Biomechanical Analysis of Acetabular Defects Reconstruction with Impaction Bone Grafting in Revision Total Hip Arthroplasty

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Abstract
An objective of this study is to investigate the influence of an amount of mixture of hydroxyapatite (HA) granules and morsellised cancellous bone (MCB) on the initial stability of reconstructed acetabulum through mechanical testing. Reconstruction was carried out using impaction bone grafting technique with four mixture ratio, then, cyclically loaded as a simulation of the motion of gait and analyzed the migration. The initial stability is highly dependent on mixture ratio and larger HA mixture ratio could give us better initial stability of the cup.

Key words
Impaction Bone Grafting, Hydroxyapatite (HA) Granule, Morcellised Cancellous Bone (MCB), Migration, Stability

1. Introduction
Aseptic loosening caused by polyethylene wear and subsequent osteolysis, is the principal limiting factor for the long-term survival in total hip arthroplasty (THA) [1]. In revision surgery for failed acetabular implants, it is focused on how to cope with the bone stock loss and achieve a stable cup fixation.

Impaction bone grafting, designated IBG, is now being applied to revision total hip arthroplasty. This technique using morcellised cancellous bone (MCB) grafts in combination with cemented cup fixation to restore bone deficiencies showed good long-term results [2-6].

However, due to limited availability of MCB and associated risk of virus transfer, alternative materials are being considered as substitutes. Bioactive ceramic, such as Hydroxapatite (HA) and Tricalciumphosphate (TCP) granules has a proven osteocompatibility and can act as an osteoinductive material [7]. HA is incorporated with in the same way as MCB, although there are concerns about using HA alone is poor osteoinductive [8]. Mixing with MCB received a lot of attention in recent years for improving ceramic incorporation. In clinical, it was reported that there were no difference in graft incorporation between patients who were treated with MCB alone and those treated with a mixture of HA [9].

Further, long-term prosthesis survival and function following revision arthroplasty with a 50/50 mixture of MCB and HA are comparable to MCB alone.

Initial stability of the reconstruction is an important factor for the long-term survival of an implant. Bolder and Verdonschot [10, 11] reported a fine stability of acetabular cups after an in vitro reconstruction of a caviatory defect model with TCP/HA particles. They performed reconstruction with mixtures of MCB and TCP/HA particles in an artificial acetabular bone defect model, then compared cup migration measured by using Roentgenostereophotogrammetric analysis (RSA) during cyclically loading condition. Using RSA, measurement is restricted under static loading condition, so it is only intermissive and difficult to analyze definitely the motion of gait.

In this study, we investigate the influence of an amount of mixture of HA and MCB on the initial stability of the cup through mechanical testing. Further, to measure continuously cup migration, we used a specially designed microscope for motion analysis at micro level, and verified availability.

2. Materials and Methods
2.1 Materials
The acetabular defects reconstruction was performed by grafting the mixture of MCB and HA into the defects. The ratio of HA mixture to MCB, referred to as HA mixture ratio, were selected to be 0, 25, 50 and 100% in terms of weight in this study.

Thirty human femoral heads were obtained from patients with femoral neck fractures and osteoarthritis during primary THA. The cancellous bone was nibbled by hand, using a roengeur. After nibbling, MCB was washed in saline solution, then stored at -70℃ until tested. To determine the particle size of MCB, sieve analysis based on Japanese Industrial Standards (JIS) was carried out. The size of MCB varied from 6 to 10 mm.

The HA particles (Covalent Materials Ltd., Tokyo, Japan), varying 2.0-5.0 mm in diameter with a porosity of 72-78% were used. The compressive strength of HA is 12-15 MPa, and that of cancellous bone is 2-7 MPa. Before testing, a little amount of water was added to the HA particles so as to keep the HA particles wet in the experiments.

2.2 Model preparation
We developed a simulated acetabular bone defects model. Composite test blocks were produced by Sawbones® #10. The rectangular parallelepiped test block had an outer cortical layer of 5 mm thickness and inner sponging part of 126×126×40 mm³. The 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 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. To obtain high reproducibility, we made outer cortical layer by aluminum alloy, although it’s mechanical property are strictly different from that of cortical bone. We created a semi-spherically shaped cavitary defect with 60 mm in diameter.

Next, we reconstructed the cavitary defect by impaction of MCB and HA into the defect. Total weight of the impacted grafts used was 30gf. The grafts were impacted using several impactors and a metal hummer. Finally we created 4 and 10 mm thick graft layers as shown in Fig.1a. Final impaction was performed by dropping a weight for 20 times with the use of an impactor of 46 mm in diameter so as to achieve the same impaction in all models. We chose a 525gf weight and dropped it from 160 mm height to give the same impaction to the models as surgeons did (Fig.2).

The bone cement (Surgical Simplex®, Stryker Ltd., Tokyo, Japan) was used. At 2.5 minutes after adding the powder to the monomer, the cement was injected in the reconstructed defect, and then the acetabular cup with 28/38 mm in inner/outer diameters (contemporary flanged cup, Stryker Ltd., Tokyo, Japan) was inserted in the defect. At the final process of the reconstruction, the cement was pressurized for 4 minutes using acetabular seal (Pressurizer, Stryker Ltd., Tokyo, Japan) and pushing handle. The models were stored at 22°C for 2.5 hours to make sure the cement polymerization (Fig.1b, c). The six reconstructed models were made at each HA mixture ratio.

### 2.3 Mechanical testing

The reconstructed model at each HA mixture ratio was cyclically loaded as a simulation of the motion of gait using an axial-torsional materials testing machine (858 Mini Bionix II, MTS Inc., USA) at room temperature of 22 ±1°C and at humidity between 30 and 40% (Fig.3). The model was fixed with a clump at 20° abduction and 0° anteverision. A cyclic load of 150-1500 N with a frequency of 1 Hz was applied for 15 minutes, followed by a cyclic load of 300-3000 N for the 15 minutes. Then the load was released for 15 minutes. The motion analysis microscope (Keyence Co. Ltd., Osaka, Japan) was used, and this equipment enabled us to capture the motion pictures continuously at high frame rates and to calculate the migration of acetabular cups at the order of 0.01 mm under such cyclic loading conditions (Fig.4).
The influences of the HA mixture ratio on the cup migration during cyclic loading, recovery of the cup migration just after unloading, denoted elastic recoil, and subsequent gradual recovery or time-dependent recoil, denoted visco-elastic recoil, were quantitatively investigated.

2.4 Motion analysis
All results were statistically analyzed, i.e. one-factor ANOVA, Tukey-Kramer method and Pearson's correlation coefficient test, to make the influence of the HA mixture ratio clear. Level of significance was set at $\alpha = .05$.

3. Results
The average of cup migration at each mixture ratio is listed in Table 1, and the maximum value is shown in Fig.5. The significant difference ($p<.01$) in cup migration was found between HA mixture ratio of 0% and that of 100%. Negative relative correlation was also found between the cup migration and HA mixture ratio ($r = -0.71$).

The elastic recoils are listed Table 2. The significant difference ($p<.05$) in elastic recoil was found between HA mixture ratio of 0% and that of 100%. Negative relative correlation was also found between the elastic recoil and HA mixture ratio ($r = -0.55$).

The visco-elastic recoils are also listed in Table 2. No significant difference ($p>.05$) as well as no relative correlation ($r = -0.11$) was found between the visco-elastic recoil and HA mixture ratio.

4. Discussion
In this study, we found the addition of HA granules to MCB made cup migration smaller. The addition of HA granules to MCB affected the elastic recoil, while no its effect on visco-elastic recoil was found. These results indicated that the mixture of HA granules with MCB stabilized the cup in loading and unloading period. These results well corresponded to the previous findings [10, 11], although each value itself was different because of the different restraint condition.

These results suggested that the use of HA granules alone was recommended to achieve initial stability of the cup. The motion analysis microscope enabled us to monitor the cup migration continuously under cyclic loading condition. We obtained the fact that the cup migration gradually increased and not be in steady state at the period of loading of 300-3000 N (Fig.4). Therefore, we carried out additional longer time testing up to 2 hours to investigate the steady or time dependent behavior of cup migration. The model with HA mixture ratios of 0% and 100% were chosen and tested. The results showed the increase of cup migration reconstructed with HA mixture ratio of 100% was larger than that of 0%, that is, HA mixture ratio of 100% requires longer time to be in steady state (Fig.6). This is probably due to that HA granules have less cohesive strength or the interparticle adhesion of HA granules is weaker. Less interparticle adhesion makes the number of the pores in the HA aggregate larger (Fig.7), and may cause the movement of the cup before enough bone induction is obtained. Consequently, to fix the cup in adequate position could be the key to get better long-term clinical outcomes.

In these circumstances, to reduce the clearance between the grafts is important. The one potential solution is to enhance cohesion of the grafts. Okada et al. demonstrated that adding MCB to HA was efficient [12]. They carried out quasi-static uniaxial compression tests.

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Table 1 Cup migration

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>HA0</th>
<th>HA25</th>
<th>HA50</th>
<th>HA100</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00±0.00</td>
<td>0.00±0.00</td>
<td>0.00±0.00</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>15</td>
<td>0.51±0.13</td>
<td>0.44±0.08</td>
<td>0.42±0.06</td>
<td>0.34±0.08</td>
</tr>
<tr>
<td>30</td>
<td>0.62±0.23</td>
<td>0.51±0.10</td>
<td>0.48±0.10</td>
<td>0.45±0.09</td>
</tr>
<tr>
<td>45</td>
<td>1.22±0.66</td>
<td>0.99±0.31</td>
<td>0.83±0.30</td>
<td>0.59±0.09</td>
</tr>
<tr>
<td>60</td>
<td>3.96±0.47</td>
<td>2.76±0.98</td>
<td>2.76±0.98</td>
<td>1.56±0.65</td>
</tr>
<tr>
<td>90</td>
<td>2.37±0.56</td>
<td>1.81±0.78</td>
<td>1.37±0.64</td>
<td>0.70±0.41</td>
</tr>
<tr>
<td>120</td>
<td>2.17±0.50</td>
<td>1.54±0.78</td>
<td>1.16±0.62</td>
<td>0.48±0.30</td>
</tr>
</tbody>
</table>

Mean ± S.D. (Unit: in mm)

Table 2 Elastic recoil & Visco-elastic recoil

<table>
<thead>
<tr>
<th>Recover</th>
<th>HA0</th>
<th>HA25</th>
<th>HA50</th>
<th>HA100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic</td>
<td>1.29±0.28</td>
<td>1.28±0.19</td>
<td>1.32±0.23</td>
<td>1.06±0.20</td>
</tr>
<tr>
<td>Visco-elastic</td>
<td>0.20±0.05</td>
<td>0.26±0.06</td>
<td>0.21±0.08</td>
<td>0.19±0.12</td>
</tr>
</tbody>
</table>

Mean ± S.D. (Unit: in mm)

Fig.4 An example of trace of cup migration by the motion analysis microscope during loading and unloading phases Duration of each loading phase was 15 minutes

Fig.5 Effect of HA mixture ratio on cup migration at the end of loading of 3000N

The "***" indicates a significant difference ($p<.01$)
and shear tests. Cohesion and shear strength were increased by the addition of HA to MCB. On the other hand, they showed that it was difficult to make the specimen with HA mixture ratio greater than 50%, and collapsed easily because of less cohesion of HA particles. This means the use of excessive HA is improper, therefore the addition of MCB to HA should be favorable. They also showed the cohesive strength increased with the addition of saline solution. Smith et al. showed that the addition of clotted blood to MCB improved cohesive strength [13]. So, the addition of any biocompatible fluid to impacted grafts is thought to get highly stabilization.

The other solution is to use well-graded grafts. Based on soil mechanics, Douglass et al. showed that a well-graded aggregate had higher shear strength than an aggregate with uniform particle size because of many interparticle contacts [14]. They only treated with MCB, but it could be applicable to the grafts with mixture of HA and MCB, or HA alone. Oonishi et al. have carried out reconstructions with HA alone, and exhibited favorable results in 4-10 year clinical results [15]. However, this method required large amount of bone cement, and therefore much attention had to be paid not to have excessive cement penetration.

As described above, reconstruction with well-graded HA alone or the addition of MCB to HA could be effective to obtain adequate initial stability.

5. Conclusion

It is concluded that initial stability of reconstructed acetabulum is strongly dependent on HA mixture ratio and larger HA mixture ratio could give us better initial stability of the cup. However, considering stabilization of cup migration, the use of HA alone is undesirable. Therefore, we recommend mixing sort of MCB to HA, or using well-graded particles.

References


