Acrylic cement creeps but does not allow much subsidence of femoral stems

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It has been suggested that the endurance of cemented femoral reconstructions in total hip arthroplasty is affected by the creep of acrylic cement, but it is not known to what extent cement creeps under loading conditions in vivo, or how this affects load transfer. We have simulated the long-term creep properties of acrylic cement in finite-element models of femoral stem constructs and analysed their effects. We investigated whether subsidence rates measured in vivo could be explained by creep of acrylic cement, and if polished, unbonded, stems accommodated creep better than bonded stems.

Our findings showed that polished prostheses subsided only about 50 μm as a result of cement creep. The long-term prosthetic subsidence rates caused by creep of acrylic cement are therefore very small and do not explain the excessive migration rates which have sometimes been reported. Cement creep did, however, relax cement stresses and create a more favourable stress distribution at the interfaces. These trends were found around both the bonded and unbonded stems. Our results did not confirm that polished, unbonded, stems accommodated creep better than bonded stems in terms of cement and interface stress patterns.

Materials and Methods

We used CT to scan an embalmed femur and created a finite-element model from the geometrical contours and densities of the CT data. We then created a finite-element model of an Exeter stem which was introduced into the bone model. The cement mantle had a minimum thickness of 2 mm. Distal to the stem tip there was no cement, simulating a space created by a centraliser. The model contained 2130 8-node isoparametric elements and 3360 nodal points (Fig. 1). The cement-stem interface was assumed to be completely bonded (simulating a surface with a high surface roughness) or completely unbonded (simulating a highly polished prosthetic surface). In the latter case, a friction coefficient of 0.25 was assumed and special gap elements (MARC Analysis Research Corporation, Palo Alto, California) were used to simulate the non-linear contact mechanics between the polished metal surface and the cement mantle.

For the bone elements, the formula of Carter and Hayes was used to transfer the bone densities obtained by retrieval studies and stress analyses have indicated that the fatigue strength of acrylic bone cement is inadequate to prevent fatigue fracture, particularly when the cement-stem interface debonds in part. Cement fractures are often associated with prosthetic subsidence. Plastic materials, such as acrylic cement, gradually deform when they are exposed to long-term loading, a phenomenon known as creep. It has been suggested that creep of acrylic cement allows the expansion of the cement mantle and subsequent prosthetic subsidence without causing cement fractures. According to Fowler et al, prosthetic components should have tapered shapes and polished surface finishes to accommodate optimally the effects of creep.

Another time-dependent property of acrylic cement, which is closely related to creep, is the gradual reduction of stress after the material has been stretched to a constant level. This is known as stress relaxation. Acrylic cement has been identified as having a high stress-relaxing potential, implying that cement stresses may reduce considerably with time, thereby extending the mechanical endurance of a hip reconstruction. The time-dependent deformation process of acrylic cement results in both creep and stress relaxation. It is certain that acrylic cement creeps, but to what extent this process is clinically important is not known.

Our aim was to determine the effects of creep in acrylic cement on the mechanical behaviour of femoral stem constructs. For this purpose we applied a method to simulate the creep process of bone cement which had been validated in an earlier study to three-dimensional finite-element models of femoral stem constructs.

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CT to elastic moduli. The elastic modulus for the cement material was set to 2.2 GPa¹¹ and Poisson’s ratio to 0.3. The creep properties of acrylic cement had been determined in earlier studies⁵-⁷ and implemented as described by Verdonschot and Huiskes.⁸ The elastic modulus and Poisson’s ratio for the prosthetic material were 200 GPa and 0.28, respectively, simulating stainless-steel prosthetic material.

One loading case was considered to be presented by the stance phases of the gait cycle. This consisted of a load of 2450 N acting on the prosthetic head with angles of 23° in the frontal and about 6° in the sagittal plane.¹² In addition, three muscle forces (gluteus minimus, medius and maximus) were also represented, acting on the greater trochanter. The resultant of these three muscle forces was about 1650 N, with angles of 24° in the frontal and 15° (directed anteriorly) in the sagittal plane.³,¹³¹⁴

The possible consequences of cement creep on the probability of failure of the cement mantle was deduced by considering the maximal and the average stress values in the cement mantle as a function of postoperative time. The effects of creep on load transfer at the interfaces were analysed by integrating the stresses over the interface surface. This resulted in the total shear, tensile and compressive forces being transferred at the interfaces.

The subsidence of the unbonded stem within the cement mantle was analysed by considering the gap created between the proximolateral stem surface and the cement mantle, as can also be estimated from radiographs in clinical practice.³

RESULTS

Around both the bonded and unbonded stems, creep reduced tensile stresses in the cement, predominantly in the external periphery of the cement mantle, whereas stress peaks around the corners of the stems were maintained. Initially, the bonded stem generated maximal tensile stresses at the lateral, exterior side of the cement mantle, which gradually relaxed due to creep of the cement (Fig. 2a). At the same time, however, the bonded stem developed higher cement stresses near the cement-stem interface, particularly at the proximal side (Fig. 2b). For this reason, the peak stress value generated around the bonded stem first reduced slightly, and then increased somewhat after 10,000 loading cycles (Fig. 3a). Around the unbonded stem, the highly stressed locations did not change during the creep process, resulting in a slight increase in tensile peak stress as the stem gradually subsided in the cement mantle (Fig. 2). Although the stress peaks around both stems changed only moderately, the effect of creep on the average value of the tensile stresses was substantial. Around both types of stem the average tensile stress value decreased by about 50% (Fig. 3b).

The stresses at the bonded cement-stem interface developed favourably due to creep (Fig. 4). The total shear force transmitted at the interface decreased by about 20% after 5 million loading cycles, whereas the tensile and compressive forces remained more or less constant. Around the unbonded stem, shear forces were lower and compressive forces higher as compared with the bonded stem. Due to creep, compressive and shear forces were increased by almost 50% after 5 million loading cycles (Fig. 4). Tensile forces at the cement-stem interface were absent due to the fact that the polished surface did not adhere to the cement mantle.

Around the bonded stem, the shear forces decreased and compressive forces increased at the cement-bone interface after creep had occurred (Fig. 5). The tensile forces remained at a constant level and were much lower (by a factor of three) when the prosthesis was assumed to be unbonded and decreased slightly due to creep. Shear forces were comparable to those generated by a bonded stem and were hardly affected by cement creep. The high compressive forces at the cement-stem interface created around the unbonded stem were transmitted to the cement-bone interface, resulting in relatively high compressive force values. They increased considerably due to creep of the cement (Fig. 5).

Although creep allowed the unbonded prosthesis to subside within the cement mantle, the actual amount of subsidence was relatively small. Immediately after the first load application, the unbonded prosthesis was forced into the cement mantle and a gap of about 25 µm was created (Fig.

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Posteromedial (a) and resection level (b) views of the tensile stress distribution in the cement mantle at the pre- and postcreep stage.

Figure 3a – The peak tensile stress in the cement mantle remained rather constant and approached the fatigue strength of the bone cement (Davies et al.\textsuperscript{18}) after 100,000 loading cycles in the case of unbonded cement-stem interface conditions, and after 5 million loading cycles with bonded cement-stem interfaces. Figure 3b – The average tensile stress generated in the cement mantle decreased around both types of stem as the creep process proceeded.
6). While the cement material crept, the stem subsided gradually in the cement mantle, but the subsidence rate decreased rapidly after the first 250,000 loading cycles. After 5 million loading cycles the gap size was about 65 \mu m.

DISCUSSION

The finite-element model used in our study is based on a number of assumptions which should be appreciated when the results are assessed. We used only one particular design of stem without any collars and assumed an ideal implantation with an intact cement mantle. We also assumed that bone properties were constant during the 5 million loading cycles, whereas it is known that bone is subject to continuous remodelling and changes in density and therefore in its mechanical properties after placement of a femoral implant. Only one loading case was considered, simulating the midstance phase of gait. Although this is the loading case most frequently applied to the reconstruction, others, such as those generated during stair-climbing, were not included in the study. In addition, the 5 million loading cycles were assumed to have been applied continuously; normally, patients have alternating periods of activity and rest. During the latter the stresses are allowed to relax to some extent, thereby reducing the constraining capacity of the cement mantle against subsidence. The stem may therefore subside somewhat when the patient becomes active again after a period of rest. The size of these subsidence steps, however, is likely to reduce in time. The reason for this is that the amount of creep depends, apart from the stress level, also on the creep history. With an increasing number of active and resting periods, the total creep strain increases and therefore reduces the creep strain rate which leads to a gradual reduction of the amount of prosthetic subsidence after subsequent resting periods. The size of this subsidence step is unknown but based on the present information it can be expected to be very small. In our present study, however, the resting periods were not included.

Lee et al. have shown that the dynamic creep rate of acrylic cement is sensitive to the age of the cement. In a dynamic four-point bending test they found a twofold increase in creep rate with seven-day-old specimens as
earlier studies,\textsuperscript{1-5} the probability of cement-bone interface failure was consistently lower in unbonded, polished stems and was further reduced by cement creep. A polished stem can therefore be considered to be advantageous. Nevertheless, the probability of cement-stem debonding, which has been considered as a potential negative asset of stems that firmly bond to their cement mantles,\textsuperscript{2} was reduced by cement creep. The probability of cement failure was lower in bonded compared with unbonded, polished stems and was not changed by creep.

Our study has shown that creep of acrylic cement results in relaxation of cement stresses and decelerates the failure process in the cement mantle. Prosthetic subsidence rates caused by creep of acrylic cement are very small and do not explain the excessive migration rates which have been reported.

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REFERENCES