The influence of surface roughness on stem-cement gaps

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We have compared the interface morphology at the stem-cement interface of standard Charnley stems with a satin finish (Ra = 0.75 µm) with identical stems which had been grit-blasted over their proximal third (Ra = 5.3 µm) to promote a proximal bond. The stems were cemented into cadaver femora using conventional contemporary cementing techniques. After transverse sectioning, we determined the percentage of the perimeter of the stem which had a gap at the interface.

There were substantial gaps (mean 31.4 ± 17.1%) at the stem-cement interface in the grit-blasted region. This fraction was significantly (paired t-test, p = 0.0054) higher than that found around the contralateral satin-finished stems (mean 7.7 ± 11.7%). Although studies of isolated metal-cement interfaces have shown that the bond strength can increase with surface roughness it cannot be assumed that this effect will be observed under clinical conditions.

Received 6 July 2001; Accepted after revision 3 May 2002

In total hip arthroplasty the use of cemented femoral stems designed to have a proximal bond has given mixed results. It has been generally assumed that rougher surfaces will result in improved stem-cement bonding because of small-scale mechanical interlocking. A stronger stem-cement bond has been an attractive design goal in the light of post-mortem retrieval studies which have suggested that loosening of the femoral stem is initiated by debonding of the stem-cement interface. The pursuit of a robust stem-cement bond has been justified further by computational studies showing that such a bond should reduce both damage to the cement mantle and subsidence of the stem. Some roughened stems, however, have had poor results and some investigators have suggested that stems with a rough finish may produce wear particles after debonding followed by bone lysis. How debonding occurs is unclear but it is believed to be the result of mechanical overloading of the interface.

Surprisingly, there are few data on the morphology of the stem-cement interface after cementation of roughened stems into human femora using clinical techniques. The findings which we report in this study were the unforeseen consequence of our attempts to produce a proximal stem-cement bond with a grit-blasted stem in cadaver femora. We had originally hypothesised that proximal grit-blasting would result in an enhanced bond between the cement and the stem. The efficacy of the grit-blasting was assessed by measuring micromovement during cyclical fatigue tests with stair-climbing loads. After loading, all the stems remained well fixed with no discernible differences between those with either a grit-blasted or satin-finished surface. Subsequent sectioning of the cemented stem constructs revealed frequent gaps at the stem-cement interface and this unexpected finding led us to examine the morphology of the stem-cement interface in more detail.

Materials and Methods

Preparation of specimens. The interface morphology of standard Charnley flanged cemented stems (DePuy, Leeds, UK) with a satin-finished surface (Ra = 0.75 mm) was compared with identical stems which had been modified to a grit-blasted surface (Fig. 1) over their proximal third (Ra = 5.3 mm) to promote a proximal bond. Henceforth, ‘satin’ will refer to stems with the standard surface and ‘grit’ to those modified by proximal grit-blasting. Six pairs of cadaver femora were selected which were of an appropriate size for the implants (mean age 73 years, range 59 to 82). The femora were radiologically screened for left-right differences or pathological abnormalities. Grit stems were randomly assigned to the left or right femur of each pair, with the contralateral bone receiving a satin stem. All the stems were cleaned ultrasonically in a detergent solution and rinsed with 95% ethyl alcohol.
Fig. 1a

Fig. 1b

Electron micrographs of the satin-finished (a) and grit-blasted (b) surfaces. The scale bar is 50 µm.

Fig. 2a

Fig. 2b

Fig. 2c

Photographs of the jig system used for the preparation of specimens. Figure 2a – The broach attachment which was used to align the femora in their pots. Figure 2b – The stem attachment with a ‘satin’ stem. Figure 2c – The stem-cement-femur construct after insertion of the stem.
The femora were broached using standard techniques under the supervision of an experienced surgeon. The distal ends of the bones were ‘potted’ in acrylic cement. A custom jig, which attached to the femoral broach, allowed the position of the broached hole to be positioned consistently relative to the distal pot (Fig. 2). Polymethylmethacrylate cement (Simplex P; Stryker-Howmedica-Osteonics, Rutherford, New Jersey) was introduced into the femoral canal using contemporary cementing techniques: ‘bottle brush’ lavage, distal canal plug, vacuum mix, retrograde fill and pressurisation. Cement was applied in a doughy state using the ‘does not stick to glove’ criterion commonly used in surgical practice. The ambient temperature was maintained at 23°C. The cement was mixed under vacuum for 90 seconds and the dough stage was reached 4 to 4.5 minutes after mixing had begun. The final position of each prosthesis was controlled by a custom jig. The stem was held such that its long axis was coincident with the long axis of the broached hole (Fig. 2).

**Microscopic evaluation of the stem-cement interface.** All specimens were transversely sectioned using a Buehler high-speed saw (Buehler Inc, Lake Bluff, Illinois) with an abrasive wheel. Beginning at the collar, sections were cut at 5 mm intervals for the most proximal 80 mm followed by 10 mm intervals for the remainder of the length of the stem (Fig. 3). They were stained with a fluorescent dye penetrant (AquaCheck WB200; Sherwin Inc, South Gate, California) and examined using an epifluorescence stereomicroscope. Images were recorded using a 2 Mpixel digital camera (pixel size 15 × 15 mm) and imported into Image Pro (Media Cybernetics, Silver Spring, Maryland) for analysis. Stem-cement gaps were identified visually and the ‘measurements’ feature of ImagePro was used to trace and record gap lengths on the perimeter of the stem. In addition, the perimeters of the stem and mantle were traced and the mean, minimum and maximum thicknesses of the cement mantle were recorded.

**Analysis of data.** For each transverse section we calculated the percentage of the perimeter of the stem which was not in apposition to cement. The gap fractions of the transverse sections were then averaged over proximal and distal zones; the proximal zone was defined by the extent of grit-blasting. The proximal and distal zones were made up of 8 and 10 slices, respectively. For each individual femur there were two measures of gap fraction, one for each zone. This averaging across zones was necessary because it was not expected that sections from individual sections in the same femur would be statistically independent. The dependence of gap fraction on the type of stem and proximal/distal zone was assessed using the paired \( t \)-test. An analysis of covariance (ANCOVA) was used to determine if the gap fraction was dependent on axial position and if this dependence was different for the grit-blasted and satin-finished stems.

**Results**

Across all slices, the average cement mantle had a mean thickness of 4.5 ± 1.4 mm (SD), a mean maximum of 9.0 mm and a mean minimum of 1.6 mm. The use of jigs to insert the stems ensured that the cement mantles were very closely matched across pairs (Fig. 4). The mean thickness of the mantle was not significantly different between the satin (4.5 ± 1.4 mm) and grit (4.6 ± 1.5 mm) groups.

There were substantial gaps at the stem-cement interface in the grit-blasted regions of the grit stems (Fig. 5). These gaps were up to 1.0 mm in width and often spanned several transverse sections. In areas adjacent to these gaps, where there was contact between the cement mantle and the grit-based surface, there was evidence of a good bond (Fig. 6). By contrast, the satin-finished areas of both the grit and the satin stems had few stem-cement gaps (Table I).

In the proximal zone, defined by the extent of grit-blasting, there were significantly more gaps around the grit stems than around the satin stems (paired \( t \)-test, \( p = 0.0054 \)) (Table I). In the distal (satin-finished) zone the grit stems were indistinguishable from the satin stems (paired \( t \)-test, \( p = 0.40 \)). Within the grit group there were significantly more gaps in the proximal regions than in the distal satin-finished regions (paired \( t \)-test, \( p = 0.0073 \)).

The gap fraction was influenced by the level of the section within the proximal region (Fig. 7). It tended to decrease from proximal to distal. This effect was significant in both groups (ANCOVA, grit \( p < 0.0001 \) and satin \( p = \).
but was significantly stronger (greater slope) in the grit group (ANCOVA, p = 0.001).

Discussion

Our study has shown that the use of a grit-blasted stem can result in significantly higher gap fractions at the stem-cement interface than when satin-finished stems are used with identical cementing and insertion techniques. For a proximally grit-blasted stem, the gaps were prevalent near the collar and became less frequent towards the distal extent of the grit-blasted region.

Sources of error. All of the specimens evaluated in our study were loaded before sectioning. However, the gaps around the grit stems could not have been caused by loading. Areas adjacent to gaps were clearly bonded and the gaps did not conform to the shape of the stem (Fig. 6). It should also be noted that all specimens were well fixed with minimal movement between the stem and bone during the loading procedures. It may be argued that the gap formation found with grit-blasted surfaces was due solely to a poor technique of insertion of the stem. However, using identical cementation techniques, we found minimal gaps using the same design of stem without a grit-blasted surface.

The femora were prepared and cemented at room temperature in our study. Bishop, Ferguson and Tepic have shown that stem-cement interface porosity is affected by differences in temperature between the stem and the bone. Polymerisation of cement begins at the warmer surface and shrinkage artifacts tend to manifest themselves at the cooler surface. In our study there was no difference in temperature between the stem and bone. This means that our technique may underestimate the stem-cement shrinkage artifact which would result in vivo when using a stem at room temperature.

Possible cause of gap formation. Recent experimental work has shown that the effect of polymerisation shrinkage is critically dependent on how the cement is constrained and the presence of pores. Voids preferentially develop at extant pores and at areas where there is no constraint of the cement. It may be that the stem-cement voids found around the grit-blasted regions were due to the preferential development of polymerisation shrinkage in these regions. The application of cement in a doughy state may allow air-pockets to form in the ‘valleys’ of the roughened surface of the stem as it is inserted. This could result in the presence of small air-filled pores over the grit-blasted surface after insertion of the stem. These pores at the interface could
serve as nucleation sites for gap formation at the stem-cement interface as the cement shrinks during curing. Further work is needed to elucidate the process of the formation of voids.

**Comparison with previous studies.** Gaps at the interface of femoral stems in a porcine model have been quantified by Wang, Franzen and Lidgren. They used an unnamed stem with a fine grit-blasted surface and reported a mean gap fraction of 15%; this is consistent with our findings if it is assumed that the stems used had a roughness somewhere between that of our grit-blasted and satin finishes. Wang et al. also reported that the gap fraction peaked at the midpoint of the stem and decreased both proximally and distally. This is not consistent with our findings and may be due to differences in the morphology of the endosteal bone or of the stem. In man the endosteal surface of the proximal femur is more textured and porous than in the pig and thus may constrain the cement mantle in a different way.

The large fraction of gaps found along grit-blasted surfaces for stems cemented in a doughy state could help to explain the recent findings of Shepard, Kabo and Lieberman. In their study, grit-blasted pins (Ra = 4.32 mm) gen-

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**Fig. 5a**

Reflected light micrograph of a grit stem illustrating a well-bonded region of stem-cement interface adjacent to a stem-cement gap.

**Fig. 5b**

Paired transverse sections taken from the most extreme specimen of a sat (b) and grit (b) stem. The anterior direction is upwards and the stems are 9.7 mm thick in the anteroposterior direction. Multiple gaps can be seen.

**Fig. 6**

Reflected light micrograph of a grit stem illustrating a well-bonded region of stem-cement interface adjacent to a stem-cement gap.

**Fig. 7**

The fraction (%) of the stem-cement interface with a gap for grit and satin stems. Data are shown for the most proximal 40 mm of the stem length. The grit-blasting on the grit stems covered the most proximal 35 mm of the stem.
erated substantially lower push-out forces when cemented at four minutes after initiation of cement mixing as compared with two minutes. Although the mechanism for this reduction in apparent strength was not determined, it was believed to be due to lack of infiltration of cement into the grit-blasted surface. If the grit-blasted stems used in our study were applied earlier in the cementation process then there may have been fewer gaps at the interface.

**Clinical relevance.** The use of a proximal grit-blasted femoral stem resulted in extensive gaps at the stem-cement interface. There are several clinical ramifications of this binding. The gaps along the grit-blasted surface could act as stress risers for the initiation of cracks in the cement mantle. With large regions of gaps, there could be much higher interface stresses in the remaining bonded grit-blasted regions, which could cause the stem to debond from the cement. If this were to occur, debris could be generated at the grit-blasted surface.\(^\text{13}\) In addition, the gaps could serve as conduits for the transport of debris.

Although studies of isolated metal-cement interfaces have shown that the bond strength can increase with surface roughness,\(^\text{13}\) it cannot be assumed that this effect will be observed under clinical conditions. In common with Shepard et al\(^\text{12}\) we think that, when a rough stem is used, an optimum stem-cement bond may be best achieved using cement in a ‘wet’ state. However, there are several important factors which must be considered before ‘wet’ PMMA is used. Injection of ‘wet’ cement is often avoided because of the adverse effect of unpolymserised monomer on the vascular system.\(^\text{14}\) In addition, because of its lower viscosity, ‘wet’ cement may alter the structure of the cement-bone interface and allow inclusions of fluid within the cement mantle.\(^\text{15}\)

This work was supported by NIH AR42017. Femoral stems were supplied by DePuy, Inc.

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.

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**Table I.** Gaps at the stem-cement interface (% of perimeter). The ‘proximal’ region was defined by the extent of grit-blasting in the grit stems

<table>
<thead>
<tr>
<th>Type</th>
<th>Mean (%)</th>
<th>SD</th>
<th>SEM</th>
<th>Range</th>
<th>p value</th>
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<td></td>
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<td></td>
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<tr>
<td>Grit</td>
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<td>17.1</td>
<td>7.0</td>
<td>16.0 to 56.9</td>
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<td>Satin</td>
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<td>4.8</td>
<td>0.2 to 31.0</td>
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<td>5.1</td>
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<td>Confidence interval for mean paired difference</td>
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<td>Distal</td>
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<tr>
<td>Grit</td>
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<tr>
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<td>0.0 to 27.2</td>
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**References**