Mechanical effects of stem cement interface characteristics in total hip replacement

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Mechanical Effects of Stem Cement Interface Characteristics in Total Hip Replacement

Nico Verdonschot, PhD; and Rik Huiskes, PhD

Stem cement debonding is 1 of the most common forms of fixation failure and is thought to be a prelude to gross loosening of a total hip reconstruction. However, the immediate consequences of debonding remains a matter of controversy. The dynamic effects of stem cement debonding in total hip reconstruction were analyzed using 3-dimensional finite element techniques. Stem cement interface conditions were assumed as completely bonded or unbonded, with or without friction. The dynamic effects were accounted for, as presented by the stance and swing phases of the gait cycle. It was found that both cyclic micromotions at the stem cement interface and stresses in the cement mantle were effectively reduced by friction. The friction cases produced failure probabilities of the cement mantle that were relatively close to the one generated by the bonded stem. The probability of mechanical failure of the cement bone interface decreased after debonding and decreased more with reduced stem cement friction. These results show that, although a firm and lasting bond between stem and cement may be desirable for preventing cement failure, the mechanical effects of a debonded stem are less detrimental than were assumed earlier. For straight tapered stem shapes subjected to the loading conditions described, a polished stem may be desirable for the cement bone interface mechanics.

From Institute of Orthopaedics, University of Nijmegen, Nijmegen, The Netherlands.

Reprint requests to Rik Huiskes, Biomechanics Section, Institute of Orthopaedics, University of Nijmegen, PO Box 9101, 6500 HB Nijmegen, The Netherlands.

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It was hypothesized that aseptic loosening of femoral total hip replacements is preceded by cement failure, which in its turn, is an effect of stem-cement debonding. This hypothesis was based on retrieval studies in which cement failure and debonding were found in association.[20] This also was confirmed by results of finite element analyses, indicating 4-fold (or higher) increases in cement stresses after the interface debonds.[13,16] Verdonschot and Huiskes[33] investigated the effect of debonding on cement endurance using damage accumulation mechanics. They predicted a completely disintegrated cement mantle after 300 million loading cycles for a bonded stem, whereas for a debonded stem, such disintegration would occur after 10 million loading cycles. However, these finite element analyses did not account for friction at the debonded interface, which has been found to attenuate the stress increasing effects of debonding.[28,29] Crowninshield and Tolbert[5] performed strain gauge measurements on postmortem implanted bonded and unbonded hip stems. Proximal cement strains were found to increase by a factor of 2 in the case of debonding. These findings compare well with the predictions of Mann et al.[28,29]

Debonding of the stem cement interface has consequences for the cement stress levels and promotes the occurrence of relative interface motions. Evidence of relative motions frequently has been found in postmortem retrieved specimens. Jasty et al[19] found that 5 of 6 femoral components removed at revision surgery had been worn, as witnessed by burnished and polished areas of the metal surfaces. In vitro measurements of relative motions suggest that they occur after long term service[27] and even soon after surgery.[2,34] Cyclic relative motions promote the formation of cement wear particles, often found around debonded cemented stems.[19,24]

Fowler et al[9] postulated that the production of wear particles at the cement stem interface is one of the prime causes for eventual aseptic loosening of femoral total hip replacements. They argued that to reduce particle production, stems should be polished. This would have the additional advantage of reduced shear stresses at the cement bone interface, thus reducing the probability of failure. This led to a controversy in the literature.[14,25] Harris[14] proposed that stems should remain bonded to reduce cement stresses and wear particle production. Polishing would weaken the metal cement bond, which would promote failure. Ling[25] suggested that polished or not, debonding would occur, so to reduce wear, polishing the stems seems sensible.

That stems, at least those with traditional surface finishes, debond, has been documented in the literature.[8,20] However, if that is accepted as unavoidable, it remains to be determined what surface finish would be best. A rough stem increases interface abrasion for any given amount of relative motion. However, it increases friction, which may reduce the amount of motion and certainly reduces cement stresses. In addition, whether or not friction increases cement bone interface stresses, as suggested by Fowler et al,[9] has not been determined.

The purpose of this study was to put this controversy into quantitative perspective. The question was, how metal cement friction influences interface motion, cement, and cement bone interface endurance in dynamic loading. For that purpose, computer simulation studies were done.

MATERIALS AND METHODS

An embalmed femur was scanned by computed tomography (CT) in slices of 4-mm thickness, perpendicular to the femoral axis at 27 locations. Using a graphics computer program, a finite element model was made of this bone using the geometric contours and densities of the CT data. A finite element model of an Exeter stem (Howmedica International, London, United Kingdom), was created and introduced in the bone model, simulating preplanning of a hip stem placement. The cement mantle had a minimum thickness of 2 mm. No cement was present distal to the stem tip, which simulated the space created by a centralizer. The model contained 2130 8-node isoparametric elements and 3360 nodal points (Fig 1). To simulate the nonlinear mechanical behavior of the prosthesis cement interface, 281 special gap elements were situated at the interface (MARC Analysis Research Corporation, Palo Alto, CA).

To determine the elastic moduli for the bone elements, the average apparent density ρ (g/cm^3) was determined using the CT data. The moduli were calculated using the formula[3]

$$E = c\,\rho^3$$

with $c = 3790$ (MPa/(g/cm^3)^3). For bone elements, Poisson's ratio was chosen as 0.35. Young's modulus for the cement material was set at 2.2 GPa[32] and Poisson's ratio at 0.3. Young's modulus and Poisson ratio for the prosthetic material were 200 GPa and 0.28, respectively, simulating stainless steel prosthetic material.

Stem cement interface conditions were assumed to be fully bonded or unbonded. In the latter case, 3 friction coefficients were considered with values of 0.0 (idealized frictionless), 0.05 (lubricated friction), or 0.25 (normal friction). The second value for the coefficient of friction identifies

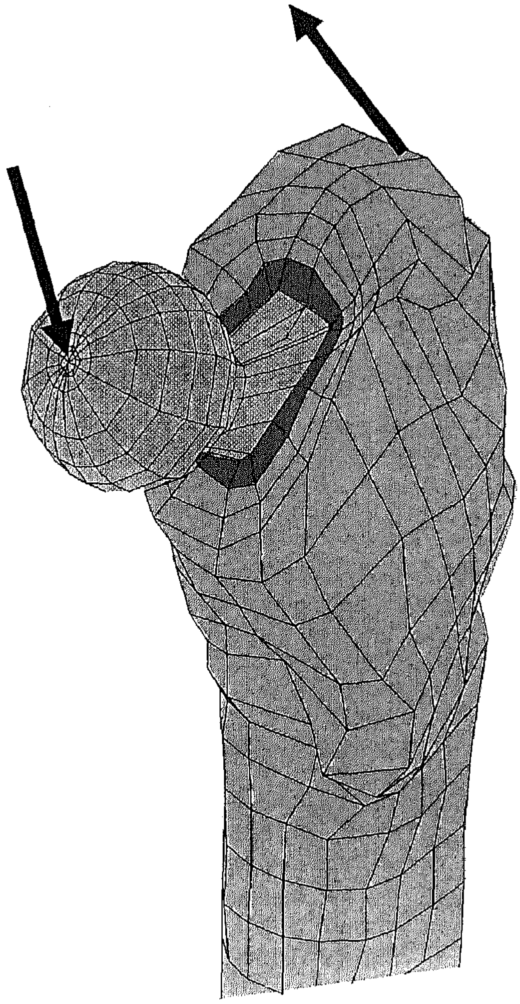

Fig 1. The proximal part of the CT based, anatomic finite element model.

friction when a highly effective lubricant is used.[31] A membrane of soft tissue between the stem and cement mantle may behave as such. The third value is realistic for friction between polished stainless steel surfaces and acrylic cement.[12,30]

The effect of the stem cement interface conditions on the failure probability of the cement mantle was analyzed by considering the tensile stress peaks generated in the cement mantle. The probability of cement failure was defined as the percentage of cement volume loaded at a higher stress level than the average strength of bone cement established in experiments.[6,23] The stress distributions were compared to the average static strength (indicating the probability of immediate failure) and the fatigue strength of bone cement after 10 million loading cycles (indicating the probability of long term failure). The average static tensile strength (S_{stat}) was taken as 44.63,[23] and the average fatigue strength (S_{fat}) as 2.39 MPa.[6]

The effects of stem cement interface characteristics on the endurance of the cement bone interface were evaluated by considering the compressive, tensile, and shear stress patterns generated at this interface. However, the failure probability is affected by a combination of these interface stresses, rather than their individual values. For this reason, the authors defined a failure index as

$$fi = \frac{(\sigma - \sigma_a)^2}{\sigma_0} + \frac{(\tau)^2}{\tau_0}$$

with σ the normal (negative for compression and positive for tension) stress and τ the shear stress at the interface.[15] A high value of failure index indicates a high failure risk. The constants for the failure index were chosen rather arbitrarily but are similar to values reported in the literature,[21,22] as σ_0 = 5.5 MPa, σ_a = –2.5 MPa, and τ_0 = 8.0. These values indicate that, for the same shear stress, tensile stresses are more deleterious than are compressive ones because they produce higher values for the failure index.

The interface stresses were calculated from the internal nodal forces at the interface. Using local coordinate systems and actual contact surfaces at the interface, these nodal forces were transformed into interface stresses. This method ensures compatibility of the interface stresses, which is not achieved when interface stresses are calculated by extrapolation of element integration point values.

Two loading cases were considered, as presented by the stance (loaded) and swing (unloaded) phases of the gait cycle. The stance phase was simulated with a load of 2450 N acting on the prosthetic head with angles of 23° in the frontal plane and approximately 6° in the sagittal plane, as established by in vivo telemetric measurements by Bergmann et al.[1] Three muscle forces (gluteus minimus, medius, and maximus) also were represented, acting on the greater trochanter. The magnitudes of these forces were estimated from Crowninshield and Brand.[4] The directions of the muscle forces were determined using the flexion angle and the points of attachment of the muscles, as described by Dostal and Andrews.[7] The result of these 3 muscle forces was approximately 1650 N, with angles of 24° in the frontal plane and 15° (directed to anterior) in the sagittal plane. In the simulation, the forces were applied from 0 to their maximal values (simulating the first load application), then reduced to 0 (simulating the swing phase of gait), and applied again from 0 to maximal values to simulate consecutive cyclic load application. In the simulations, 3 consecutive load cycles were considered.

RESULTS

The behavior of the reconstruction was different during consecutive load application, depending on the bonding conditions of the stem cement interface (Fig 2). For a bonded stem, all stresses increased from zero to their maximal values when load was applied for the first time. When the load was released, they returned to zero again, and this was repeated in every consecutive loading cycle. For a frictionless, unbonded interface the same happened; be it that between zero and full load, the stem subsided relative to the cement. Interface slip occurred in the range of 205 to 237 μm, depending on location (Fig 3). After load release, the stem returned to its original position. In any consecutive load cycle, this behavior was repeated. When friction was assumed, the stem also subsided during the first application of the load, with a reduced interface slip of 106 to 156 μm (lubricated friction) or 22 to 48 μm (normal friction). However, when the load was removed, the stem did not return to its original position but remained stuck in the cement mantle, thereby stressing cement and bone, even with no external load applied. During consecutive load cycles, cyclic slip occurred in the same manner as for the frictionless stem but to a much lesser extent. The cyclic slip ranged from 1 to 37 μm and from 1 to 17 μm in cases of lubricated and normal friction, respectively (Fig 3).

After load application, tensile stress patterns in the cement mantle depended largely on the stem cement interface conditions (Fig 4). Because of bending of the structure, the bonded stem generated stress concentrations, particularly at the proximal and the distal sides of the prosthesis. The unbonded stems subsided in the cement mantle, producing circumferential tensile (hoop) stresses, particularly around the lateral edges of the stem. The highest stress peaks were found for the frictionless interface. Maximal tensile cement stresses increased by a factor of 6.3 in this case, relative to the bonded one (Fig 5).

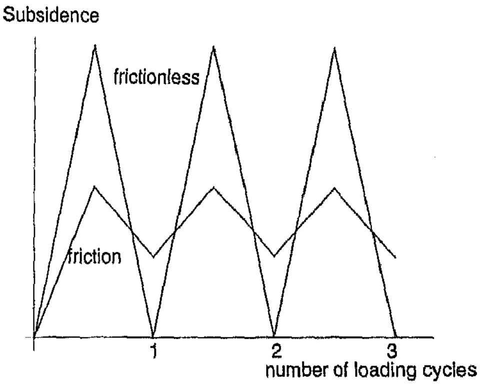

Fig 2. The subsidence pattern of unbonded stems. With a frictionless stem cement interface, the stem returned to its original position after unloading. With friction, the stem did not return to its original position but remained stuck in the cement mantle.

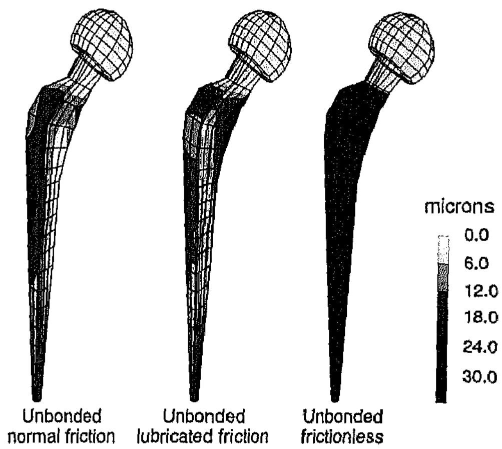

Fig 3. The cyclic slip patterns at stem cement interface.

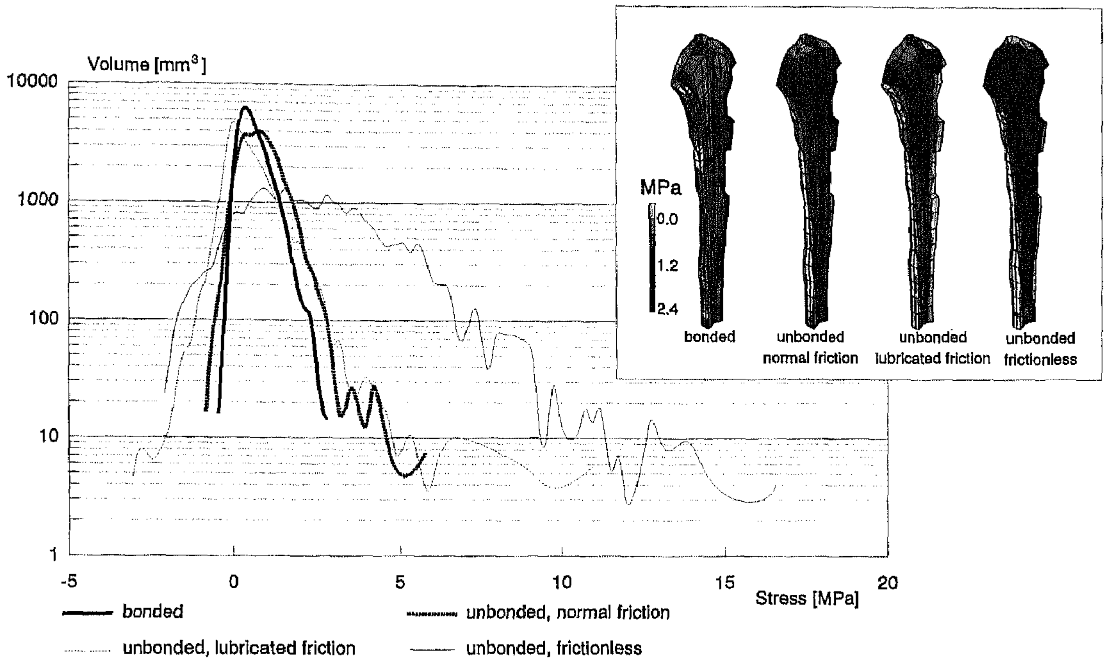

Fig 4. The tensile stress distribution in the cement mantle after loading. The inset shows how these stresses were distributed in a part of the cement mantle.

This factor was reduced to 4.1 and 2.2 for lubricated and normal friction, respectively. Comparing the stress distribution with the strength data revealed that the probability of immediate failure of the acrylic cement was virtually 0 in all cases. However, after 10 million loading cycles and its associated (fatigue) damage accumulation, failure is more likely (Fig 6). The completely bonded stem produced the lowest cement failure probability (0.3%), whereas the unbonded frictionless stem produced the highest failure probability (approximately 47%). The cement failure probabilities for the unbonded stems with friction were relatively close to that of the fully bonded one. The increase in failure probability from normal to lubricated friction was only marginal.

When the load was released, cement stresses returned to 0 for the bonded and frictionless, unbonded stems. However, with friction at the stem cement interface, the cement stresses were not fully released (Figs 5, 7) because of the sticking mechanism. Thus, in reality, the stresses cycle between these rest values and maximal, not between 0 and maximal. The cyclic stress amplitudes are reduced, which may increase the cement fatigue life beyond what was assumed.

The averaged failure index for the cement bone interface decreased with friction at the stem cement interface (Fig 8). The bonded stem produced an index almost twice that of the unbonded, frictionless one. It seemed that debonding reduced the index for two reasons. First, the interface area exposed to tensile stresses was reduced (Fig 9A). Second, the average compressive stresses increased (Fig 9B). Although the average interface tensile stress increased around the unbonded frictionless stem (Fig 9B), the interface area over which it was distributed decreased (Fig 9A), leading to a decrease of total tensile force distributed at the cement bone interface around the unbonded stem, as compared with the bonded 1. Shear stresses at the cement bone

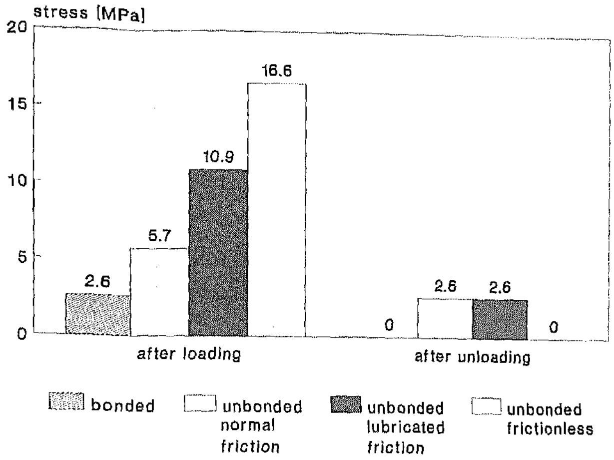

Fig 5. Peak tensile stresses in the cement mantle after loading and unloading.

interface were not reduced by a reduction of stem cement friction (Fig 9B). On the contrary, the average shear stress increased with almost 50% from the bonded to the unbonded, frictionless case. The shear stress at the cement bone interface can be decomposed in axial and circumferential components. Its increase in value for the unbonded stems primarily was caused by an increase in circumferential components, rather than in the axial ones.

DISCUSSION

Although the finite element model used in the analyses was 3-dimensional, CT based, and anatomic, and realistic loading conditions were applied, it remains a schematic representation of reality. Clinical experiments may be more realistic but provide little control over experimental conditions. With animal and laboratory models as intermediates, computer models are remote from reality but offer virtually complete control over experimental conditions. The computer model allowed the authors to vary interface characteristics, while all other relevant parameters remained the same. Thus, a conclusion can be drawn exclusively about the effects of the interface characteristics. The results described in this study should be considered in that light.

The mechanical properties of the materials were assumed as isotropic and independent of

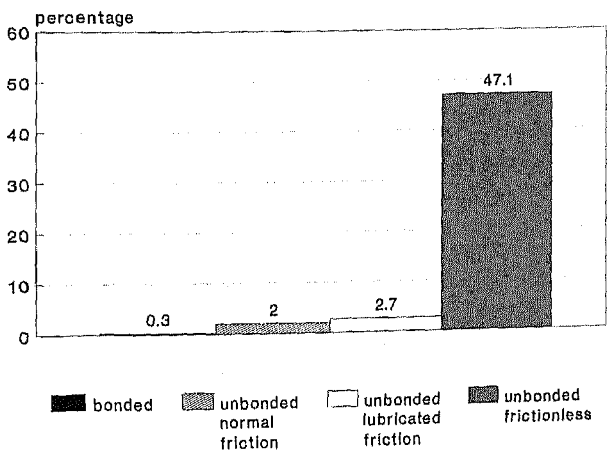

Fig 6. Cement failure probabilities after 10 million loading cycles.

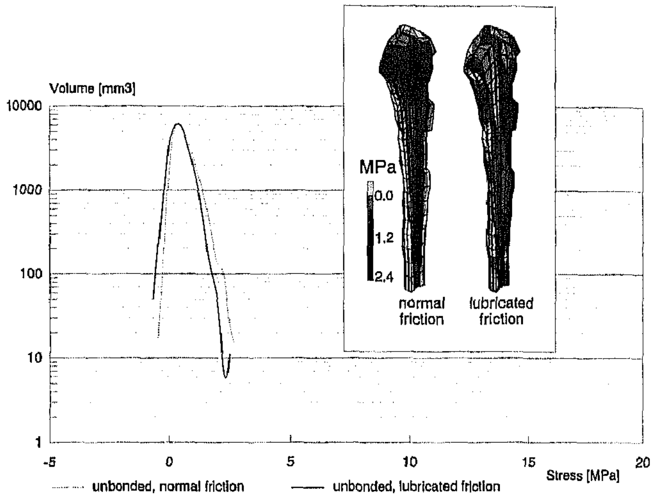

Fig 7. The tensile stress distribution in the cement mantle after unloading. The inset shows how these stresses were distributed in a part of the cement mantle.

time. In reality, bone is anisotropic and is subject to continuous remodeling. In addition, acrylic cement may experience aging and creep. The study considered midstance phase loading conditions only. Other loading modes, such as those generated while climbing stairs, were not included. However, in this study the effects of stem cement debonding were evaluated on a relative basis. The loading parameters used are assumed to be adequate for this purpose. The fatigue properties of bone cement used to determine the failure probabilities of the cement mantles were based on fatigue data of fully reversed compressive tensile experiments as reported by Davies et al.[6] This is not the real loading mode to which bone cement around femoral implants is exposed because it is loaded from zero or rest values to a maximal one, as shown in this study. However, Gates et al[11] reported that the compressive portion of the loading cycle had little effect on the number of cycles to failure. For this reason, it can be assumed that these fatigue data suffice to study the qualitative effects of stem cement debonding on cement failure. The constants in the cement bone failure index were chosen based on a limited number of experiments, which did not include the biologic response to the stress levels acting on the interface. Thus, these con-

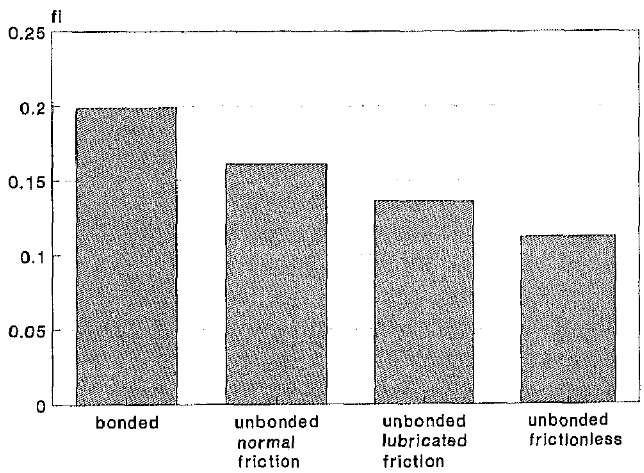

Fig 8. The averaged failure indexes of the cement bone interface.

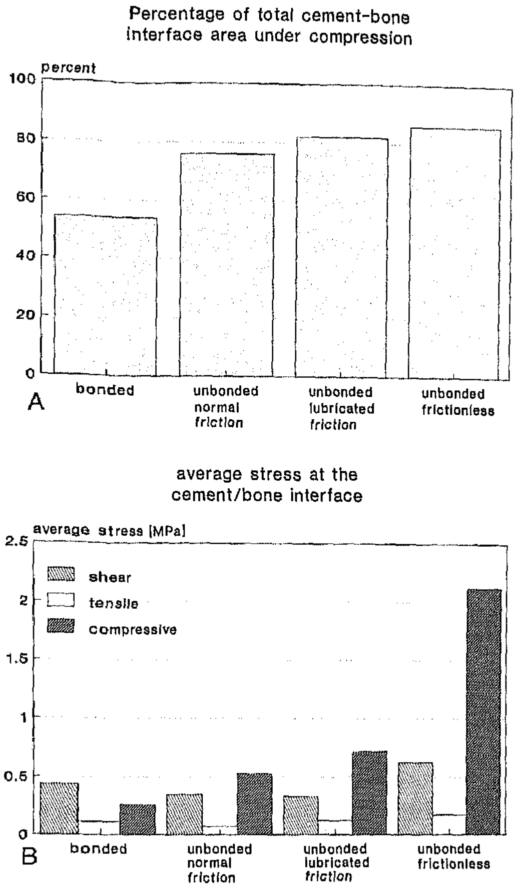

Fig 9A–B. (A) The percentage of total cement-bone interface area under compression. (B) Average stresses at the cement bone interface. Shear stresses are distributed throughout the entire cement bone interface area. The average values of the normal stresses (tensile and compressive) were calculated over the interface area where they were acting.

stants should be regarded as approximations of reality, which can be used only for qualitative comparisons.

These simplifying assumptions limit the applicability of the model, and the results should be interpreted in the right perspective. The model allowed the authors to vary stem cement interface characteristics exclusively, while keeping all other parameters constant. Thus, general effects of these interface conditions could be studied. It was not the objective to study endurance of hip replacement in variable patient conditions. However, it must be appreciated that only one particular type of stem was studied, with a collarless, straight tapered shape. Because the contour of stem shape is an important parameter for the mechanical behavior of unbonded stems,[17] results may be different for other kinds of designs. If calcar collar contact is obtained, it may limit the cyclic micromotions and stem subsidence and lower proximal cement stresses.[14] These advantages may be diminished by the pivot mechanism of the collar upon loading, which tilts the stems into varus, and the fretting between the undersurface of the collar and the subjacent cement or the bone.[25] The effects of a collar were not considered in this study.

The ranges of the cyclic micromotions found were quite realistic. Walker et al[34] reported maximal relative motions of cemented stems between 30 and 40 μm with a load of 1000 Newtons. Burke et al[2] evaluated the initial stability of 7 femoral components cemented in postmortem femurs. They found average relative motions of approximately 11 μm in the axial direction and 5 μm in the rotatory direction, using simulated single limb stance loading conditions. Maloney et al[27] measured the stability of 11 stems retrieved at autopsy from patients who previously had cemented total hip arthroplasty. Simulating single limb stance loading conditions, they found axial relative motions in the range of 3 to 36 μm. Rotary motions were in the range of 4 to 43 μm. These numbers are in the same ranges as the ones found in this study: between 20 and 40 μm, depending on the coefficient of friction. The frictionless stem cement interface generated much higher cyclic micromotions, on the order of 200 μm. This illustrates that a small amount of friction at the stem cement interface effectively reduces relative motions.

Although it has always been known that frictionless assumptions are unrealistic and that friction reduces cement stresses, the extent of this reduction was not fully appreciated in earlier analyses. Assuming no friction at the stem cement interfaces, a 4-fold (or higher) stress increase in comparison with a bonded interface was predicted.[13,16] Using a friction coefficient of 0.22, Mann et al[28,30] found a 2- to 3-fold stress increase in the cement mantle. In this study, these results were confirmed because stress peaks increased with factors of 2 and 6 for normal and no stem cement friction, respectively. The unbonded components subsided in the cement mantle, thereby producing stress peaks around the corners of the stem. Eventually, these stress peaks may lead to cement cracking, which was confirmed in retrieval studies.[20] These maximal stress peaks may induce failure, and the parts of the cement mantle that are stressed at a level higher than the (fatigue) strength of the material also may fail.

This can be judged by the probability of cement failure as assumed in this study. The probability of immediate cement failure was virtually 0 for all cases, indicating that if cement failure occurs, it is because of fatigue, not an immediate static overload. After 10 million loading cycles and its associated (fatigue) damage accumulation, failure becomes more likely. The lowest probability of cement failure by fatigue was produced by the bonded stem. Although the unbonded stem, with friction assumed, produced higher stress peaks in the cement mantle than in the bonded one, the overall cement failure probabilities were similar. This was caused by only a small part of the cement mantle being exposed to these higher stress peaks. If frictionless conditions are assumed, a large part of the cement mantle would be exposed to excessive stress levels, causing a high probability of failure after 10 million loading cycles. However, frictionless conditions are paradigms of ultimate lubrication and do not exist in reality.

The probability of cement failure was defined as the percentage of cement volume loaded at a higher tensile stress level than the (fatigue) strength of bone cement. Although the results are not presented here, the authors also considered the equivalent Von Mises and a modified Von Mises stress criterion, accounting for a 2-fold increased compressive strength with respect to the tensile one; the authors also compared the levels to the (fatigue) strength of bone cement in the same way as that used to compare tensile stress levels. Although the absolute values of the failure probabilities changed, the trends remained the same.

The probability of cement fatigue failure around a debonded stem with friction at the stem-cement interface is reduced additionally by cement stresses not being fully released after unloading because the stem remains stuck in the cement mantle because of friction. As a consequence, the cyclic stress amplitudes are decreased, which reduces the stress intensity factor, as described by the theory of fracture mechanics. According to this theory, a reduced stress intensity factor results in an elongation of the periods of crack initiation and propagation. Thus, they reduce the probability of cement failure. This phenomenon was confirmed in a preliminary laboratory study in which the authors tested the tensile fatigue properties of bone cement, cyclically loaded between 0 and 12 MPa and between 4 and 12 MPa. Specimens of the former group failed at an average of 27,600 cycles (standard deviation, 11,100 cycles), whereas those of the latter group failed at the statistically significant higher number of loading cycles of 186,600 cycles (standard deviation, 71,900 cycles) (Student's t-test, $N = 5$, $p = 0.01$).

Fowler et al[9] hypothesized that unbonded stems, when polished, would generate only low shear stresses at the stem cement interface, resulting in reduced shear stresses at the cement bone interface. However, this study shows that shear stresses at the cement bone interface increased, even with a frictionless stem cement interface. This increase could be explained by the increase of shear stress components in the circumferential direction. Despite these increased shear stress levels, the failure index of the cement bone interface was reduced when friction at the stem cement interface was reduced. This reduction was caused predominantly by increased compression at the cement bone interface. The highest failure index of the cement bone interface was produced in the case of a bonded stem-cement interface. This potential negative asset of bonded stems recently was demonstrated clinically by Gardiner and Hozack,[10] who analyzed 17 early failed femoral prostheses that had been manufactured with a surface coating to enhance the strength of the stem cement interface. In all cases, they found that the cement bone interface had loosened, whereas the cement remained firmly bonded to the stem.

This study shows that although a firm and lasting bond between stem and cement may be desirable for preventing cement failure, the mechanical effects of a debonded stem are less detrimental than was assumed earlier.[14] From the perspective of cement bone interface mechanics, it may even be advantageous, at least for straight tapered stem shapes. It has been documented from retrieval studies that stems tend to become debonded from the cement.[20] The overall survival ratio of cemented stems usually is quite good.[26] The authors present results that show that, contrary to what was thought earlier, this seeming contradiction is not really a contradiction. The frictionless interface is a paradigm of ultimate lubrication and is not realistic. In the same way, the bonded stem cement interface may be seen as a paradigm of ultimate strength, which also is not realistic; at least, there is no proof in the literature that it is.

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