In Vitro Prediction of Cement Damage in Cemented Hip Arthroplasty

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Introduction

An increasing number of hip revisions are needed every year. Loosening of the femoral component is often associated with cement fractures and disruption of the stem-cement interface (Verdonschot et al., 1997). The loads acting on the hip joint during daily activities contribute to the failure of the fixation of cemented hip stems. Recent investigations provide a body of fractographic evidence that indicates fatigue failure and fatigue crack propagation as the primary cement failure mechanisms, contributing to aseptic loosening of the prosthesis (Lewis, 1997). Fatigue fracture of the bone cement is a very frequent cause of loosening (McCormack et al., 1999).

In the present study, an experimental 3D model was developed to represent the implant structure. It was subjected to a simulated physiological load history. Cement damage was quantified, using dye penetrants, for different stem designs and for different levels of loading activities.

Methods

The damage induced by cyclic loading in the cement mantle was evaluated for two types of cemented stems: Lubinus SP II, Muller curved. The Lubinus SP II (Waldemar Link) was used as a clinical gold standard due to the good survivorship of this prosthesis (Malchau et al., 1993). Conversely, the Muller Curved stem (supplied by JRI) was used as a reference as a clinically less successful design (Malchau et al., 1993). Seven stems of each type were implanted in synthetic composite femurs (Mod. 3103, Pacific Research Labs). Composite femurs were chosen to reduce the sources of variability, other than those associated with the stem behaviour and the implantation procedure (Cristofolini et al., 1996). Radiopaque, low viscosity PMMA bone cement was used (Cemex RX, Tecres) using a 3rd generation technique, including vacuum cement mixing (Optivac, Scandimed) and retrograde injection.

Two types of test protocols were used, to simulate two different load histories:

• In the first protocol (which has already been extensively validated, Monti et al., 1999), one million sinusoidal loading cycles were applied. Three load components were applied: axial force (compression), axial torque (retroversion) and bending (in the frontal plane), reproducing stair climbing activities. Stair climbing was chosen because it has been demonstrated to be the physical activity most critical for the stability of hip prostheses (Bergmann et al., 1995). Three specimens of each type were tested with this protocol.

• The second protocol was defined more recently (Saponara et al., 2001) as an evolution of the previous one, to include all the possible peak activities, replicating the most severe possible scenario. The following activities were included (Table 1): stair climbing and descending, car entry and exit, bathtub entry and exit, and stumbling. Load values and direction were assigned to each activity, based on the literature. The load peaks occurring in about 24 years of patient life (about 1 million cycles) were applied to replicate a load history that can represent a conservative, though realistic, loading scenario of an active hip patient. In order to obtain a similar confidence interval to the previous protocol four specimens of each type were tested with this protocol.

The femurs were instrumented with displacement transducers to measure the relative interface motion under load between the stem and the cement mantle (Saponara et al., 2000). The loading setup and sensors are sketched in Figure 1.

After loading, the cement mantles were inspected to assess the amount and quality of damage induced by the cyclic loading. First, the femurs were carefully sectioned longitudinally in two parts, to allow safe extraction of the stems. The condition of the stem-cement interface was observed in the two parts with the aid of red dye penetrants (Rotvel Avio B, American Gas & Chemical Company), followed by foam emulsification (Velemulsior). The two parts of each femur were reassembled by applying a thin strip of
bone cement along the sectioned longitudinal edges. The number and length of cracks in each slice were quantified using the dye penetrants and an optical microscope with a magnification range of 20x to 120x. The positions and lengths of each visible crack (>0.01 mm) were recorded. The cracks were classified according to whether they crossed the entire mantle thickness or not, as the former classification is considered most critical, leading to gross loosening. In addition, the location of cracks in the mantle was recorded: at the cement-bone interface, stem-cement interface, within the bulk cement, near a macro bubble (>1 mm). The number and length of cracks was normalised for total cement volume of each specimen. Areas where a network of cracks was identified were measured, as these regions are those that first lead to cement fragmentation, and to the production of debris. Additionally, to confirm that the sectioning processes did not produce artifacts, four control specimens were inspected where no load history had been applied. No cracks were observed, thus confirming the absence of artifactual cracks. Finally, retrieval specimens from revision hip operations performed at the Rizzoli Orthopaedic Hospital were examined for clinical comparison. Three Muller retrievals were available with enough cement to allow reconstruction of a significant portion of the cement mantle.

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>Axial Force [% BW]</th>
<th>Bending Mom. [% BWm]</th>
<th>Torque [% BWm]</th>
<th>cycles/day</th>
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<tr>
<td>Stairs up</td>
<td>370</td>
<td>3.00</td>
<td>4.60</td>
<td>54</td>
</tr>
<tr>
<td>Stairs down</td>
<td>404</td>
<td>5.08</td>
<td>4.40</td>
<td>54</td>
</tr>
<tr>
<td>Bath tub entry/exit</td>
<td>498</td>
<td>4.03</td>
<td>6.19</td>
<td>2</td>
</tr>
<tr>
<td>Car entry</td>
<td>587</td>
<td>6.91</td>
<td>6.34</td>
<td>2</td>
</tr>
<tr>
<td>Car exit</td>
<td>534</td>
<td>5.26</td>
<td>5.16</td>
<td>2</td>
</tr>
<tr>
<td>Stumbling</td>
<td>807</td>
<td>11.92</td>
<td>7.01</td>
<td>weekly</td>
</tr>
</tbody>
</table>

Table 1: Activities and load components for the physiological protocol

Figure 1: Loading setup

Figure 2: Number of cracks per unit volume for the two stem designs, for the low load history (stair climbing only, left), and for the more severe one (physiological protocol, right), divided by position along the stem.

Figure 3: Area of the cracks per unit volume for the two stem designs, for the low load history (stair climbing only, left), and for the more severe one (physiological protocol, right), divided by position along the stem.
Results & Discussion

Figures 2 and 3 report the crack counts per unit volume, and the area of the cracks per unit volume, for the two load histories and for the two stem designs. As expected, a larger number of cracks and a larger area were found when the more severe load history was applied. The low load history generally caused single radial cracks (Figure 4), whereas the more severe one produced several regions of cement mantle disruption, due to a network of micro-cracks (Figure 5). Additionally, more cracks were observed in the Muller specimens, for both load histories. Moreover, the diaphysis region where more cracks were observed in the Muller specimens (distal) had significantly more cracks than the equivalent diaphysis region for the Lubinus (mid-stem). The cement mantles from the three Lubinus specimens from the first protocol showed cracks associated with voids (some defects existed in the cementation) in the distal zone of the cement mantle. All the mantles for three Muller implants presented single radial longitudinal cracks at the cement-metal interface associated with the sharp corners of the stem (Figure 6).

The cracking pattern found in the ex vivo retrievals was in agreement with the specimens tested in vitro. Specifically, the density of cracks, the extension, and the location of the cracked cement corresponded to those in the specimens subjected to the most severe load history.

The readouts from the displacement transducers confirmed that differences existed between the two stems designs, and between the two load histories, with higher elastic displacements and permanent migrations being found for the Muller stems and for the more severe load history (Monti et al. 1999, Saponara et al. 2001).

A methodology was successfully implemented to quantify the damage in the cement mantle around cemented hip stems. It was able to detect differences associated with different load levels, and to discriminate between different prosthetic designs.

![Figure 4: Individual radial cracks associated with a low load history in a Muller specimen](image1)

![Figure 5: A network of cracks associated with a high load history in a Muller specimen, possibly leading to cement disruption](image2)

![Figure 6: Typical proximal macro-cracking in a Muller specimen](image3)

References


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