Effect of calcium triphosphate cement on proximal humeral fracture osteosynthesis: a finite element analysis

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ABSTRACT

Purpose. To measure the effect of void-filling calcium triphosphate cement on the loads at the implant-bone interface of a proximal humeral fracture osteosynthesis using a finite element analysis.

Methods. Finite element models of a 3-part proximal humeral fracture fixed with a plate with and without calcium triphosphate cement augmentation were generated from a quantitative computed tomography dataset of an intact proximal humerus. Material properties were assigned to bone fragments using published expressions relating Young’s modulus to local Hounsfield number. Boundary conditions were then applied to the model to replicate the physiological loads. The effect of void-filling calcium triphosphate cement was analysed.

Results. When the void was filled with calcium triphosphate cement, the pressure gradient of the bone surrounding the screws in the medial fracture fragment decreased 97% from up to 21.41 to 0.66 MPa. Peak pressure of the fracture planes decreased 95% from 6.10 to 0.30 MPa and occurred along the medial aspect. The mean stress in the screw locking mechanisms decreased 78% from 71.23 to 15.92 MPa. The angled proximal metaphyseal screw had the highest stress.

Conclusion. Augmentation with calcium triphosphate cement improves initial stability and reduces stress on the implant-bone interface.

Key words: bone cements; finite element analysis; fracture fixation, internal; shoulder fractures

INTRODUCTION

Proximal humeral fracture accounts for 10% of all fractures,1 and its incidence was 6.6 per 1000 persons per year.2 It is the third most common fracture in the elderly population, and a major cause of pain and disability.3,4 Outcome in older patients is poor owing to the combined effects of weak osteoporotic bone, reduced healing capacity, and poor compliance with physiotherapy.

There is no consensus on the most appropriate management. Hemiarthroplasty has been recommended for all complex fractures.5 Good
functional results were reported in a long-term follow-up of 33 patients treated with a Neer-II prosthesis. Hemiarthroplasty provides pain relief, but the results with respect to shoulder function vary. Locking plate osteosynthesis also achieves good results, but the use of rigid fixed angle devices resulted in an unexpectedly high failure rate in older osteoporotic patients. The importance of bone quality when using rigid fixed angle devices has been highlighted.

As patients age, bone loss within the humeral head may lead to formation of a central bone void. Therefore, for stable osteosynthesis in older patients, supplemental materials (autografts, allografts, artificial bone, and bone cement) to fill in the bone void are necessary, especially between the humeral centre and the lateral area. Synthetic bone graft substitute requires no donor site, matches more closely the mechanical properties of the native cancellous bone, and is replaced over time by creeping substitution. Increased construct stability facilitates early range of motion and therefore better functional outcome and also reduces the frequency of reoperation.

The presence of the central bone void concentrates the loads at the screw tips within the medial fracture fragment. Filling the bone void with calcium triphosphate cement distributes the loads along the entire length of the screws. This reduces the peak loads at the screw-bone interface. This finite element analysis measured the effect of void-filling calcium triphosphate cement on the loads at the implant-bone interface of a proximal humeral fracture osteosynthesis.

MATERIALS AND METHODS

A fresh cadaveric shoulder from a donor aged 86 years and weighed 61 kg was used. The specimen was stripped of soft tissues and stored at -20°C. Prior to testing, the specimen was defrosted overnight at 4°C in a sealed plastic container to prevent desiccation. Quantitative computed tomography, with slice thickness of 0.5 mm, scanned the specimen with a saline phantom to create a 3-dimensional model of the humerus. Boolean subtraction was applied to create a model of an anatomically reduced 3-part proximal humeral fracture with a smooth-edged central bone void. The size of the bone void was representative of that described by Yamada et al.

A stereolithographic representation of a proximal humeral locking plate with screws was created. The stereolithographic was simplified in that the screws themselves were modelled as smooth, conically tipped cylinders with a diameter of 3 mm. The length of the screws was adjusted individually so that the screw tip laid exactly 3 mm within the surface of the humeral head, and optimal surgical fixation was simulated. The screw threads were not simulated, as interactions at this scale fell below the slice resolution of the scan and could generate aberrant results. A finite element mesh of the construct was generated using an automated meshing algorithm. Contact interactions between the components were defined as no movement along the interface between screws and the surrounding materials to simulate a perfect screw purchase. Sliding contact was allowed between the fracture fragments.

Mechanical strength within the humeral head has been extensively reported in laboratory and clinical studies. To accurately simulate the bone fragments, material properties were assigned to cancellous bone on an element-by-element basis using the parent quantitative computed tomography dataset based on the relationship between radiological density and Young’s modulus (specifically for the humerus). This method gave a calculated range of Young’s modulus for cancellous bone from 0.56 to 1.12 GPa. An elastic modulus was assigned to those elements representing cortical bone. Bone was modelled as an isotropic, linear elastic, and heterogeneous material with a Poisson’s ratio of 0.3. The screw and plate were modelled as an isotropic, linear elastic material, with an elastic modulus of 110 GPa, and a Poisson’s ratio of 0.3 (commercial titanium).

The effects of the humeral head packing with and without calcium triphosphate cement were compared. To simulate the void, a negligible elastic modulus was assigned to simulate fracture haematoma. The calcium triphosphate cement was simulated as an isotropic, linear elastic material with an elastic modulus of 1.52 GPa, and a Poisson’s ratio of 0.3. To simulate a complete bond between the cement and the surrounding bone, no movement was allowed along the boundary between the 2 materials.

All models were inclined 52.2° to the vertical; 6° of freedom constraints were applied to the distal portion and a distributed load of 500 N was applied to the articular surface (Fig. 1). These boundary conditions replicated physiological loads on the proximal humerus at 90° abduction.

RESULTS

Peak loads were at the screw-bone interface within
the articular fragment. In the presence of the central bone void, areas of compression (red) and tension (blue) were adjacent to the screw holes in the medial bone fragment (Fig. 1). When the void was filled with calcium triphosphate cement, the pressure gradient of the bone surrounding the screws in the medial fracture fragment decreased 97% from up to 21.41 to 0.66 MPa (Fig. 2). Peak pressure on the fracture planes decreased 95% from 6.10 to 0.30 MPa and occurred along the medial aspect (Fig. 3). The mean stress in the screw-locking mechanisms decreased 78% from 71.23 to 15.92 MPa; the angled proximal metaphyseal screw had the highest stress (Fig. 4). The screw locking mechanisms were representative of the load distributed along the length of the screw.

**DISCUSSION**

Finite element analysis enables calculation of the effects of void-filling calcium triphosphate cement on the interactions within the construct under load. In our finite element analysis, augmentation with calcium triphosphate cement for proximal humeral fracture osteosynthesis enabled several modes of action and resulted in a 97% reduction in peak pressure gradient at the implant-bone interface and a 78% reduction in stress at the screw-locking mechanisms. The cement distributed the load across a larger area of the screw threads and acted as a load-sharing buttress. In the presence of the bone void, the load was concentrated on smaller areas of the screw-bone interface and

**Figure 1** Fracture fixation and loading.

**Figure 2** Pressure distribution within the humeral head.

**Figure 3** Pressure in fracture planes.
likely to cause a loss of grip of the screws and hence lateral migration of the articular fragment and screw cut-out. These models predict construct failure when the void is left open secondary to screw penetration into the glenoid fossa.\textsuperscript{16,39}

When the void was filled with calcium triphosphate cement, a 95\% reduction of pressure along the medial column of the fracture planes was noted. Support of the medial column of the proximal humerus has reported to decrease the rate of complications.\textsuperscript{14,16,40,41} A lack of medial support led to a screw perforation rate of 30\%, compared with 6\% in fractures with an intact medial support.\textsuperscript{16} Filling the void with calcium triphosphate cement provides support to the medial column without having to surgically expose the area. This is crucial as surgical exposure and direct medial buttress plating could compromise the blood supply to the humeral head.\textsuperscript{42,43}

A number of second-generation locking plates with variable geometric configurations have come into clinical use. These implants enable optimal anchorage of the screws. The 78\% reduction in stress at the screw-locking mechanisms is particularly meaningful to variable geometry fixed-angle devices, as the ability to target the proximal locking screws requires a more mechanically complex device with either softer materials or small moving parts which may be more prone to failure. Any reduction in stress on these venerable areas will reduce the likelihood of failure.

The findings of our study are consistent with those in 2 other studies.\textsuperscript{34,44} In 18 pairs of cadaveric humeri fixed in 3 different modes and augmented with calcium phosphate cement,\textsuperscript{44} construct stability (under torsion and compression) improved after augmentation as evidenced by reduced interfragmentary motion. In a computational analysis and a cadaveric study of a 2-part proximal humeral fracture fixed with a locking plate and augmented with calcium triphosphate cement,\textsuperscript{34} the importance of accurately assigning material properties to the bone was highlighted. Cortical and cancellous bones were considered a single entity with correlation of mechanical properties to radiological density based on human and bovine bones as described by Carter and Hayes.\textsuperscript{45} In our study, more accurate analysis was yielded, as material properties were assigned using human humerus–specific relationships.\textsuperscript{35} In addition, we used an anatomically reduced 3-part fracture as described by Yamada et al.\textsuperscript{23} and movement (sliding contact) at the fracture planes was allowed. Both studies agree that augmentation with calcium triphosphate cement improves initial stability and reduces stress on the implant-bone interface.

The use of a simplified load to replicate the forces on the proximal humerus has been reported,\textsuperscript{44,46} but it over-simplifies \textit{in vivo} loading. Further studies are needed to develop a validated mechanical model of the shoulder when loads are applied from the muscle attachments, with a rolling-sliding contact at the glenohumeral interface. Calcium triphosphate cements can be replaced over time by the surrounding bone by means of creeping substitution.\textsuperscript{28} This biological action affects the stability of the construct, but is absent from this model.

Despite these limitations, our study enabled investigation of the effect of void-filling calcium triphosphate cement in an anatomically reduced fracture with a central bone void and prediction of failure modes when the void was not filled. Reduced pressure gradients in the implant-bone interface and the medial column provided initial stability for the fixation.

\textbf{DISCLOSURE}

No conflicts of interest were declared by the authors.
REFERENCES


