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Femoral component loosening in hip arthroplasty

Cadaver study of subsidence and hoop strain

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To aid in understanding loosening following cemented total hip arthroplasty, we conducted a cadaver study of the proximal femur with implanted cobalt-chromium and titanium femoral components of recent design, loaded through the head of the prosthesis. Stem subsidence and strain in the proximal femur were measured. After proximal support of the implant collar was removed, we found that cobalt-chromium implants had a greater tendency to subside than titanium implants. Subsidence of a femoral component within the cement mantle caused an increase in tensile hoop strain measured in the proximal cortex. When implants were loaded until failure of the cortex, a direct relationship between increase in subsidence and increase in cortical hoop strain was demonstrated. Our data show that implants that resist subsidence into the cement mantle tend to decrease hoop strains in the proximal femoral cortex.

The effects of stem subsidence under load on the magnitude of strain in the cortex has received little attention in experimental and analytical studies of proximal femoral biomechanics. Markolf et al. (1980) showed that the presence of an implant collar in contact with the calcar reduces subsidence of a cemented femoral component, but they did not measure strain values in the femoral cortex during or after subsidence of the stem. Huiskes (1980) and Hampton et al. (1981) used finite element models to show that slip and tensile loosening at the interface between stem and cement has a highly significant effect on cement and interface stresses. Crowninshield & Tolbert (1983) measured the strain distribution in the cement surrounding bonded and loose femoral stems and demonstrated higher strain levels in the proximal cement when the stem was loose. Barb et al. (1981) demonstrated that cement precoating can prolong a stem-cement bond and decrease the tendency for the stem to subside in the cement. We recently measured circumferential strain in the cement mantle surrounding a femoral component and demonstrated that if subsidence of the stem occurs, high levels of hoop strain are generated in the mantle and gross failure of the mantle can result (Manley et al. 1985).

At present, little is known about the effects of implant slippage on the state of strain in the femoral cortex. In addition, it is not known whether the material characteristics of an implant have any influence on its tendency to subside.

We have studied stem subsidence under load with titanium alloy and cobalt-chromium alloy femoral components in cadaver specimens.

Materials and methods

Femoral components. Three designs in current clinical use were selected for their substantially different geometric features (Figure 1). The Harris series (A) consisted of a forged cobalt-chromium alloy Howmedica HD2 and a machined titanium alloy Hexcel Anatomic. The teardrop-shaped inset in the HD2 was filled with epoxy and ground smooth prior to testing to ensure a con-

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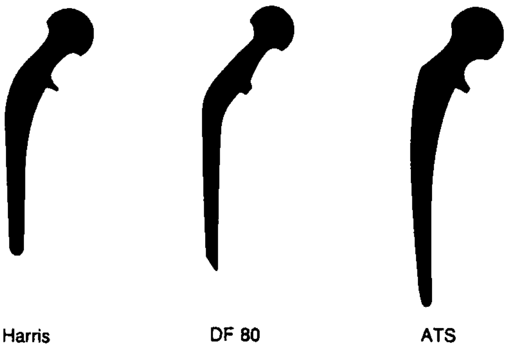

Figure 1. Femoral components used in the study.

sistent stem geometry within this series. The DF80 series (B) consisted of two stems: a 13-mm-diameter forged titanium alloy stem routinely produced by Zimmer and a cast cobalt-chromium copy of the DF80 design made for this study by the manufacturer. The ATS series (C) was composed of a forged cobalt-chromium stem alloy produced by Howmedica and a machined titanium alloy TPL6 implant produced by Kirschner Medical.

Cadaveric specimens. Nine embalmed cadaveric specimens were prepared for testing. Three femora were allocated to each series of stems and were prepared for implantation with standard surgical instrumentation for the implants. Five uniaxial strain gauges (Micro-Measurements EA-13–062AQ-350) were bonded to each femur (Figure 2). Gauges aligned circumferentially to measure cortical hoop strains were located 5-mm distal to the resection cut; at a point corresponding to midlength of the stem and at the stem tip. Gauges aligned longitudinally to measure axial strains were located adjacent to the most proximal and most distal circumferential gauges. Prior to implantation, each femoral component was coated with a 0.125-mm film of water-soluble latex-release agent (Kwikmold, Adhesive Product Corp., Bronx, New York) to facilitate later removal of the stem from the cement and to prevent adhesion of cement to the implant. A latex plug was inserted in the distal canal and the stem was implanted using Zimmer high-viscosity bone cement. A small spacing jig was used to ensure that a 1-mm-thick cement layer was trapped consistently between the component collar and the resected calcar femorale. All the stems were implanted in the neutral position and the stem orientation was confirmed by radiography prior to testing. An MTS extensometer was attached between the neck of the femoral component and the proximal femoral cortex to measure stem subsidence (Figure 2).

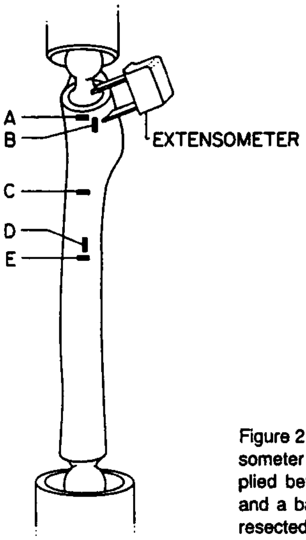

Figure 2. Strain gauge and extensometer placement. Load was applied between the femoral head and a ball joint inserted into the resected distal femur.

Comparative testing. All the testing was performed in a servohydraulic MTS testing machine. For each femur, load was applied through two polyethylene acetabular cups, one articulating with the head of the femoral component, the second with a ball-ended peg cemented into the distal medullary canal (Figure 2). An angle of 20 degrees between the loading axis and the femoral shaft was maintained throughout the tests. Load was applied in 100 N increments every 5 seconds up to a maximum of 3.5 kN. Load, strain gauge, and extensometer data were recorded automatically at every loading increment up to the maximum load and again after the applied load had been returned to zero.

After the specimen had been subjected to this loading regime, a 0.5-mm -thick saw cut was made through the cement layer trapped between the implant collar and the calcar femorale to simulate the loss of collar-calcar contact due to proximal femoral remodeling. The testing protocol was repeated. On completion of the two tests, the femoral component was removed from the femur by driving a wedge between collar and resected calcar. The cement mantle was partially removed with a cement eater and the second prosthesis of the same geometry was implanted in the same bone with additional cement. Testing was conducted as before. The same testing regime was used for all three femora allocated to each series of stems and for all three stem series.

All the data were analyzed for significance using the Wilcoxson signed ranks test based on differences. A value of $P < 0.05$ was taken as the criterion for significance.

Failure testing. Two additional femora were prepared and fitted with strain gauges. The commercial stems from the DF80 and ATS series were implanted with a 5.0-mm gap between the component collar and the resected calcar. This gap was achieved by not fully seating the prosthesis against the calcar rather than by the resection of additional bone. Latex coating of the implant was not used in these two tests. Using the same loading configuration as before, increasing load was applied in 100 N increments at 5 second intervals until femoral failure occurred. Load, strain gauge, and extensometer data were recorded througout. The failed specimen was photographed and the implant and cement mantle were removed from the femur for failure mode analysis.

Results

In spite of the differences in design of the stems from series to series, similar trends in each of the three data sets were observed (Figure 3).

With contact maintained between the collar and the calcar, longitudinal strain data in the proximal femur (gauge B) showed that all the titanium alloy stems produced larger strains than their stiffer cobalt-chromium alloy counterparts. Circumferential strains in the same region did not differ between the two stem materials for all three series of stems. The longitudinal strain levels in the region of the distal stem (gauge D) were only marginally higher for the cobalt-chromium alloy stems than for the titanium alloy stems.

When collar-calcar contact was eliminated, the longitudinal strains in the calcar region were reduced for both the cobalt-chromium and titanium alloy stems ($P < 0.01$). An increase in circumferential strain magnitude in the proximal cortex after removal of contact was observed with the cobalt-chromium alloy stems. No increase occurred with the titanium alloy stems.

The magnitude of irreversible subsidence suffered by all three cobalt chromium stems was less than that measured for their titanium counterparts ($P < 0.005$, Table 1).

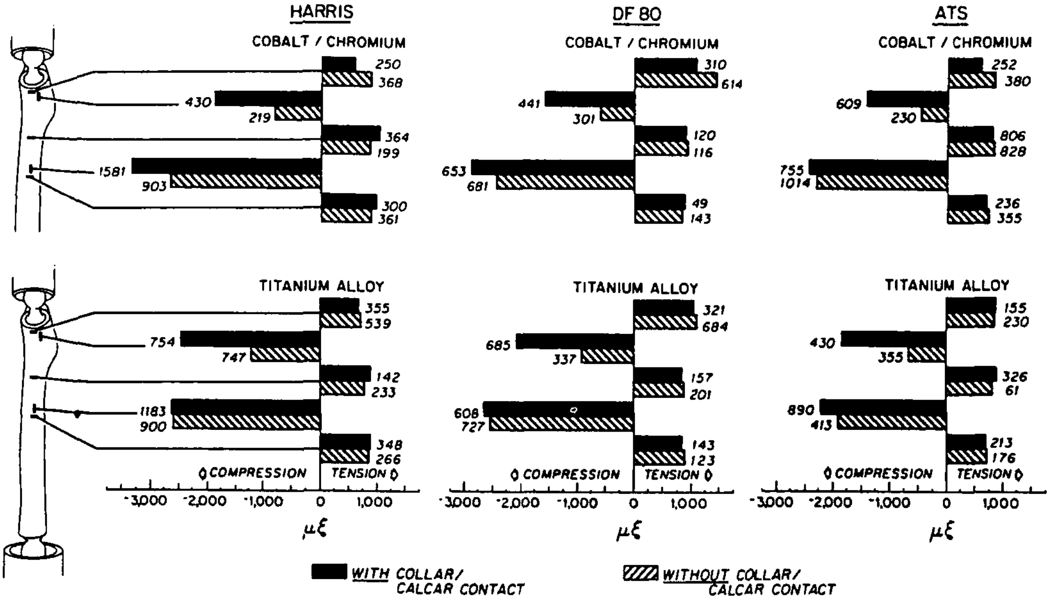

Figure 3. Strain data collected for the three series of stems. For each strain gauge, the length of the bar shows the mean strain value calculated for three tests in different femora. The number at the end of each bar is the standard deviation associated with the mean.

Table 1. Mean values (SD) of component subsidence (mm) for each stem series.

	Ti	CoCr	Ti/CoCr (%)
Harris	0.40 (0:27)	0.85 (0.06)	47
DF80	0.95 (0.24)	0.50 (0.09)	52
ATS	0.80 (0.09)	0.30 (0.03)	38

The load versus subsidence plots for the two specimens loaded to failure showed that the relative displacement between implant and bone measured by the extensometer initially increased linearly with increasing load, and then stepwise incidents of displacement of the implant into the mantle began to occur. Comparison of the subsidence and the proximal circumferential strain gauge data showed that hoop-strain magnitude increased similarly to increase in subsidence magnitude; discontinuous stepwise increases in hoop strain occurring concomitantly with stepwise increases in subsidence. Failure of both specimens was by longitudinal splitting of the cortex (Figure 4). After removal of the implant and cement mantle from the femur, failure of the mantle was found to have occurred obliquely at the proximal stem and transversely at the stem tip.

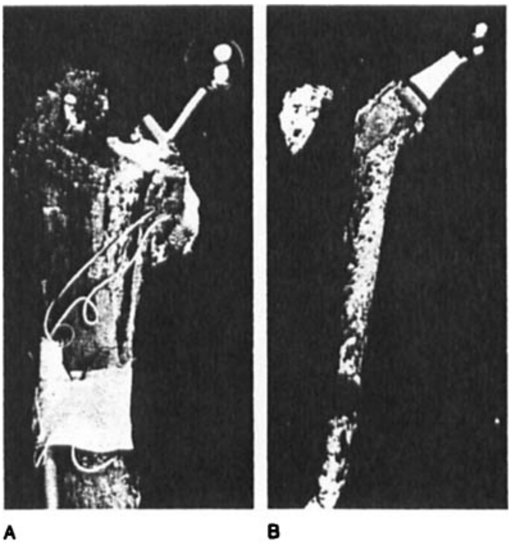

Figure 4.
A. The appearance of a femoral specimen at failure.
B. The femoral component and cement mantle after removal from the femur.

Discussion

This study has examined the hypothesis that femoral-component subsidence causes an increase in hoop-strain magnitude in the femoral cortex. Quantitative strain values measured in an individual test were found to be highly dependent on the particular femur used; a finding that accounts for the large standard deviations of the mean strain values. However, trends in data comparisons from bone to bone were consistent; for example, longitudinal strain in the proximal femur measured with all three stem designs always was greatest with the titanium compared with cobalt-chromium implants.

A general observation is that in the proximal region of the femur, the longitudinal strain measured was highly dependent upon the presence of contact between the collar of the femoral component and the calcar femorale. For both alloy materials, decreases were found in the longitudinal strains measured in the proximal cortex when contact between the collar and calcar was eliminated. Regardless of the presence or absence of calcar-collar contact, the titanium alloy stems produced greater longitudinal strains in the proximal cortex than did their cobalt-chromium alloy counterparts. These data show that load transfer to the proximal cortex is dependant on stem stiffness and confirm earlier work by Oh & Harris (1978), Markolf & Amstutz (1980), Crowinshield et al. (1981), Lewis et al. (1981), Manley et al. (1983).

The circumferential strain data recorded from the proximal femur was consistent also from stem series to stem series. When the implant collar was in contact with the calcar, there was no difference in proximal circumferential strain measured with the titanium or cobalt-chromium implants. Once collar-calcar contact had been removed, the increase in circumferential strains with cobalt-chromium alloy stems coincided with subsidence of these implants. By comparison, the lesser subsidence of the titanium implants was associated with lower values of hoop strain. Thus, a clear relationship between subsidence and hoop strain was established. The most probable reason for the differences in subsidence of stems fabricated from different alloys, but to the same geometry, is stem stiffness; the stiff cobalt-chromium stems tending to retain their original geometry under load and subsiding into the cement mantle, the more flexible titanium stems bending and wedging between the medial and lateral walls of the cortex.

When specimens were loaded to failure, stepwise increases in subsidence occurred simultaneously with stepwise increases in hoop strain. This behavior is similar to that seen in the comparative tests and suggests that the latex coating used in these latter tests did not compromise these data. Inspection of the specimens loaded to failure showed longitudinal femoral splitting, oblique cracking of the cement mantle and transverse fracture of the distal cement plug. This failure mode is the result of a log-splitting effect that occurred when the implant was forced into the cement. Failure of these femora occurred at a subsidence of only 1.5 mm. This is substantially less than the subsidence measured radiographically by Cameron & McNeice (1980), Hampton et al. (1981), Olsson (1981), and Phillips (1982). Because longitudinal cracking of the femur in vivo is not commonly reported, gross migration of implants seen in follow-up radiographs must occur between bone and cement after removal of cortical support. The reason for bone remodelling around the femoral component is most probably multifactorial; thermal effects from cement (Mjöberg 1986), bone lysis, the presence of wear debris, and a changed stress environment have all been implicated (Lanyon et al. (1981), Goldring et al. (1983), Mjöberg et al. (1984b), Bauer et al. (1987). Subsidence of an implant within the cement also may be a factor in this process. Transverse failures of the cement mantle at the stem tip seen on follow-up radiographs shows that subsidence between stem and cement can occur in vivo. Our data show that an increase in hoop strain in the cortex is associated with this type of stem migration.

In summary, our study has shown a direct relationship between implant subsidence and hoop strain in the proximal cortex. The effects of this relationship on the loosening process in vivo are not clear. Although the removal of proximal support and subsidence of a prosthesis modify the magnitude and distribution of strains that occur when the stem remains in a stable position, the hoop strains recorded were about 30 per cent of the values reported by Lanyon et al. (1981) and Frost (1983) as being necessary to induce bone remodelling. It is possible that under repetitive loads associated with activity, the cumulative effects of subsidence within the mantle and increased hoop strain in the cortex contributes to remodelling of the cortical shell and migration of the stem and cement mass at the cement-bone interface. Further remodeling could occur at the subsidence-hoop strain-remodeling cycle repeats. In any event, our data show that stems which resist subsidence into the mantle will minimize hoop strains in the proximal femoral cortex.

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