen zone 1 (76%). At the levels of Gruen zones 6 and 2 the entire cross-section was almost filled with cement. Cement sometimes reached the endosteal surface in other Gruen zones. The mean peak impaction forces exerted with the impactors were negatively correlated with the porosity of the graft.

Impaction allografting with the potential to restore bone stock is an attractive technique for the treatment of failed total hip replacement (THR). However, a high prevalence of subsidence of the stem (>10 mm) and intra- and post-operative fracture has been associated with the procedure.1,12 Other clinical studies have reported more promising results.3-8

Examination of specimens taken at post-mortem and biopsy showed that the allograft bone remodelled in only a few millimetres peripherally, while the inner zone consisted of mainly necrotic allograft partially embedded within fibrous tissue.9-12 Tagil and Aspenberg13 demonstrated in a bone-chamber model that this fibrous tissue enhanced the compressive strength of the allograft layer. However, the long-term behaviour of this fibrous tissue bone composite is not known.13

The mechanical and biological environments to which allograft bone is subjected in a revision hip arthroplasty are not clear. Most research has focused on morsellised allograft bone alone, omitting the infiltration of the cement into the graft.14-19 The structural properties and thickness of this graft-cement composite layer may be important factors in determining the strength of the cement-graft-cortical-bone complex. The degree of impaction of the graft has been shown to influence both the shear strength of the allograft layer and the incorporation of the graft, but has not been determined in a clinically relevant circumstance.15,20 Analysis of retrieved specimens has focused mainly on a qualitative description of the incorporation of allograft bone and not penetration of cement or the porosity of the graft.9-12 The impaction forces which are required to achieve firm packing of the bone chips remain unknown, hence the variability seen in clinical practice and the prevalence of fractures. An incomplete cement mantle, which may lead to its subsequent fracture with subsidence of the stem, has been described but no detailed histomorphometric analysis is available.21 Our study attempts to describe the morphology of the graft-cement-cortical bone complex as it appears after an impaction allografting procedure.

The objectives in this clinically relevant cadaver model were to determine the porosity of the graft, the thickness of the cement mantle, the penetration of the cement into the allograft bone and the residual layer of allograft free from cement at various sites within the femur. The forces transmitted during impaction of the graft were also measured.

Materials and Methods

We osteotomised the necks of six fresh frozen human cadaver femora. Then, using a high-speed burr, all the cancellous bone was removed from the proximal femoral metaphysis and local lytic defects were created in the diaphysis to simulate cavitary bone loss which might be encountered at the time of revision THR. Three experienced surgeons (PM, BAM, CPD) performed the impaction allografting, each on two cadaver femora, using the X-Change revision system (Howmedica Inc,
Diagram showing the 14 levels which were matched based on anatomical landmarks. The levels were grouped according to the zones of Gruen et al.22

Rutherford, New Jersey). Before impaction, the intramedullary canal was occluded 2 cm beyond the most distal lytic defect with a plastic plug stabilised by two Kirschner wires. Three to four fresh frozen femoral heads were used for each specimen. They were thawed in water, cut into blocks, 10 x 10 x 25 mm in size, and morsellised in a Lere bone mill (DePuy, Warsaw, Indiana). None of the articular cartilage, fat or bone marrow was removed from the morsellised allograft chips. The size distribution of the particles of the bone chips was determined in a sample of defatted bone by sieving analysis as described by Brewster et al.15 The chips were passed through sieves with successively smaller pores, using mesh sizes of 0.6, 1, 2, 2.36, 3.35, 4 and 8 mm (0.6 to 4 mm, Fisher Scientific, Nepean, Ontario, Canada; 8 mm, custom made).

A load cell (MC3-6-1000; AMTI Inc, Watertown, Massachusetts) was placed below the femur during the procedure to measure the impaction forces which were acquired at a frequency of 2.5 kHz and stored in a personal computer.

The procedure was carried out according to the guidelines of the X-Change revision system (Howmedica Inc) with one exception. The surgeon began using the proximal impactors when the distal impaction line, i.e. the depth that the tip of the stem will reach on implantation, was reached with the distal impactors. In four of the six specimens the distal impactors were used past the distal impaction line.

After impaction, two packages of low-viscosity Simplex cement (Howmedica Inc) were mixed and injected into the medullary canal in a retrograde manner. A proximal femoral seal was applied and the cement pressurised with a Prism II cement gun (DePuy). The pressure was maintained until the viscosity of the cement was appropriate for the insertion of the double-tapered polished Exeter stem (Howmedica Inc). After the cement had polymerised, anteroposterior and mediolateral radiographs were obtained to verify the position of the stem before it was removed. Coloured bone cement prepared by mixing Simplex cement and food colouring (Scott-Bathgate Ltd, Winnipeg, Canada) was used to fill the cavity left by the stem to distinguish the bone cement from the stem in the histological sections.

The femora were cut in transverse sections 6 mm thick with a diamond saw (Exakt Technologies Inc, Oklahoma City, Oklahoma). From the 27 to 36 sections obtained from each femur, 14 were used to match to 14 levels, based on anatomical landmarks and the tip of the stem (Fig. 1). These levels were grouped into five areas of the zones of Gruen, McNeice and Amstutz22 and subjected to non-decalcified histomorphometric analysis (Fig. 1). The sections were fixed in 10% buffered formalin and then dehydrated in 70%, 95% and 100% ethanol. The dehydrated sections were infiltrated with a light-curing resin (Technovit 7200; Kulzer Ltd, Wehreim, Germany) in an incubator. Subsequently, the resin was polymerised under ultraviolet light. The bone cement was not dissolved during this procedure. From each 6 mm section a section was cut 400 µm thick, ground to 100 µm and stained with Alizarin Red S. The histological sections were photographed with a high-resolution digital camera (1600 x 1200 pixels; CoolPix 950 Nikon; Melville, New York) and stored for image analysis.

The porosity of the impacted allograft, the thickness of the cement mantle, the penetration of the cement and the thickness of the remaining allograft layer were measured in anteroposterior, posterior, lateral and mediolateral quadrants for each section using Image-Pro 4.5 (Mediacybernetics, Silver Spring, Maryland) (Fig. 2).

The porosity of the unimpacted morsellised allograft was determined by loosely packing four moulds measuring 23 x 33 x 15 mm (Exakt Technologies Inc) with graft chips. These specimens were processed and analysed as with the sections of the femur.

**Statistical analysis.** The porosity of the allograft, the mean thickness of the cement mantle, the mean penetration of the cement and the mean thickness of the allograft layer were compared using a two-way repeated measures analysis of variance (ANOVA) with the level and the quadrants as factors. The normality of the data was checked by Q-Q plots and the sphericity by Mauchly's test. Huynh-Feldt adjustment was used when necessary. The mean peak impaction force was calculated from the measured force and grouped into a mean distal and proximal impaction force according to the type of impactor used. Linear regression models were used to determine the porosity of the allograft as a function of the depth.
Photograph and diagram of five sections in all Gruen zones from a typical specimen. The different patterns in the diagram indicate the materials present in each section. Each section was divided into anterior, posterior, medial and lateral quadrants.

Fig. 2

The distribution of the size of the particles of the allograft chips in a semilogarithmic plot. The ordinate indicates the percentage by weight of particles smaller than the size given by the abscissa. For example, as indicated by the dashed line, 50% of the particles used in this experiment were smaller than 4 mm.

Fig. 3
of impact force. Student-Newman-Keuls analysis was used for post-hoc comparisons and the level of significance was 5%.

Results
The distribution of the size of the particles of bone chips is shown in Figure 3.

The mean porosity of the impacted graft was highest proximally at the levels of Gruen zone 1 (mean 73.4%, confidence interval (CI) 71.0 to 75.8) and lowest at the levels of Gruen zone 4 (mean 52.7, CI 47.5 to 57.9). The difference was statistically significant (p = 0.02) (Fig. 4). No significant difference was observed among the four quadrants (i.e. anterior, posterior, lateral and medial, p = 0.09). The interaction between the levels and the quadrants was not statistically significant (p = 0.26). The porosity of the unimpacted graft was 81% (CI 77 to 84). The porosity of the graft distally at the levels of Gruen zone 4 correlated negatively with the mean peak impaction force exerted with the distal impactors (r = 0.95, p = 0.004) and proximally with the mean peak force exerted with the proximal impactors (r = 0.81) (p = 0.048; Fig. 5). The maximum impaction force was 1630 N with the distal and 2150 N with the proximal impactors.

The mean thickness of the cement mantle from the levels of Gruen zones 1 to 5 and 3 was 1.7 mm (CI 1.5 to 1.9). No significant differences were found among the four quadrants (p = 0.18) or along the length of the stem (p = 0.08) (Fig. 6). The interaction between the levels and quadrants was not statistically significant (p = 0.25). In general, the cement mantle was not uniform in the quadrants, as shown in Figure 2. It exceeded 2 mm in some places and was absent in others.

Below the tip of the stem at the levels of Gruen zone 4, the mean penetration of cement (1.7 mm, CI 1.2 to 2.2) was significantly lower (p < 0.001) compared with that in the proximal part of the femur (Fig. 6). In the posterior quadrant (Fig. 2) at levels 5 to 9 the mean penetration of cement was significantly higher (9.2 mm, CI 8.3 to 10.2) compared with that in the other quadrants (5.4 mm, CI 5.0 to 5.8, p = 0.02). The interaction between the levels and the quadrants was statistically significant (p = 0.02). There was only a weak correlation (r = 0.55, p < 0.001) between the penetration of the cement and the porosity of the graft.

The mean distance from the stem to the cortex in the posterior quadrant at levels 5 to 8 (13.4 mm, CI 12.1 to 14.7) was significantly larger than that in the other quadrants (8.1 mm, CI 7.3 to 8.9, p < 0.001).

The mean residual layer of impacted graft free from cement at the levels of Gruen zones 6 and 2 was signifi-
cantly thinner (0.5 mm, CI 0.1 to 1.0, p < 0.01) than that at the levels of Gruen zones 1, 7 and 1, and 4 (Fig. 6).

There were no significant differences among the quadrants (p = 0.43). The interaction between the levels and the quadrants was statistically significant (p < 0.001).

Discussion
Clinical studies and reports on retrieval analysis and the basic biomechanical properties of morsellised allograft bone are available, but the morphology of the stem-cement-graft complex has not been described before. As with any study using a cadaver model there are limitations. The impaction grafting was performed under ideal conditions. The femur was rigidly fixed which may have led to tighter impaction of the graft chips. Since there was no intramedullary bleeding in the model its influence on the penetration of the cement is uncertain. However, experimental measurements in primary THRs have shown that penetration of the cement is not affected substantially by the intramedullary bleeding pressure.23,24

The distribution of size of the bone particles used in our study was similar to that reported by Brewster et al.15

The mean porosity of the graft was highest proximally in the level of Gruen zone 1 and only 7% lower than that in the unimpacted graft. By contrast, in Gruen zone 4, the porosity of the graft was 28% lower than that in the unimpacted material, illustrating the greater effectiveness of the distal impactors since the mean impaction forces were generally lower at this level compared with more proximally (Fig. 4). No significant differences in the porosity of the graft were found among the quadrants, which indicated that the difference in the anteroposterior and mediolateral angles of tap of the proximal impactors did not affect porosity. The relatively large variations of porosity in Gruen zones 5 and 3 were probably due to the slight variation in impacting technique. Two of the three surgeons (BAM, CPD) used the distal impactors past the recommended distal impaction line (X-Change System Operative Technique, Howmedica Inc), which resulted in tighter packing of the bone graft around the distal third of the stem but a higher impaction force with the proximal impactor was required for the appropriate position of the canal. This tighter impaction around the tip may be beneficial for the stability of the construct. The correlation of the mean peak impaction force with the porosity of the graft indicated that a higher mean impaction force resulted in a denser packing of the graft chips.
The mean thickness of the pure cement mantle, excluding the cement which had penetrated the allograft layer, was lower than expected. It exceeded the required 2 mm in some areas but was inadequate or absent in others (Fig. 2). The significance of the thin mean and partially incomplete cement mantle is not fully understood. The extensive penetration of cement which produces a substantial cement-graft composite implies that a thicker mantle of pure cement may not be necessary. However, bone particles within the cement mantle may give rise to cement or bone-cement-composite fractures which have been described previously and were associated with subsidence of the stem. Further investigation is required to elucidate the biological and mechanical implications of these observations.

The mean penetration of cement was higher than expected. In Gruen zones 6 and 2, almost the entire cross-section was filled with bone cement. The simulated lytic defects in this zone were generally filled with graft-cement composite. In other zones, the cement was sometimes in contact with the endosteal cortex. This could be beneficial if no cortical remodelling was required. However, Dai et al. have shown that inorganic bone particles embedded in cement can be replaced by new bone and form a viable cement-bone interface. The shear strength of this viable interface was significantly higher compared with cement alone, but we do not know if these findings are applicable to impaction allografting. The weak correlation between the mean penetration of cement and the porosity of the graft suggests that other factors such as the pressure gradient of the pressurised cement and the presence of fat and bone marrow may determine the penetration of cement.

The residual layer of graft was smallest in Gruen zones 6 and 2 and largest proximally. The optimal thickness of the graft probably depends on the location. However, biopsy and post-mortem studies have shown that only a few millimetres of the allograft bone is replaced by viable bone. Therefore a thin layer of graft with a viable bone-cement interface may be sufficient.