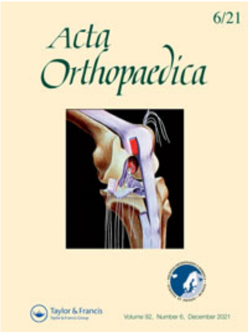

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Particle size of bone graft and method of impaction affect initial stability of cemented cups

Human cadaveric and synthetic pelvic specimen studies

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ABSTRACT We determined the effect of bone graft particle size and impaction technique on the initial stability of cemented acetabular cups. First, acetabular reconstructions were performed in human cadaveric pelvic bones in which type 2 AAOS cavitary defects were created. Reconstructions were made with small bone grafts (average 2 mm) produced by a bone mill or large bone grafts (average 9 mm) produced by hand with a rongeur. All chips were made from freshly-frozen femoral heads. Impaction was done using acetabular impactors and a hammer. We did a loading experiment with a gradually increasing dynamic load up to 3000 N. We used radiostereometric analysis (RSA) to determine cup stability. The cups were more stable when large bone grafts were used. Because of limitations of the cadaver model, we developed a synthetic acetabular model. For validation of this model, we repeated the experiments using small and large bone grafts. The results with both models were similar. In the synthetic model, we compared impaction with hammer and impactors with the reversed reaming technique using manual compression on the reamer. The latter method resulted in more migration. We recommend firm impaction with a hammer of large bone grafts for optimal stability of the cup.

Impaction bone grafting with morselized bone grafts and a cemented cup can restore bone defects on the acetabular side. The method is effective in primary and revision surgery (Slooff et al. 1984, Schreurs et al. 1998, Welten et al. 2000, Bolder et al. 2001, Schreurs et al. 2001). These long-term reports are based on bone chips produced by hand with a rongeur. The latter method leads to relatively large bone chips, but is time-consuming and tedious. Therefore, bone mills were introduced. However, most bone mills produce bone chips with a considerably smaller particle size than those made with a rongeur. Little is known about the factors affecting the stability of acetabular cups obtained after bone impaction grafting combined with cemented cup placement. A report, based on lever-out testing, suggests that impaction grafting with a smaller chip size may reduce cup stability (Ullmark 2000). However, the largest chip size used in that study was considerably smaller than chips produced by hand with a rongeur.

Traditionally, bone grafts are impacted with impactors and a mallet. However, some surgeons use a modified impaction technique in which the bone grafts are impacted using an acetabular reamer in a reversed direction in combination with manual compression on the reamer (Mallory et al. 2000). It is not known whether impaction with the reversed reaming technique results in stability of the cup like that obtained using acetabular impactors and a metal hammer.

The aims of this study were threefold. First, we studied whether the bone graft particle size obtained with impaction grafting and cemented cup placement affects the initial cup stability in a human cadaveric pelvic bone model. Our second aim was to develop a synthetic acetabular defect model and to compare it with human specimens. Our third aim was to use it to study the effects of the impaction technique on cup stability by comparing impaction with impactors and a metal hammer to the reversed reaming technique.

Table 1. The groups tested

Group [a]	Model	Grafts	Impaction technique	N
Large I	Human pelvic bone	Large	Firm impaction	6
Small I	Human pelvic bone	Small	Firm impaction	6
Large I	Artificial model	Large	Firm impaction	5
Small I	Artificial model	Small	Firm impaction	5
Small R	Artificial model	Small	Reversed reaming	5

[a] I = Impaction using impactors and a mallet
[a] R = Impaction using reversed reaming

Material and methods

PreparatŠn of the morselized bone grafts

All grafts were produced from freshly-frozen human femoral heads, obtained from a bone bank. These heads had been excluded from clinical use because of bacterial contamination. They were stored at –80 °C, pending tests. The heads were divided longitudinally into two parts and prepared in two ways. From one part of the head, the cancellous bone was nibbled by hand, using a rongeur that produced large pure cancellous bone chips. To determinethe particle size of the bone grafts, we measured 100 particles with a ruler and determined the largest distance. The average graft diameter was 9.1 (8.2–10.0) mm. From the second part of the femoral head, we removed the cartilage. Thereafter, it was milled with the smallest rasping blade of the Noviomagus bone mill (Spierings Medische Techniek, Nijmegen, The Netherlands), as is our practice in femoral revisions, using the bone graft impaction method. The chips therefore consisted of cortico-cancellous bone. The average graft diameter was 2.1 (1.6–2.6) mm. In both groups, bone grafts made from several femoral heads were mixed to form pools of graft material to minimize the effect of mechanical variation between them.

Human cadaveric pelvic model

4 freshly-frozen pelvic bones were available. During harvesting, all soft tissue was removed and the bones were stored at –80 °C, pending tests. After thawing, the pelvis was potted in polymethylacrylate to facilitate both surgical handling and mechanical testing. Both acetabuli of the pelvic bones were over-reamed using a 58 or 60 mm acetabular reamer, depending on the size of the acetabulum. In the acetabulum thus prepared, a 38 mm reamer was used for additional overreaming, to simulate a standardized cavitary defect bilaterally (D'Antonio et al. 1989). Reconstructions in the pelvic bones were implanted as pairs. Two surgeons (BWS, JWMG), with experience in using the bone impaction grafting technique, did the reconstructions. Initially, the first surgeon operated on the left side and used large bone chips and on the right side with the small grafts. When re-using the pelvic bones, the second surgeon reconstructed the left side with small bone chips and the right side with the large bone grafts. However, during the first mechanical testing, 2 pelvic bones failed. Therefore, the first surgeon performed 8 reconstructions, while the second surgeon did 4 (Table 1). Impaction grafting was done using metal impactors of various sizes and a metal hammer (Stryker Howmedica X-Change acetabular impactors system). Defects were reconstructed layer by layer. The diameter of the final impactor was 50 mm, thereby creating sufficient space for the bone cement mantle around the cup. We inserted the bone cement (Surgical Simplex, Stryker Howmedica Osteonics, Limerick, Ireland) with a cement gun into the defect 4 minutes after adding the powder to the monomer. The cement was pressurized with an acetabular seal (65 mm pressurizer, DePuy International Ltd, Blackpool, England) and a pushing handle. A polyethylene cup with an outer diameter of 44 mm (Exeter RSA cup, Stryker Howmedica Osteonics, Newbury, UK) was inserted 6 minutes after mixing was started.

Dynamic loading of the reconstructions was performed with an MTS loading device (MTS Systems Corporation, Minneapolis, Minnesota, USA). We used radiostereometric analysis (RSA) to calculate translations and rotations. 8 spherical tantalum markers were attached to the cup.

Figure 1. The synthetic acetabulum model with a central cavitary defect. The porous structure is clearly visible.

We inserted 3 clusters of 3 markers at standard locations in the iliac, ischial and pubic bones. The human cadaveric pelvic bones were placed underneath the MTS loading device at 45 degrees abduction and 0 degrees anteversion of the cup, so that the direction of the load displaced the cups superiorly and medially into the largest thickness of the grafts layer. Dynamic loading was applied at a frequency of 1 Hz in four stages, starting at 0–750 N with further staged increments of 750 N up to 0–3000 N at the last stage. Each stage lasted 900 cycles. To permit elastic and time-dependent recoil of the grafts, we also studied the migration of the cups after unloading and 15 minutes after unloading. At the beginning and at the end of each load increment, RSA exposures were made at a static load to measure cup migration. Migration of the gravitational center of the 8 tantalum cup markers was taken to represent the migration of the implant relative to the bone. We used the vectorial length of the translation in 3 directions.

Artificial acetabulum model

We developed a synthetic model (Figures 1 and 2). Composite test blocks were produced by Sawbones. The cylindrical test blocks had an outer cortical layer of 3 mm thickness and an inner spongious part of 68 mm in diameter. A standard large cell rigid polyurethane foam with a porosity of 22–23% simulated the trabecular bone. The cells of the foam had a diameter ranging between 0.5–2.0 mm. The appearance of the foam closely resembled that

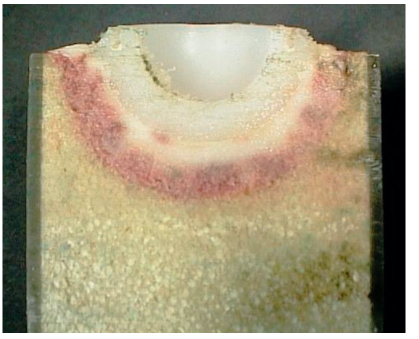

Figure 2. Transection of the reconstructed model shows a graft layer with sufficient space for an adequate cement mantle around the cup.

of cadaveric cancellous bone. However, the foam consisted of a 95% closed cellular structure unlike the open cell structure of human bone. The foam density was 120 kg/m^3, the compressive strength 0.85 MPa and the compressive modulus 25.8 MPa. We created a standardized central cavitary defect with a 60 mm acetabular reamer.

We used three reconstruction methods in this model. Each reconstruction was done 5 times (Table 1). The same investigator (SBTB) did all the reconstructions. Like the experiments in the cadaveric pelvic bone model, in two series the defect was reconstructed, using small or large impacted bone grafts and cemented cup placement. We used the same set of instruments as in the human cadaveric pelvic bone model. A final impactor of 46 mm in diameter created a superior graft layer with a thickness of 10 mm and 4 mm inferiorly. A thicker superior grafts layer was chosen in all series to simulate a larger superior defect. In the third series, we performed reconstructions using the reversed reaming technique with small bone grafts. The latter grafts were inserted into the defect and impaction was done using an acetabular reamer in a reversed direction with manual compression on the reamer. The last reamer used had an outer diameter of 46 mm. In all 3 series, we inserted bone cement (Surgical Simplex, Stryker Howmedica Osteonics, Limerick, Ireland) with a cement gun into the defect 4 minutes after adding the powder to the monomer. The cement was pressurized with an acetabular seal (65 mm pressurizer, DePuy International Ltd, Blackpool, England). Then the acetabular cup (Exeter RSA cup, Stryker Howmedica Osteonics, Newbury, UK) with an

Table 2. Migration (in mm) of the cups in human cadaveric pelvic bones

Load (N)	Time (min)	Large chips Mean	SD	N	Small chips Mean	SD	N
750	0	0.37	0.24	6	0.55	0.18	6
750	15	0.32	0.08	6	0.66	0.23	6
1500	15	0.56	0.26	6	0.87	0.18	6
1500	30	0.48	0.23	6	1.21	0.25	6
2250	30	0.67	0.32	5	1.46	0.21	2
2250	45	0.77	0.32	3	1.67	0.37	2
3000	45	0.99	0.07	3	1.78	0.40	2
3000	60	1.27	0.06	3	1.98	0.54	2

Table 3. Migration (in mm (SD)) of the cups in the artificial acetabulum models

Load (N)	Time (min)	Large chips Mallet impaction	Small chips Mallet impaction	Small chips Reversed reamer
1500	0	0.46 (0.16)	0.76 (0.12)	0.89 (0.12)
1500	15	0.57 (0.19)	1.08 (0.16)	1.29 (0.16)
3000	15	0.80 (0.25)	1.38 (0.15)	1.62 (0.18)
3000	30	1.35 (0.42)	1.84 (0.18)	2.19 (0.20)
0	30	0.82 (0.37)	1.34 (0.20)	1.65 (0.20)
0	45	0.77 (0.34)	1.18 (0.20)	1.46 (0.19)

effective outer diameter of 40 mm was placed in a standardized way. All reconstructions were stored at 6 °C for 24 hours to permit complete cement polymerization.

Dynamic loading was done, as in experiments using the human cadaveric pelvic bone models. Since the stability of the model itself was less critical than in the cadaveric human pelvic bones, the staged increment was 1500 N instead of 750 N per stage. A static rotation torque of 3 Nm was also applied simultaneously to allow for a more critical loading regime of the cups. Migration of the center of the 8 tantalum cup markers was taken to represent the migration of the implant relative to 6 tantalum markers circumferentially placed in the cortical layer of the synthetic model.

Statistics

Statistical analysis of the effect of impaction grafting with large or small bone grafts in the human pelvic bones was done using the Wilcoxon signed-rank test, significance at $p = 0.05$. The effect of bone graft particle size and impaction technique on cup stability in the synthetic models was statistically analyzed, using a two-sided unpaired t-test, significance at $p = 0.05$. An F-test was used to compare the variance of the results of impaction grafting with large and small bone grafts in the human pelvic bones or the synthetic models.

Results

In the cadaveric specimens, only 3 of 6 reconstructions with large bone grafts and 2 of the 6 reconstructions with small bone grafts could be loaded to the maximum of 3000 N. Fractures of the pubic bone which occurred during loading with 2250 N, prevented full loading of the other reconstructions. There were no failures of the reconstructions due to the dynamic loading. Impaction grafting with small bone grafts resulted in a higher migration than impaction with large bone grafts (Table 2). This difference was statistically significant after dynamic loading with 1500 N ($p = 0.03$). At higher loads too few specimens were available for statistical comparison.

There were no failures in the synthetic models. As with the experiments in the cadaveric specimens, we found greater cup migration after impaction grafting with small bone grafts (Table 3). This difference was statistically significant at all measuring points ($p < 0.05$), apart from the one after 15 minutes of recovery ($p = 0.06$). The results after reconstruction using pelvic bones or synthetic acetabulum models were similar (Tables 2 and 3). The variance in the results obtained from the pelvic bones did not differ from those using the synthetic models ($p > 0.05$).

Defect reconstruction with the reversed reaming technique resulted in greater cup migration than with the use of impactors and a metal hammer (Table 3). This difference was statistically significant at the end of dynamic loading with 3000 N ($p = 0.02$) and after elastic recovery of the grafts ($p = 0.04$).

Elastic recoil was about 0.5 mm in all groups with no significant differences between the groups. Time-dependent recoil was small in all groups. Rotation due to the rotation torque in the series in the synthetic models was small with no significant differences between the groups.

In the synthetic model, cup rotations were small without any difference between large and small grafts (p = 0.09–0.24) or between firm impaction and reversed reaming (p = 0.11–0.76).

Discussion

We found that cemented cups were more stable when the reconstruction was performed with large bone chips and when a firm impaction with metal impactors and a hammer was used. These findings have clinical implications and are supported by good long-term clinical studies in which firmly impacted large bone grafts were used (Schreurs et al. 1998, Welten et al. 2000, Schreurs et al. 2001, Bolder et al. 2001).

Simplified models provide information about the mechanical characteristics of impacted morselized bone grafts (Brewster et al. 1999, Giesen et al. 1999, Bavadekar et al. 2001). Shear tests suggest that an optimal grading of the particles with a combination of several chip sizes should optimize the initial stability (Brewster et al. 1999). However, in most simplified models, the interaction with the bone cement of the bone grafts is not considered. Since we believe this is an important interaction as regards the stability of the complete reconstruction, we decided to use a more realistic model in this study. First, we performed reconstructions in human cadaveric bones. Failure of the model before failure of the reconstruction interfered with an adequate comparison of the reconstructions. It was also uncertain whether re-usage of the specimens interfered with the final outcome. The synthetic acetabulum model was introduced to overcome these problems. Moreover, these models are easier to obtain and handle. When comparing the results of reconstructions in the synthetic models to the human pelvic bones, we found no significant differences. However, such a comparison has limitations because the tests in both models were not performed in the exact same way. The numerous failures in the human pelvic bones at higher loads also interfered with an accurate comparison.

Some limitations of our study should be mentioned. We did not control the degree of impaction. As in clinical practice, the reconstructions were done by manual impaction on the grafts. We agree with Bavadekar et al. (2001) that it is very difficult to duplicate a clinical situation. To improve reproducibility, one surgeon did all the tests in the synthetic acetabulum model. We compared large pure cancellous bone chips with smaller cortico-cancellous grafts produced with a bone mill. We made this choice because of its clinical relevance. It may be that cortico-cancellous grafts are more stable than cancellous bone chips. However, on the basis of Bavadekar et al.'s study (2001), this is unlikely and therefore was not regarded as relevant in this study.

Producing large pure cancellous bone chips by hand is time-consuming. For impaction grafting on the femoral side, smaller chips must be used based on the femoral dimensions. These chips are made with a bone mill after removal of cartilage. It is tempting to use these chips also on the acetabular side. However, most commercially available bone mills produce particles, which are usually smaller than 3.5 mm (Wallace et al. 1997a). We found that reconstructing acetabular bone defects with large-sized bone grafts results in a higher initial stability of the cups than when reconstructed with smaller-sized ones. This accords with the findings of Ullmark (2000). Most studies on the effect of graft particle size have described the initial stability of femoral implants. They found that the mechanical stability of a femoral stem could be improved by using larger-sized bone chips (Malkani et al. 1996, Smith et al. 1996, Eldridge et al. 1997, Wallace et al. 1997b).

We believe that firm impaction of bone grafts is needed to ensure adequate stability of the cup (Slooff et al. 1993). This hypothesis was confirmed in the present study. Use of the reversed reaming technique to impact the bone grafts reduced initial cup stability. In clinical work, this method is also used together with very small slurry bone grafts, which are produced by reaming the trabecular bone in the femoral head. We did additional tests in the synthetic model with these slurry bone grafts and the reversed reaming technique. These cups showed a 3 times greater migration in relation to the reconstruction with impacted large bone chips using the same testing protocol. In our opinion, this method, especially in combination with slurry grafts, is not adequate for reconstruction of acetabular defects.

When using cortico-cancellous grafts, every effort should be made to prevent inclusion of cartilage since these remnants can interfere with mechanical characteristics (Bavadekar et al. 2001) and with the incorporation of the grafts in the long run (Weidenhielm et al. 2001, van der Donk et al. 2002). Another factor that may affect the stability of acetabular cups includes defatting of the bone grafts before impaction (Dunlop et al. 2000, Ullmark 2000). Recent studies have shown that pulse lavage cleaning of bone grafts can be done without compromising the incorporation of the grafts (van der Donk et al. 2003).

At this time, we recommend the use of the bone impaction grafting technique, as originally advocated by Slooff et al. (1984). Although it is a time-consuming procedure, long-term clinical results proved satisfactory, with extensive incorporation of the grafts in the bone defects (van der Donk et al. 2002). A modification of this method has not yet been shown to improve performance and it should therefore be introduced with caution.

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