Cement Oscillation Increases Interlock Strength at the Cement–Bone Interface

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Abstract

Modern cementing techniques aim to improve the interlock between bone and cement and to establish a durable interface. Cement penetration is generally believed to influence interface failure, but current methods for improving the cement–bone interface are inadequate. Oscillation is the reciprocated movement of an object through its balanced position, or the quantum physics of systematic fluctuation back and forth near an average value (or trimmed value). To increase the interlock strength at the cement–bone interface, we designed a cement oscillator according to the principles of vibrational mechanics. To evaluate the effect of oscillation on the quality of interlock strength at the cement–bone interface, we randomly divided 156 femoral bones of adult pigs into 2 groups, oscillated and control, and performed mechanical tests to assess interlock strength at the cement–bone interface. The filling effect of bone cement was observed and analyzed under a stereomicroscope, and then each oscillated femur was compared with a control femur. The interlock strength at the cement–bone interface in the oscillated group was significantly greater than in the control group ($P<.05$), and the filling effect in the oscillated group was also better than that in the control group ($P<.05$). Our findings show that oscillation of bone cement significantly increases interlock strength at the cement–bone interface, point the way for clinicians to develop a high-performance and pragmatic fixation technique for prostheses to increase interlock strength, and will be of considerable practical importance in helping to prevent aseptic loosening of cemented prostheses.

See commentary below by Dr Søren Overgaard.

Cemented prostheses are widely used because they generally remain firmly fixed during the early postoperative stage. However, aseptic loosening is an important long-term complication of total hip arthroplasty (THA) and is in part responsible for the increasing number of patients requiring revision surgery.[1] Some problems with artificial joint replacement include asymmetric distribution of cement between prosthesis and bone, formation of air bubbles, and weak interlock, which leads to aseptic loosening and affects prosthesis survival.[2] Clinical retrospective analysis has indicated that the main cause of weak cement for an artificial prosthesis is insufficient interlock strength at the cement–bone interface.[3-5]

Modern cementing techniques aim to improve the interlock between bone and cement and to establish a durable interface.[6] Cement penetration is generally believed to influence interface failure, but current methods for improving the cement–bone interface are inadequate.[7,8] Oscillation is the reciprocated movement of an object through its balanced position, or the quantum physics of systematic fluctuation back and forth near an average value (or trimmed value).[9] To increase the interlock strength at the cement–bone interface, we designed a cement oscillator according to the principles of vibrational mechanics. Our primary objective was to evaluate the effect of cement oscillation on the quality of interlock strength at the cement–bone interface. Cement oscillation was performed in our experiment groups, with no oscillation performed in our control groups. Afterward, the interlock strength at the cement–bone interface was analyzed by mechanical testing, and the filling effect of bone cement was observed by stereomicroscopy and tested by professional image analysis.

Materials and Methods

We used the femoral bones of 10-month-old male pigs for our study because the medullary cavity of pigs, similar to that of human femoral bones, contains abundant bone trabeculae. The average length of cancellous bone at the distal end is 6 cm, and the intermediate portion of the medullary cavity is filled with yellow bone marrow.

We used Osteobond Copolymer Bone Cement (Zimmer, Warsaw, Indiana); a bone-cement oscillator we designed that was manufactured by the School of Mechatronics Engineering of the Harbin Institute of Technology, Harbin, China (Figure 1); an electron omnipotent material experimental machine (Instron, Norwood, Massachusetts); an MTS 810 fatigue machine (MTS Systems, Eden Prairie, Minnesota); a microtome (SP 1600; Leica, Shanghai, China); and a stereomicroscope (S8APO; Leica).

Our experiment was based on a third-generation cementing technique, which involves the use of a power brush; pulsatile lavage; hydrogen peroxide; vacuum-mixed, low-viscosity cement; retrograde filling; plugging of the femoral canal; and femoral cement pressurization.

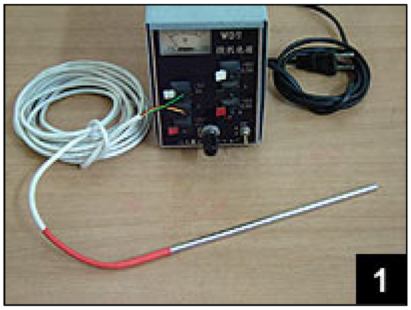


Figure 1: The bone-cement oscillator we designed was manufactured by the School of Mechatronics Engineering of Harbin Institute of Technology, Harbin, China.

Model Grouping

We randomly assigned 156 fresh pig femoral bones to one of several groups:

Mechanical experiment group (140 bones).

- Pull-out groups: pull-out oscillated group A1 and pull-out control group A2 (20 bones each);
- Push-out groups: push-out oscillated group B1 and push-out control group B2 (20 bones each); and
- Fatigue groups, divided according to different press loads: fatigue oscillated group C1 and control group C'1, fatigue oscillated group C2 and control group C'2, fatigue oscillated group C3 and control group C'3 (10 bones each).

Imaging experiment group (16 bones).

- Oscillated group D1 and control group D2 (8 bones each).

Specimen Preparation

Experimental bone model preparation. All proximal ends of pig femoral bones were removed from the intermediate piece, and the length of the model bone was found to be 5 cm. After removing the femoral condyles, we used a file to remove all obstacles in the medullary cavity and we ensured that the cavity diameter was 1.5 cm and the trabecular bone retained a thickness of at least 0.3 cm. The cavity was cleaned with a brush, pulsatile lavage, and hydrogen peroxide. The cavity was aired out to remove moisture from the intertrabecular spaces, the plug was inserted into the medullary cavity, and the cavity depth was fixed at 4 cm.

Filling bone cement. In all experiment groups, 10 g of bone cement was mixed at room temperature in the recommended ratios and kneaded for 30 seconds to allow air bubbles to be released. While the bone cement was perfused into each medullary cavity with a bone-cement gun for 10 seconds, the bone-cement oscillator was powered at 5 V with a frequency of 800 Hz. After the bone cement was placed in the prepared cavity, the oscillating probe was inserted into the medullary cavity and kept in the center axis. Oscillation lasted 20 seconds and was followed by pressurization. In the control groups, no oscillating probe was inserted in the filling process.

In the preliminary experiment, oscillation was tried for both 10 seconds and 30 seconds. We found that results were better at 20 seconds than at 10 seconds and that because the viscosity of cement increases as time passes, the difference in results at 20 seconds vs 30 seconds appeared to be unremarkable. Therefore, to ensure good results and a good margin of time for prosthesis insertion after oscillation, we used 20 seconds as the oscillation period.

Test Model Preparation

In the pull-out oscillated groups, the long axes of the bone-cement column and the medullary cavity were aligned vertically. In the distal section, 4 dots 2 cm apart were selected for perforating along the long axis of the model, and 2 U-shaped steel wires were inserted into each hole through the loading plate and twisted together along the long axis of the model (Figure 2A).

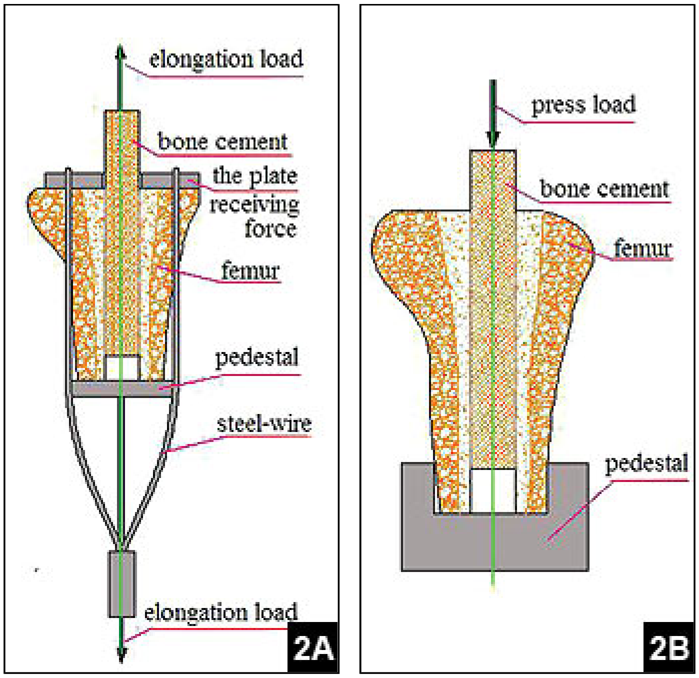


Figure 2: The mechanical delineation of a pull-out group (A). The axes of the bone-cement column, the medullary cavity, and the loading pillar were aligned vertically. The mechanical delineation of a push-out group (B). The axes of the bone-cement column, the medullary cavity, and the pedestal were vertically aligned. The top surface of the bone-cement column was vertical to the long axis of the model. A space at least 10 mm in height in the distal medullary cavity had no bone cement.

In the push-out oscillated and fatigue oscillated groups, the model was fixed in the pedestal with the long axes of the bone-cement column, the medullary cavity, and the pedestal aligned vertically (Figure 2B).

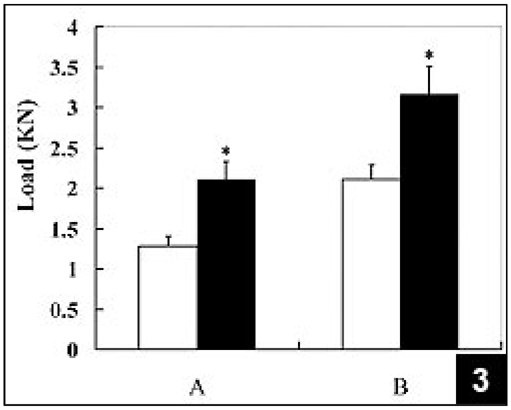
In the imaging experimental groups, after the bone cement was added any overflow was removed.

Mechanical Testing

Pull-out group A and push-out group B were tested at room temperature on the electron omnipotent material experimental machine. When the tensile force (group A) or pressure (group B) reached a certain level during the mechanical testing of each model, the bone-cement column was pulled out at the same time the electron omnipotent material experimental machine stopped and displayed the maximal load.

The result of each test was recorded on a computer. A Student *t* test was used as the statistical treatment method in 2 sets of samples (A1 and A2, B1 and B2). *P* values of <.05 were obtained for all groups (Figure 3).

In the fatigue groups, the mean of the ultimate shear strength of the cement–bone interface obtained from the push-out experiment group was 3159 N. Prepared models were divided into 3 groups: oscillating group C1 and control group C’1 were pressed with 30% of the ultimate shear strength of the cement–bone interface; oscillating group C2 and control group C’2 were pressed with 50% of the ultimate shear strength; and oscillating group C3 and control group C’3 were pressed with 70% of the ultimate shear strength (n=10 each group). The fatigue tests were performed at room temperature using the MTS 810 fatigue machine. Each specimen was tested using a sinusoidal loading pattern with a frequency of 5 Hz. A stroke limit was defined to discontinue cyclic loading when the axial displacement reached 2 mm. After many instances of fatigue breakdown with a set load, the mold itself became fatigued. When subsidence was apparent in the bone-cement column, the machine stopped and the fatigue data were recorded by a computer.



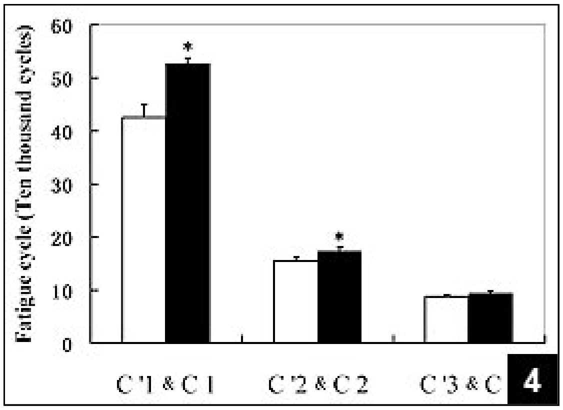
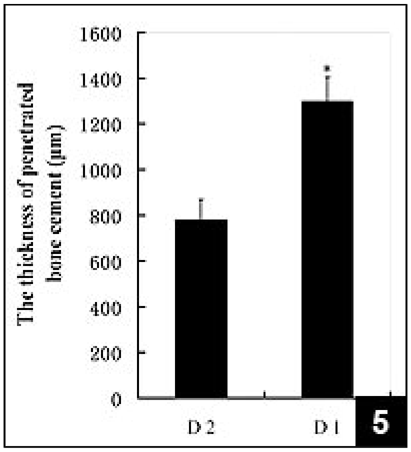


Figure 3: Statistical analysis of pull-out group A and push-out group B. A Student *t* test was used as the analysis method in pull-out group A (A1 and A2) and push-out group B (B1 and B2). For all results, P.05. The open boxes are control groups; the black boxes are experiment groups. **Figure 4:** Statistical analysis of the fatigue groups. In comparisons between C'1 and C1, C'2 and C2, and C'3 and C3, Student t tests were used as the analysis method. P values were .05 in the C'1 and C1 groups and C'2 and C2 groups, which means that the difference between experiment groups and control groups was significant except for the C'3 and C3 groups. Test results appeared insignificant when the fatigue load approached the ultimate shear strength of the cement–bone interface. The open boxes are control groups; the black boxes are experiment groups. **Figure 5:** Statistical analysis of the imaging group. A Student *t* test was used as the analysis method. All results were P.05. D2 is the control group; D1 is the experiment group.



A Student *t* test was used as the statistical analysis method for these groups. *P* values of <.05 in groups C1 and C'1 and in groups C2 and C'2 were obtained, but not in groups C3 and C'3 (Figure 4).

Imaging Observation and Analysis

After the imaging models were prepared, 3 slices were sectioned at approximately 600 μm thickness from the equal-appearing interval position of each model, and each slice was stained with hematoxylin-eosin. The fine structures of the slices were observed under a stereomicroscope at magnifications ×10 and ×63. All images of bone cement permeated to the bone trabeculae were collected on a computer.

Under the stereomicroscope at a magnification ×63, the radius of the cavity subtracted from the distance from the center point of the cavity to the border of the penetrated bone cement was defined as the thickness of penetrated bone cement. With professional image-analysis software (Motic Med 6.0; CMIAS, Beijing, China), we measured the thickness of penetrated bone cement at 12, 3, 6, and 9 o'clock on each slice.

Data regarding thickness of penetrated bone cement were recorded, and a Student *t* test was used as the statistical method. A *P* value of <.05 was considered statistically significant (Figure 5).

Results

General Observations

In the pull-out group, neither breakage nor loosening of the loading pillar was found, and the steel wire did not fracture during mechanical testing. When the tensile force reached a certain level, the bone-cement model was removed entirely after being pulled out gradually. In group A1, the thickness of the bone-cement column was well proportioned and the bone cement was better integrated with the medullary cavity without local discontinuance and filling incompleteness. In group A2, the bone-cement column appeared asymmetric in thickness, poorly integrated with the medullary cavity, and had some voids.

In the push-out group, the bone-cement column did not break or loosen and the appearance of the bone-cement column was similar to that of the pull-out group.

In the fatigue group, after the models became fatigued, cracks appeared in the cement–bone interface and the bone-cement columns subsided. In the experiment groups, the bone-cement column was uniform in thickness and in diameter, but in the control group, some gaps appeared in the bone-cement column.

Stereomicroscopic Observations

Under the stereomicroscope at a magnification 310, the bone cement in group D1 was well proportioned in the spaces between bone trabeculae, and the thickness of penetrated bone cement was greater than that of control groups. In group D2, discontinuities existed in the band of penetrated bone cement (Figure 6). At a magnification ×63, the bone cement in group D1 was tightly integrated with bone trabeculae and well distributed in the cavity of cancellous bone. In the D2 group, however, the bone cement was not well integrated with bone trabeculae and there appeared to be some interspaces (Figure 7).

Discussion

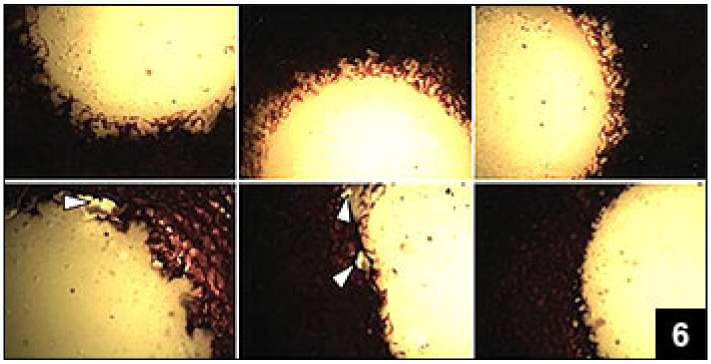
The filling technique in this study was based on the traditional third-generation cementing technique, but in the experiment groups oscillation was added to the process and the filling effect was improved significantly. In the experiment groups, the thickness of the bone-cement column was well proportioned and the bone cement was better integrated with bone trabeculae than in the control groups. No local discontinuity or filling incompleteness existed in the experiment groups, whereas in the control groups the thickness of the bone-cement column was asymmetric, the bone cement was poorly integrated with medullary cavity, and voids existed. The mechanical testing showed that in the experiment groups, the interlock at the cement–bone interface was significantly stronger than in the control groups. The reason was that while the bone cement was liquid, the oscillator could promote good distribution into cancellous bone space, strengthen the integration between cement and bone, and increase the strength of interlock at the cement–bone interface accordingly.

Pull-out and push-out tests are common methods for evaluating properties of cement–bone interfaces. In our study, through pull-out and push-out tests we found that the mechanical strength of the cement–bone interface was remarkably enhanced by oscillation. In addition, our results showed that the shear strength of the cement–bone interface is significantly greater than the tensile strength, which falls well within the range reported in previous investigations.[10]

Fatigue is a process by which a gradual localized permanent structural change occurs in a material subjected to cyclic loading. The process culminates in cracks or complete failure after a sufficient number of cycles. Fatigue failure can occur at stress levels considerably lower than the static strength of a material, and the ultimate shear strength of the cement–bone interface corresponds to the maximum push-out load.[11] In our study, the mean of the ultimate shear strength of the cement–bone interface obtained from the push-out tests was 3159 N. The cyclic load was then chosen corresponding to 30%, 40%, and 70% of the ultimate shear strength.[12] Prepared fatigue models were relatively divided into 3 groups (C1 and C’1, C2 and C’2, C3 and C’3). We found that the differences between C1 and C’1 and between C2 and C’2 were significant, but there was no remarkable difference in the C3 and C’3 group. The fatigue life of the model was determined with the use of cyclic loads, with magnitude defined with respect to the ultimate strength of the interface.[13] The cyclic load of the C3 and C’3 group approached the ultimate shear strength of the cement–bone interface, so test results appeared insignificant.

The strength of the interlock is determined by the degree of meshing of bone cement and bone trabeculae: the more bone cement that enters bone trabecular spaces, the more tightly they combine and the more firmly the prosthesis is fixed.[14,15] If the interlock strength at the interface is increased, both the frequency of micromovement and the generation of bone-cement debris will be reduced.[16] When the cement–bone interface is a uniformly tight and containing interface, the abrasion debris that causes an inflammatory reaction, osteolysis, and prosthesis loosening cannot enter the interface, so inflammatory reaction is prevented and the frequency of loosening is reduced.[17,18] For these reasons, the bone-cement technique is greatly improved by increasing the strength of interlock at the cement–bone interface, prolonging the useful life of the prosthesis accordingly.

Polymethylmethacrylate (PMMA) bone cement is typically placed with pressure, which increases the flow of the cement and promotes filling of the void. With pressure, PMMA cement is forced into cavities of trabecular bone. The resulting mechanical interlocking between the cement and natural surface interstices of the bone increases initial stabilization. However, the pressure applied by surgeons is sometimes uneven, which will lead to local discontinuity or filling incompleteness and will consequently increase loosening of the implanted prosthesis.[19]



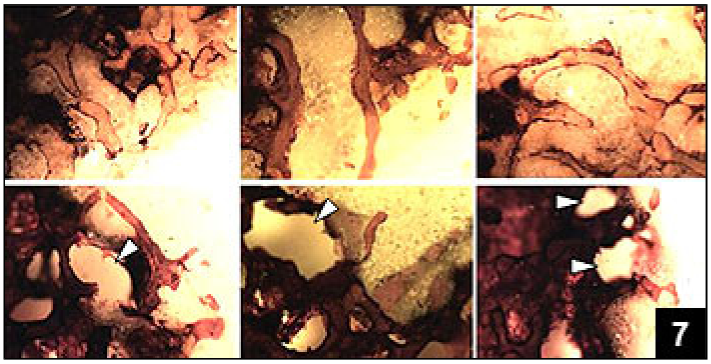


Figure 6: Appearance of the experimental group (top row) and control group (bottom row) under the stereomicroscope (magnification 10). Arrowheads indicate gaps in the control group. **Figure 7:** Appearance of the experimental group (top row) and control group (bottom row) under the stereomicroscope (magnification 63). Arrowheads indicate gaps in the control group.

We used the oscillation principle to develop a bone-cement oscillator. It works by rotating the oscillo-axle at high speed. After bone cement is in place and the bone-cement oscillator is inserted into the center of the medullary cavity, not only can oscillation create better penetration of bone cement, which consequently strengthens the combination intensity between bone cement and bone trabeculae,[4,20] but it can also ease the injection by reducing the pressure required.[21] This way, the occurrence of micromovement when contact between bone cement and bone trabeculae is too tight can be avoided, reducing the amount of bone and bone-cement debris produced.

With the use of a stereomicroscope, we also found that the bone cement was well proportioned in the spaces between bone trabeculae and that the thickness of permeated bone cement was wider than that of control groups. These differences may be caused partly by uneven pressure during the filling process. Under identical experimental conditions, however, the statistical difference was significant, mainly because in the control groups the distribution of the bone cement to bone trabeculae was poor as there was no oscillation. In the oscillated groups, the bone-cement oscillator not only increased the interlock strength at the interface of bone cement and bone, but also improved the distribution of the bone cement.

Every effort was made in our study to evaluate the effect of cement oscillation on the quality of interlock strength at the cement–bone interface. However, the study has limitations. First, the frequency of the bone-cement oscillator was a fixed value and could not be modulated. Second, the oscillator produced a better filling effect between 40 and 60 seconds; therefore, the question underlying our research is whether the cement was introduced earlier than is usual in clinical practice. Further studies are needed to prove the feasibility of incorporating the bone-cement oscillator into clinical practice. We also found, however, that procedure duration and effect of bone-cement oscillation depend not only on the quality of the oscillator but also on the properties of bone cement. Apart from necessary improvements to the oscillator, improvements are necessary to the properties of bone cement, which is beyond the scope of our study. Our future research efforts will be directed at modifying the design of the oscillator so it can operate at faster and slower speeds. However, only in concert with suitably improved bone cement can the oscillator produce optimum filling.

This study shows that oscillation of bone cement significantly increases interlock strength at the cement–bone interface. Our results point the way for clinicians to develop a high-performance, pragmatic fixation technique for prostheses to increase interlock strength at the cement–bone interface. Our findings will also be of considerable practical importance in the future for helping prevent aseptic loosening of cemented prostheses.

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COMMENTARY

Søren Overgaard, MD, PHD

This article evaluated in an experimental study the effect of cement oscillation on the quality of interlock strength at the cement-bone interface in addition to the filling effect of bone cement. The results showed that the interlock strength and the filling of cement into bone were significantly greater in the oscillated group than in the control group.

These findings are most likely explained by interdigitation of the cement into the trabecular bone. This indicates that application of oscillation in the cement may be an advantage and is supported by clinical studies showing that better cement penetration increases cup stability.[1] In addition, sealing off the cement-bone interface may prevent particles from migrating into the interface, thereby reducing the likelihood of a local inflammatory response.

Before use in the daily clinic, the effect of oscillation on cement must be evaluated in proper design studies.

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