BIOMECHANICAL COMPARISON OF THE SLIDING HIP SCREW AND THE DOME PLUNGER

effects of material and fixation design

JACK CHOUeka, KENNETH J. KOVAL, FREDERICK J. KUMMER, GLEN CRAWFORD, JOSEPH D. ZUCKERMAN

From the Hospital for Joint Diseases Orthopaedic Institute, New York, USA

We studied the biomechanical behaviour of three sliding fixation devices for trochanteric femoral fractures. These were a titanium alloy sideplate and lag screw, a titanium alloy sideplate and dome plunger with cement augmentation, and a stainless-steel sideplate and lag screw. We used 18 mildly osteoporotic cadaver femora, randomly assigned to one of the three fixation groups. Four displacement and two strain gauges were fixed to each specimen, and each femur was first tested intact (control), then as a two-part fracture and then as a four-part intertrochanteric fracture. A range of physiological loads was applied to determine load-bearing, load-sharing and head displacement. The four-part-fracture specimens were subsequently tested to failure to determine maximum fixation strengths and modes of failure.

The dome-plunger group failed at a load 50% higher than that of the stainless-steel lag-screw group (p < 0.05) and at a load 20% higher than that of the titanium-alloy lag-screw group (NS). All 12 lag-screw specimens failed by cut-out through the femoral head or neck, but none of the dome-plunger group showed movement within the femoral head when tested to failure. Strain-gauge analysis showed that the dome plunger produced considerably less strain in the inferior neck and calcar region than either of the lag screws. Inferior displacement of the femoral head was greatest for the dome-plunger group, and was due to sliding of the plunger.

The dome plunger with cement augmentation was able to support higher loads and did not fail by cut-out through the femoral head. Its sliding potential was maintained, retaining the biomechanical advantages of the sliding screw.

Accepted 8 May 1994; Accepted 5 August 1994

A great variety of implants has been used to treat intertrochanteric fractures. Rigid nail-plate devices which do not allow fracture impaction are known to have high complication rates, up to 40% for unstable fractures (Dimon and Hughston 1967; Harrington and Johnston 1973; Jensen, Sonne-Holm and Tondevold 1980). These include nail penetration, metal fatigue and cutting-out as the fracture impacts into a more stable position (Laros 1975; Jensen et al 1980). Sliding nail and screw devices, developed in the 1970s, provide secure fixation while allowing controlled impaction (Harrington and Johnston 1973; Jacobs, McClain and Armstrong 1980; Høgh 1982). Sliding devices are load-sharing, in contrast to rigid nail plates which are load-bearing (Jacobs et al 1980), and allow early mobilisation and weight-bearing. They are now the most common method of fixation of both stable and unstable intertrochanteric fractures.

A major complication of the use of sliding screws is superior cutting-out through the femoral head (Simpson, Varty and Dodd 1989; Wainer et al 1990; Pitsaer and Samuel 1993; Rokito, Koval and Zuckerman 1993). Improper placement is a contributing factor (Doherty and Lyden 1979; Davis et al 1990; Rokito et al 1993), especially in patients with severe osteopenia (Blanton and Biggs 1968; Harrington 1975; Laros 1980).

Much work has been done on the biomechanical properties of the sliding screw, including analysis of plate angle (Kyle, Wright and Burstein 1980; Meislin et al 1990; Den Hartog, Bartal and Cooke 1991), optimal screw positioning within the femoral neck and head (Davis et al 1990; Den Hartog et al 1991; Wu and Shih 1991), the effect of anatomical reduction (Den Hartog et al 1991) and the use of displacement osteotomies (Chang et al 1987; Den Hartog et al 1991).

The use of methylmethacrylate cement has been advocated to improve fixation (Harrington 1975; Bartucci et al...
1985). Müller (1962) introduced this technique, while Muhr, Tscherner and Thomas (1979) stressed that the aim was to maintain stability of the fracture-implant construct until bony healing. Cheng et al (1989) found that cement augmentation provided early stability, but that improper use led to late complications. Bartucci et al (1985) reported that the use of cement in the proximal fragment only was enough to prevent screw penetration through the femoral head. This technique requires care to avoid intrusion of cement into the fracture site, which could interfere with healing. Extravasation into the surrounding soft tissues must also be avoided.

We have studied a new device which is designed to facilitate injection of cement into the femoral head. The Alta expandable dome-plunger system (Howmedica, Rutherford, New Jersey) has a built-in mechanism for cement delivery that theoretically eliminates the risk of cement extrusion. The cement is kept away from the barrel of the sliding device, maintaining its potential to allow impaction.

Our study compared the Alta dome plunger with cement augmentation with two different sliding hip screws: the Alta sliding hip screw and the Richards Classic sliding hip screw (Smith and nephew Richards, Memphis, Tennessee). All three systems were tested in both stable and unstable intertrochanteric fractures, and the resulting strains and displacements for physiological loads, loads to failure, and mechanism of failure were determined.

MATERIALS AND METHODS

Sixty adult cadaver femora were obtained from embalmed specimens. Anteroposterior radiographs allowed measurement of the neck-shaft angles and excluded any bony lesions. From these we selected 18 mildly osteoporotic femora with a Singh index (Singh, Nagra and Maini 1970) of 4 and bone density on DEXA scanning of less than 0.8 g/cm$^2$. These were then randomly assigned to one of three fixation groups (Fig. 1):

1) the Richards Classic sliding hip screw (stainless steel);
2) the Alta sideplate unit with lag screw (Ti-6Al-4V alloy); or
3) the Alta sideplate unit with dome plunger and cement augmentation (Ti-6Al-4V alloy).

Each specimen in turn was fitted with strain and displacement gauges to record the biomechanical response to loading of the intact femur, and of the femur after two- and four-part simulated intertrochanteric fractures. All specimens were finally tested to failure to determine the mode and mechanism.

Specimen preparation. Specimens were double-wrapped in airtight bags until testing to avoid drying. The distal condyles were removed and the shafts potted with bone cement in steel tubes (Fig. 2). Unidirectional strain gauges (Omega EA-06-125-AC-120; Omega Engineering, Stamford, Connecticut) were fixed to the inferior neck and to the femoral shaft below the lesser trochanter and linked to a digital strain indicator (MicroMeasurements P-3500, Vishay Technology Inc, Greenboro, North Carolina). Four digital electronic linear gauges (IDC-25E, Mitutoyo, Tokyo, Japan) were fixed to the frame of an MTS 410 servohydraulic testing machine (MTS Systems, Minneapolis, Minnesota) with oversize plunger heads placed to contact specific head and shaft positions to measure true head displacement. These displacement gauges were placed as follows (Fig. 2):

D1, perpendicular to the shaft at the lateral aspect of the greater trochanter;
D2, perpendicular to the shaft and slightly lateral to the lesser trochanter;
D3, perpendicular to the shaft at the posterior aspect of the head; and
D4, parallel to the shaft of the femur on the inferior aspect of the head.

Application of load. The shaft was mounted in an angle vice at 25° adduction in the coronal plane and neutral in the sagittal plane to simulate the anatomical loading of a single-leg stance (Frankel 1960; Chang et al 1987) (Fig. 2). The MTS machine loaded the femoral head with compression loads by means of a flat polished plate. Load was manually increased in 200 N increments to 1200 N with displacement and strain-gauge readings at each 200 N load. After sequential loading of the four-part fracture specimens, loads were continuously applied until failure at a rate of 1 cm/min, recording load-deformation curves.

Instrumentation and testing. All specimens were first tested intact to serve as self-controls. Two-part intertrochanteric fractures were then created by cutting the circumference of the cortical bone at the intertrochanteric line with a thin-blade reciprocating saw. One of the three fixation methods was then performed. All the sideplates had a 135° barrel orientation, and screws were inserted after reaming over a guide pin placed in the centre of the femoral neck and head under direct vision. The paths of the two lag screws were pre-tapped.

For the Alta dome plunger, cement insertion was by placing a small bolus of doughy cement into the dome before it was mounted on the insertion tool. After insertion into the femur, the tool was tightened to extrude the cement into the surrounding cancellous bone.

After instrumentation, each specimen was examined radiographically for proper screw placement and tested mechanically as described to 1200 N. Four-part intertrochanteric fractures were then created by sawing and made unstable by discarding both the posteromedial and the greater trochanteric fragments. The specimens were then restented to 1200 N, after reduction of the fractures had been ensured by tightening the compression screw to provide secure contact of the fracture fragments. The Alta dome plunger does not include a compression screw, and reduction for this group was therefore achieved by manually compressing the plunger within the barrel of the sideplate.
Finally, the fixed four-part unstable fractures were tested to failure, with maximum load to failure measured from the load-deformation curve. After testing, the femora were photographed and radiographed to record the mechanism of failure and displacement of the device. When the mechanism of failure was not obvious, the femoral heads were sliced in half in order to inspect internal morphology.

Analysis of data. Each femur served as its own control. Load-deformation and load-strain curves were generated and fitted to a regression equation by the method of least squares. A Pearson correlation coefficient of greater than 0.90 was considered acceptable.

Reproducibility of the study was assessed by repeating randomly selected tests and comparing results. Student’s t-test was used for statistical analysis of the three groups, taking a p value of 0.05 or less as statistically significant.

RESULTS

The femora in the three groups were compared with reference to the Singh index, bone mineral density, and neck-shaft angle. There were no statistically significant differences.

Maximum load to failure. The maximum loads to failure were: Richards Classic hip screw, 3795.8 ± 816.4 N; Alta lag screw, 4732 ± 1496.6 N; and Alta dome plunger, 5591.7 ± 1370.2 N. There was a significant difference between the results for the Richards and the Alta dome-plunger groups (Fig. 3).

Mode of failure. The mode of failure was usually obvious. In all but two of the 18 femora tested (89%), the implant remained virtually intact throughout testing. In the other two specimens, both in the Alta dome-plunger group, one implant failed by bending of the lag screw and the other by pull-out of the cortical screws allowing movement of the sideplate from the femoral shaft. In neither specimen was
there any movement of the expanded dome in the femoral head on either radiographic or cross-section evaluation.

All the Alta lag screws cut out superiorly through the head. Five of the six (83%) Richards sliding screws cut out superiorly, and one failed by fracture through the superior neck. In the Alta dome-plunger group, failure was by fracture or crush of the inferior neck in five (83%) and separation of the sideplate unit in one. There was no movement of the dome within the femoral head in any of the Alta dome-plunger group.

**Strain-gauge analysis.** Strain data were recorded as percentages of those of the intact femur. For the two-part fracture situation, both the inferior neck and calcar strain gauges showed no significant differences between the Richards Classic and Alta lag-screw groups at any load tested. The Alta dome-plunger group showed significantly less strain than either of the other groups at all loads, and a change from compression to tension in the gauge adjacent to the lesser trochanter (Fig. 4).

Percentage of strain for the intact femur at each load for the three devices (mean ± sd). Figure 4a – Strain gauge 1, at the base of the inferior neck. Figure 4b – Strain gauge 2, in the medial calcar region. The tensile forces produced by the Alta dome plunger in the calcar region are shown.
Method has been used in many experiments on the mechanics of the sliding hip screw because it simulates the major component of physiological loading during walking (Chang et al 1987; Clark, Crofts and Saleh 1990; Meislin et al 1990; Rosenblum et al 1992).

**DISCUSSION**

The Alta dome plunger was able to bear nearly 50% greater loads than the Richards Classic sliding screw and 20% more than the Alta lag screw before failure. This result appears to be directly related to the increased diameter of the load-bearing portion in the femoral head. The dome plunger has a projected area within the head (area of the device through a plane perpendicular to the applied load) that is 38% greater than the Alta lag screw and 74% greater than the Richards lag screw. Cement extruded from the dome plunger further increases this area, adding to the load-bearing ability in the osteoporotic femora which we used.

The most striking finding was the difference in failure modes of the three devices. None of the specimens in the dome-plunger group showed superior cut-out; none showed any demonstrable movement of the dome in the femoral head. Failure in this group was at higher loads, by crushing of the inferior neck into the proximal femoral shaft, demonstrating that sliding had been maintained. In contrast, the two lag-screw groups failed by superior cut-out (Fig. 6). Again, this appears to be related to the projected area occupied by the device in the femoral head.

The mechanical strength and stiffness of an implant depend on its material properties and design; the biomechanical behaviour of the implant is determined by both its mechanical properties and the response of the surrounding bone. Thus, it is often impossible to isolate a particular characteristic such as design or material and draw conclusions on its biomechanical effects. Analysis of the results obtained for the three devices must therefore take into account their respective materials, designs, and interactions with surrounding bone.

In our study the variables included material as well as design-related factors such as bending stiffness, projected area of fixation in the femoral head and sliding characteristics. The Richards screw is of stainless steel, while both Alta devices are of titanium alloy with a modulus of elasticity half that of stainless steel and therefore twice as flexible, given identical designs. The differences between the two Alta devices show how design geometry can influence mechanical properties. Analysis of bending stiffness, using standard formulae for beam bending, showed that the smaller internal hole made the Alta lag screw 25% stiffer than the Alta plunger. Similar calculations showed that the Richards screw was 45% stiffer than the Alta plunger and 13% stiffer than the Alta lag screw. Thus, in these implants, design is more important than material in contributing to stiffness.
When the devices were tested in isolation, without bone, they had similar sliding characteristics and consequently similar load-displacement behaviours. We therefore conclude that interaction of the devices with surrounding bone is the differentiating factor in determining biomechanical behaviour.

The projected area of the device within the head also affected strain and displacement. Strain in both the calcar region and the inferior neck was significantly lower for the Alta dome plunger, while inferior head displacement was greatest. In all our tests on all three devices inferior head displacement combined crushing of the bone within the femoral head and sliding of the shaft within the barrel. In the Alta dome plunger, there was no motion of the dome within the head and all inferior displacement was due to sliding, which resulted in compressive failure of the medial neck at higher loads. Crushing of bone within the head and its resulting downward translation tend to increase the strain in the medial neck and calcar, as seen with both lag screws. The sliding ability of the dome plunger is thus enhanced by its mode of fixation. The femoral strains measured for the Richards screws were similar to those obtained from previous experiments in our laboratory (Chang et al 1987; Rosenblum 1992).

The sliding behaviour of each specimen was somewhat variable. Some specimens in each group showed no sliding: one of six in the dome-plunger group and two of six in each of the lag-screw groups.

Lateral displacement recordings showed that the slope of the load-displacement curve generated by the dome plunger was approximately twice that for the Richards screw. This means that more load was needed to produce the same displacement: the construct was stiffer and stronger. Displacement perpendicular to the plane of the applied load was minimal and showed no significant difference among the three groups.

The Alta dome plunger created tensile strains in the calcar region in comparison with the compressive strains of the lag-screw devices, making it more of a load-bearing than a load-sharing device. Although it was the strongest implant, this may be at the expense of unloading the bone in the calcar. The significance of this will require investigation by a well-controlled clinical trial.

The increase in projected surface area provided by the dome plunger increased the overall strength of fixation and improved sliding ability, but the surgical procedure requires the removal of a greater amount of bone, making it technically more difficult and risking damage to the cortical bone. The use of cement, however, increases surface area without the need for excessive reaming. The larger reaming size required for the insertion of the dome plunger allows it to be inserted without twisting, and avoids any torque during this phase of its application: this is a possible advantage over a standard lag screw. The reamer for the femoral neck however is 14 mm in diameter compared with 10 mm for the Alta lag screw and 9 mm for the Richards lag screw.

The insertion of cement is simplified with the Alta dome plunger, but certain precautions are essential. One must be certain that joint penetration does not occur during insertion of the guide pin, since this would allow cement to be extruded into the joint during pressurisation.

Conclusions. The Alta sideplate with dome plunger is an alternative to the sliding hip screw for the fixation of intertrochanteric hip fractures. It has greater load-bearing capabilities and superior cut-out is minimised, while sliding is enhanced by the fixation in the femoral head. Insertion does not produce torque on the proximal fragment, but it requires a larger reamed canal. Cement augmentation is simplified by the internal delivery system.

The authors thank Howmedica and Smith & Nephew Richards for supplying the implants and instrumentation used in this study. We would also like to thank Drs Benjamin Blair and Robert Casar for their advice and assistance.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.
REFERENCES


Evans FG, Lissner HR. Stresscoat deformation studies of femur under static vertical loading. Anat Rec 1948;100:159-90.


