Effect of calcium triphosphate cement on proximal humeral fracture osteosynthesis: a cadaveric biomechanical study

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ABSTRACT

Purpose. To evaluate the effect of filling a central humeral bone void with calcium triphosphate cement on the strength and stability of an osteosynthesis in elderly cadavers.

Methods. 14 fresh cadaveric shoulder specimens obtained from 11 donors (mean age, 91.5 years; mean body weight, 61 kg) were divided into 2 age- and sex-matched groups. A standardised 3-part proximal humeral fracture with a central bone void was created in each specimen. Each specimen was reduced and fixed with a locking plate. In half the specimens the central bone void was packed with calcium triphosphate cement. The intra-fragmentary motion and the load and mode of failure were recorded.

Results. Respectively in the test group and controls, the intra-fragmentary motion was 1.0 and 6.4 mm, and the peak displacement at the 500 N load was 1.8 and 9.1 mm. The Cohen’s $d$ was 1.6 to 2.7 for all load steps, indicating a large effect of the calcium triphosphate cement on strength and stability. The mean difference in the failure load was 300 N ($p<0.05$).

Conclusion. Construct stability and failure load improved significantly when the central humeral bone void was filled with calcium triphosphate cement.

Key words: biomechanics; bone cements; fracture fixation, internal; shoulder fractures

INTRODUCTION

Among all fractures in the elderly population, proximal humeral fractures are the third most common and a major cause of pain and disability.1,2 In such patients the outcome is usually poor, owing to a combination of osteoporotic bone, reduced healing capacity, and associated injury to the rotator cuff and soft tissues.

Locking plate osteosynthesis has achieved good results in patients with good bone quality.3–12 Nonetheless, the use of rigid locked implants in osteoporotic bones may lead to failure, with valgus collapse of the articular fragment and...
screw penetration into the glenoid fossa.\textsuperscript{13–15} In older patients, a central humeral bone void may compromise stable osteosynthesis and thus supplemental materials such as autografts, allografts, artificial bone, and bone cement should be used.\textsuperscript{16} Fixation augmented with natural or synthetic void fillers for the central humeral bone void has achieved satisfactory outcome.\textsuperscript{17,18}

In osteoporotic patients, the use of autologous bone grafts may be limited, owing to the lack of suitable cancellous grafts at donor sites. Calcium triphosphate cement is more accessible than allografts and is not biologically inert, which is superior to conventional bone cement. It matches the mechanical properties of the cancellous bone and can be replaced by the surrounding bone via creeping substitution.\textsuperscript{19} Increased construct stability facilitates early rehabilitation, improves functional outcome, and reduces the risk of reoperation in patients with proximal humeral fractures.\textsuperscript{20–22} This study evaluated the effect of filling the central humeral bone void with calcium triphosphate cement in elderly cadavers.

**MATERIALS AND METHODS**

14 fresh cadaveric shoulder specimens obtained from 11 donors (mean age, 91.5 years; mean body weight, 61 kg) were divided into 2 age- and sex-matched groups. The humerus was removed via an extended deltopectoral approach, stripped of soft tissues, and stored at -20°C. Prior to testing, specimens were defrosted overnight at 4°C in sealed plastic containers (to prevent desiccation).\textsuperscript{23} The specimens were then mounted vertically in a 10-cm steel box section, which was reproducible. The humeral shaft was fixed in place with Simplex rapid dental cement. The length of each specimen proud of the dental cement was 150 mm.

An osteotomy was made at the level of the surgical neck using an oscillating saw. The volume of each humeral head was determined by water displacement. A standardised bone void of 20\% by volume was created in each humeral head. No cortical bone was removed. An osteotomy was then made at the greater tuberosity. The centre of the bicepital groove and the posterior aspect of the articular cartilage were used as anatomic landmarks to ensure a consistent osteotomy.

Specimens were then reduced and fixed with Kirschner wires. In the test group, the central humeral voids were filled with calcium triphosphate cement (Hydroset Injectable, Stryker, Ireland) [Fig. 1]. In the controls, the voids were left unfilled. Specimens were then fixed with a locking plate and screws (Arthrex Suture Plate, Athrex, USA). The specimens were then allowed to cure for 24 hours at 37°C in sealed plastic bags, so as to reach full strength.\textsuperscript{24}

The intra-fragmentary motion was measured using an optoelectronic camera system, which continuously tracked the 3-dimensional motion of the sensors at a frequency of 50 Hz. The sensors were placed at standardised points on the greater tuberosity, articular surface, and humeral diaphysis (Fig. 2). The accuracy of the system was 0.1 mm when the passive sensors were maintained within an inner reference cone of 1.5 m. The passive sensors were composed of a rigid array of reflective spheres. Because the array centre point was elevated (60 mm above the bone surface), movements of the passive sensors were larger than displacements of the bone fragments. To adjust for this potential error, a pivot procedure was performed to precisely define the spatial relationship between the centre point of the reflective array and the bone fragment.

**Figure 1** A central humeral bone void is filled with calcium triphosphate cement.

**Figure 2** The specimen is mounted in a mechanical test apparatus. Sensors are placed at the greater tuberosity, articular surface, and humeral diaphysis.
To simulate joint reaction forces at 90° of arm abduction, the steel channel holding the specimen was rigidly bolted to a metal wedge, which was 52.2° to the horizontal plane. The load was then applied vertically using a biaxial servo hydraulic testing machine (Fig. 2). Loads were applied via a machined Teflon glenoid with a contact area of 30 mm². The upper surface of the Teflon glenoid was smooth to enable it to translate in the horizontal plane, so as to minimise bending of the specimen.

A stepwise loading protocol of 1000 cycles at a frequency of 1 Hz with 100 N increments was used until failure. To minimise error owing to bending below the surgical neck, the sensor attached to the diaphysis was assigned as the global reference. The relative motions of the articular fragment and greater tuberosity under cyclic loading were then sampled (at 50 Hz). The mode and load of failure for each specimen were recorded.

For each cycle, the 3-dimensional vectors were defined as the movements of the articular and greater tuberosity fragments relative to each other, and relative to the diaphyseal reference. The mean summation of the magnitudes for these 3 vectors for each 1000 cycle load increment was then calculated as construct stability. Data were discarded if they pertained to cases where construct failure occurred during the load increment or after an exponential rise in instability.

According to a mean inter-fragmentary motion for each incremental load, Cohen’s $d$ value of 0.2 to 0.3 was considered a small effect, whereas 0.5 to 0.8 a medium effect and $>0.8$ a large effect. The incremental failure load was analysed using a 2-tailed Student’s $t$ test. A $p$ value of $<0.05$ was considered statistically significant.

### RESULTS

Respectively in the test group and controls, the intra-fragmentary motion was 1.0 and 6.4 mm, and the peak displacement at the 500 N load was 1.8 and 9.1 mm (Table). The load increment replicated physiologic loading on the humeral head at 90° of arm abduction. An 85.5% decrease was noted in the rate of progression of intra-fragmentary motion from 100 N to 500 N loads, calculated from the line of best fit (Fig. 3). The Cohen’s $d$ was 1.6 to 2.7 for all load increments.

<table>
<thead>
<tr>
<th>Specimen no.</th>
<th>Sex/age (years)</th>
<th>Failure load (N)</th>
<th>Displacement at each load increment (mm)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100 N</td>
<td>200 N</td>
<td>300 N</td>
</tr>
<tr>
<td>Control group</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 (pair 1)</td>
<td>F/96</td>
<td>500</td>
<td>0.26</td>
<td>0.52</td>
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<tr>
<td>2</td>
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<td>0.50</td>
<td>1.76</td>
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<tr>
<td>3 (pair 2)</td>
<td>M/90</td>
<td>500</td>
<td>0.26</td>
<td>0.76</td>
</tr>
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<tr>
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<tr>
<td>8</td>
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<td>9</td>
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<td>13 (pair 3)</td>
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<td>700</td>
<td>0.25</td>
<td>0.39</td>
</tr>
<tr>
<td>14 (pair 1)</td>
<td>F/96</td>
<td>800</td>
<td>0.17</td>
<td>0.23</td>
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Cohen’s $d$ for each load step between test and control groups

<table>
<thead>
<tr>
<th>Load (N)</th>
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<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>200</td>
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<tr>
<td>300</td>
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<tr>
<td>400</td>
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<tr>
<td>500</td>
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</tbody>
</table>

Figure 3 Rate of progression of instability in the test and control groups.
steps (Table), indicating a large effect of the calcium triphosphate cement on strength and stability.26

For the 3 pairs of specimens, those in the control group failed earlier than those in the test group, and the mean difference in the failure load was 300 N (p<0.05). Two failure modes were noted. The first entailed loss of purchase of the screws in the humeral articular fragment. This was followed by collapse into valgus impaction of the fracture fragments with a large rotational displacement of the articular fragment relative to the plate and subsequent penetrations of the screw tips through the articular surface. The second failure mode entailed failure of the construct at proximal diaphyseal screws; the articular fragment, plate, and greater tuberosity remained undisplaced relative to each other (Table).

Valgus collapse (impaction of the bone fragments towards the plate and screw cut-out) was the failure mode in all controls, whereas in the test group the failure mode in 5 of the 7 specimens entailed sequential screw pull-out of diaphyseal screws.

DISCUSSION

A central humeral bone void shortens the effective length of the screws. Filling the void with calcium triphosphate cement improves implant anchorage and acts as an internal buttress. This prevents the fragments from collapsing towards the plate. As the screws are locked to the plate, any lateral displacement of the articular fragment may cause the screw tips to enter the joint. Augmenting bone stock with calcium phosphate cement has conferred significant mechanical advantages in other cadaveric studies.23,27

In our study, bone specimens were further weakened by creation of standardised bone voids. This may have exaggerated the effect of calcium triphosphate cement. In clinical practice, patients of such advanced ages are likely to be treated conservatively. All constructs could withstand the normal physiologic loading defined by Poppen et al.28 The number of cadaveric specimens was small but comparable to that in other studies.23,29,30 The use of synthetic analogues would have enabled more tests to minimise inter-specimen variability, but there was no synthetic analogue that could accurately simulate the bond between bone and calcium triphosphate cement.

The use of a simplified load to replicate forces on the proximal humerus has been well reported,23,30 It represents an over-simplification of in vivo loading. In our study, valgus impaction and screw cut-out were common modes of failure. This matches the failure modes of a fixed angle device in osteoporotic patients.15 As loading protocol predicts failure modes, our simulation of the in vivo loading on the proximal humerus was therefore reasonable.

This cadaveric biomechanical study enabled reproduction of clinical failure modes. It used a pivot procedure to minimise offset errors and deliver the loads via a horizontally sliding Teflon glenoid to reduce errors owing to proximal cantilever bending.

CONCLUSION

Augmenting existing bone with synthetic substitute avoids harvesting of cancellous autografts. Calcium triphosphate cement is more accessible than allografts, and its mechanical properties are superior to conventional bone cement, as it more accurately matches the properties of the surrounding bone.27 The use of void-filling synthetic bone graft substitute to augment locking plate fixation of proximal humeral fractures (with poor bone stock) enables less intra-fragmentary motion and higher ultimate failure strength.

DISCLOSURE

No conflicts of interest were declared by the authors.

REFERENCES