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THE EFFECT OF POLYMETHYLMETHACRYLATE BONE CEMENT VIBRATION ON THE BONE-CEMENT INTERFACE

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Abstract

Low frequency vibration of polymethylmethacrylate (PMMA) bone cement reduces the viscosity of the cement by shear thinning. The effect of this low frequency vibration on the bone-cement interface was studied using microfocal radiography (MFR) and scanning electron microscopy (SEM). Effects were studied *in-vitro* and *in-vivo*. *In-vitro*, samples of Palacos low viscosity PMMA were placed on blocks of Kiel bone and vibrated. MFR and SEM demonstrated an improvement in the appearance of the bone-cement interface. *In-vivo*, PMMA was injected into the upper tibia of the dog. An assessment of the effect of high and low pressure injection, and the effect of added low frequency vibration of the cement was made. The effect on cement penetration was studied using MFR and SEM. It was found that vibration produced an improved bone-cement interface compared to low pressure injection, and an interface comparable to that obtained with high pressure injection.

Key Words: Bone cement, bone, polymethylmethacrylate (PMMA), scanning electron microscopy, microfocal radiography, vibration, *in vivo*, *in vitro*.

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Introduction

The technique of cemented total hip replacement introduced by Charnley depends on the development of an adequate bone-cement interface to support the cement mantle surrounding the component [1]. Following a successful operative procedure the immediate stability of the prosthesis is produced by a mechanical interlock between the polymethylmethacrylate (PMMA) cement and the cancellous bone. Over the following months bone remodeling takes place which produces a thin mantle of bone surrounding the cement plug, this mantle of bone is supported by a network of trabecular bone.

Recent improvements in bone cementing technique have concentrated on preparation of the bone surface using lavage and brushing, improving the mechanical qualities of the cement by better mixing and increasing cement penetration using low viscosity cement injected under pressure [3]. We have been concerned by difficulties with these techniques which include the problems in handling low viscosity cement and the theoretical risk of very high pressure cement injection causing bone devascularisation.

In the construction industry, the pouring of concrete into shuttering moulds is assisted by vibrating the shuttering [2]. This process has the effect of fluidising the aggregate mixture of stones and sand, making it easier for air bubbles to rise to the surface and compacting the mixture by allowing the sand to take up the spaces between the larger stones. It therefore appeared that the use of mechanical vibration to improve the bone-cement mechanical interlock would be worth investigating. Mechanical testing of PMMA shows that its viscosity is reduced by vibration in the 100-750 Hz range at an acceleration of 3-10 g [4], this effect is caused by shear thinning.

We have, therefore, carried out experiments to determine the alteration in the appearance of the bone-cement interface produced by mechanical vibration. To evaluate the alteration, we used scanning electron microscopy (SEM) and microfocal radiography (MFR).

Materials and Methods

In vitro study

Blocks of Keil bone (deprotinated calf vertebral bone, B. Braun Ltd.) 1.5 x 1.5 x 1 cm^3 were obtained and wetted in saline. One half ml of Palacos E (Merk Ltd.) low viscosity PMMA cement was placed on each block of bone. Five bone samples were vibrated at 500 Hz, acceleration 50 m s^{-2} for 20 seconds and five control samples were left undisturbed for cement to run into the bone under gravity.

For SEM, the bone was removed from the cement to display the cement surface using buffered EDTA (ethylenediaminetetraacetic acid) solution. We had previously found that EDTA had no effect on the appearance of the PMMA. After removal of bone the cement was prepared for SEM by stub mounting and gold sputter coating. Specimens were examined using a JEOL 840-A SEM.

For MFR slices of Keil bone, 2 mm thick, were prepared. The MFR X-Ray set used is an experimental, demountable device with a horizontal beam which can be used for macroradiography. It has a very fine (25 μm) focal spot size. The set has a hairpin filament, stationary copper anode and tungsten target. The inherent filtration of the tube is about 0.05 mm Al equivalent. The 25 micrometer focal spot is produced by the use of a biased focusing ring. Magnification is determined by the air gap between the object being radiographed and the film. A focus-film distance of 2000 mm was used and 10x magnification radiographs were obtained. Exposure parameters were 45 kVp, 18 mA on industrial X-ray film.

In vivo study.

The tibial plateau was exposed bilaterally in six 20 kg dogs under general anaesthesia. The upper tibia was reamed using a 6 mm auger type drill bit in order to obtain a reamed channel 20 mm long, as uniform as possible in diameter and free from excessive bone debris. The channel was washed out with three flushes of physiological saline. A double mix of Palacos E low viscosity PMMA cement was prepared by gentle mixing for one minute. At two minutes, the cement was injected and pressurised using 60 ml syringes connected to a gas supply and pressure gauge. This enabled injections to be made at high pressure (500 mm Hg) or low pressure (50 mm Hg). Vibration could be applied to the tibia using a Hall Micro Air reciprocating bone saw (Zimmer GB) with the saw output connected to the bone by a simple bracket fastened to the bone using a single 3.5 mm AO cortical screw. The frequency of vibration of the bone and acceleration induced in it were measured using a Piezo-electric accelerometer connected to a real time analyser (Scientific Atlanta). Measurement of the vibration parameters was undertaken to ensure that the induced vibration was sufficient to produce the alteration in cement flow noted in previous experiments.

All animals were examined using standard radiography, three were used for other experiments. Three were used for imaging of the bone-cement interface after the following methods of injection: (1) Low pressure injection of PMMA; (2) High pressure injection of PMMA; and (3) Low pressure injection of PMMA with vibration applied for 40 seconds after injection.

Bones were divided into sections using a band saw whilst being kept frozen with liquid nitrogen. Four 2 mm sections were taken from each bone for MFR and were cleaned with a brush prior to radiography. Adjacent thicker sections were taken and divided into quarters to provide four sections for SEM. These had cortical bone removed and were placed in EDTA solution to remove remaining bone prior to preparation for SEM examination.

Results

In-vitro study

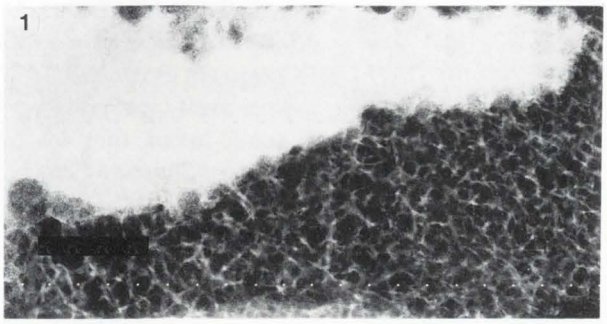
The microfocal radiographs of the control bone show penetration of cement to about 1 mm (Fig. 1). In the vibrated bone cement, penetration is much further, up to 4 mm (Fig. 2).

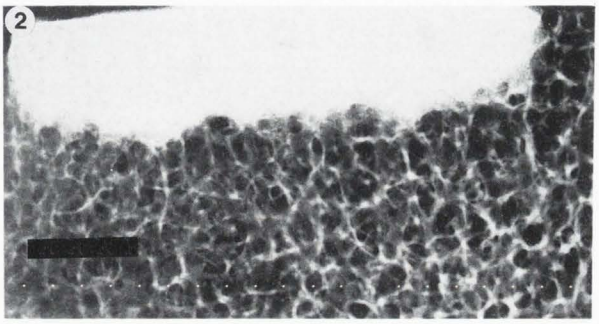
The scanning electron micrographs show that in control samples, the PMMA flows into the interstices of the cancellous bone (Fig. 3). The individual streams of PMMA are easy to recognize and the ends of the PMMA streams have rounded heads to them. The ends of the PMMA streams do not coat the cancellous bone very well. In the vibrated samples (Fig. 4), there is more bone material left adherent to the PMMA, the ends of the PMMA streams are more sharply cut off, and the PMMA appears to coat the bone trabeculae more effectively.

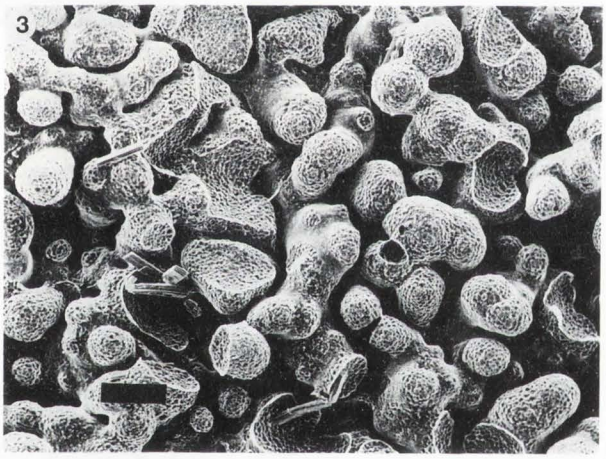
In vivo study

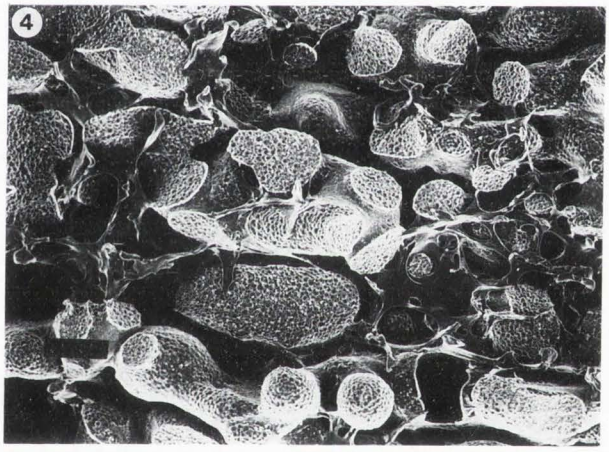
Multiple slices were examined from each specimen and typical MFR radiographs are shown. Low pressure cement injection produced only a minimal ingress of cement into the bone in one quadrant. In the remainder, the bone-cement interface was sharply defined with a lucent line in each quadrant (Fig. 5). High pressure injection produced a much more marked penetration. Penetration was improved around the whole circumference but was variable, measuring between 0.6 and 2 mm (Fig. 6).

In the low pressure injection combined with vibration, there is a improvement of the bone-cement interface compared to the low pressure injection penetration.









Figures 1 and 2: Microfocal radiographs showing cement penetration. Scale 2 mm. The cement (which appears white due to radiopaque dye) is placed on top of the bone and flows downwards. **Fig. 1**: Control bone showing cement penetration of 2 mm. **Fig. 2**: Vibrated bone showing cement penetration of 4 mm.

Figure 3: Scanning electron micrograph of cement surface in *in-vitro* control sample, after removal of bone using EDTA. The ends of the streams of PMMA are seen end on, from the direction of the bone. Scale 1 mm.

Figure 4: Scanning electron micrograph of cement surface in *in-vitro* vibrated sample. The ends of the PMMA streams are flat, and appear to coat the bone trabeculae more closely than in the control sample. Scale 1 mm.

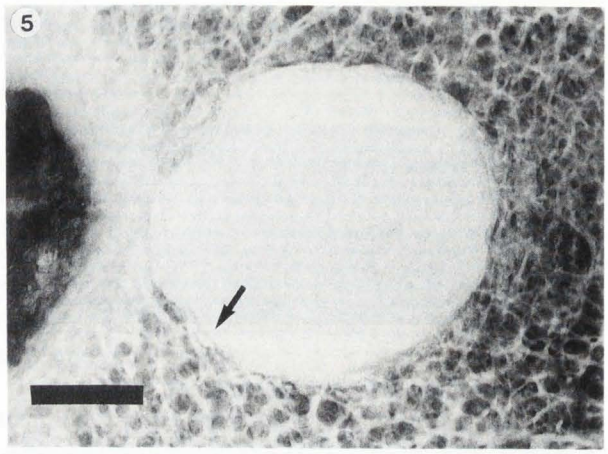
Penetration of 1 mm is seen throughout the circumference (Fig. 7).

SEM of the bone-cement interface *in-vivo* shows a featureless surface reflecting minimal cement penetration following the low pressure injection (Fig. 8). Following high pressure injection, there is a marked improvement in the bone-cement interlock with cement well moulded to the trabecular structure of the bone (Fig. 9). With vibration there is a similar marked improvement but due to differences in the structure of the cancellous bone, it is difficult to distinguish the effect from the high pressure injection (Fig. 10).

Discussion

Changes in the mechanical bone-cement interlock can be studied using mechanical tensile testing. Mechanical strength is related to depth of cement penetration and the mechanical properties of the bone. Since it is difficult to obtain sufficient *in-vivo* specimens for mechanical testing, and since the mechanical strength of the interface is related to PMMA penetration, we decided to use visual techniques to evaluate cement penetration.

Both the MFR and SEM studies we have undertaken show the effect of vibration in improving the interlock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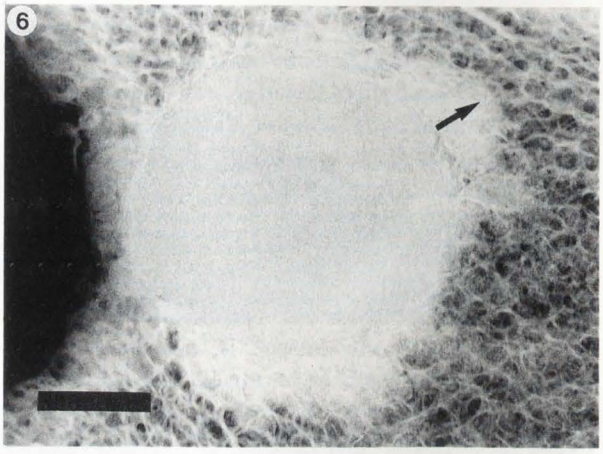
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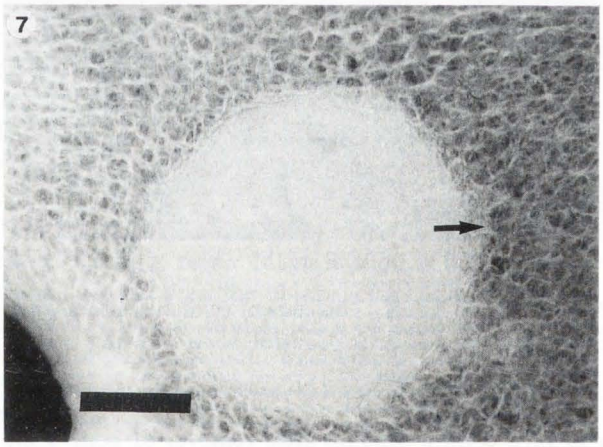
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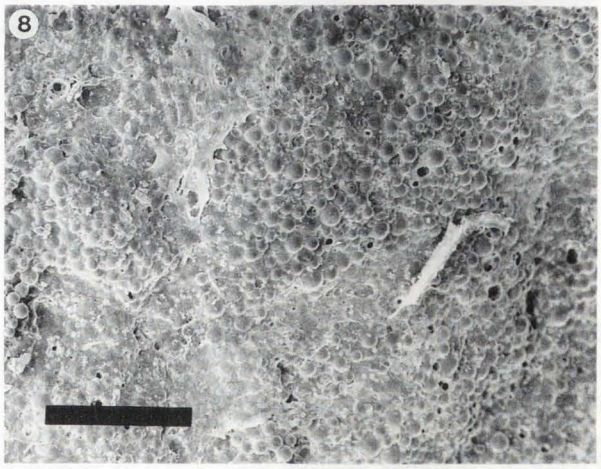
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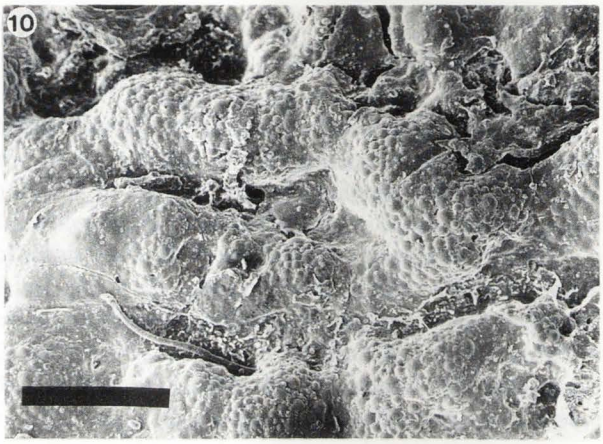
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Figure 5: Microfocal radiograph of *in-vivo* low pressure injection. The PMMA appears as a white circle 6 mm diameter in the upper tibia. Throughout most of the circumference, there is poor penetration of cement onto bone with lucent lines between cement and bone (arrow). Scale 2 mm.

Figure 6: Microfocal radiograph of *in-vivo* high pressure injection. Penetration was improved compared to low pressure injection, with variable penetration of 2 mm in some areas (arrow) but only 0.6 mm in other areas. Scale 2 mm.

Figure 7: Microfocal radiograph of *in-vivo* low pressure injection with cement vibration. A uniform increase in cement penetration of 1 mm is seen (arrows). Scale 2 mm.

Figure 8: Scanning electron micrograph of cement surface following low pressure injection *in-vivo*. The surface of the cement is flat, there has been little interlock between the cement and bone. Scale 500 μm.

Figure 9: Scanning electron micrograph of cement surface following high pressure injection *in-vivo*. The cement streams are well moulded onto the bone trabeculae, and there is some residual bone material remaining after removal of bone mineral using EDTA. Scale 500 μm.

Figure 10: Scanning electron micrograph of cement surface following low pressure injection with cement vibration *in-vivo*. There is an improvement in the moulding of the PMMA to the bone compared to low pressure injection, but it is difficult to distinguish this from the effect of high pressure injection. Scale 500 μm.

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between bone and PMMA cement *in-vitro*, when assessed by visual techniques.

In vivo, there are more differences in the exact qualities of the cancellous bone of the animals used, in each tibia it was only possible to obtain one or two good slices as the cancellous bone of the upper tibia gives way to fatty marrow after about 2 cm. Detailed comparisons are thus difficult but it appears that the low pressure injection, combined with vibration, has produced a uniform improvement in the quality of the interface whereas the high pressure injection has produced more marked increases in penetration, up to 2 mm, in some areas.

The two techniques provide useful complementary information. The MFR provides information over a wider area and allows bone trabecular structure to be observed. The SEM provides a more detailed local visualisation of the bone-cement interlock, but is difficult to interpret due to local differences in bone structure in the small areas studied.

Clinical Implications

Long term follow up of cemented femoral stems shows only a low loosening rate, it is therefore impossible to be sure of the long term effects of improvements in cementing technique until they have been studied for over ten years. Loosening rates will depend on the mechanical environment of the prosthesis, biological factors, such as developing osteoporosis, and inflammation caused by polyethylene debris and particulate cement debris.

PMMA cement is available in two forms, high viscosity (doughy) and low viscosity as used in this study. Since the chemistry of high and low viscosity PMMA are similar, it may be that vibration will enable the viscosity of doughy cement to be temporarily reduced during cement injection and thus the benefits of low viscosity cement may be obtained without the problems of handling and back-bleeding associated with low viscosity cement. The technique may, however, be most useful for cemented revisions where it is wished to use cement to carry antibiotics but pressurisation is difficult due to the lack of a good cancellous surface. It is a simple matter to apply vibration to the femoral shaft with the shank of a reciprocating bone saw applied to it and vibration of the type we have used is unlikely to damage the femur.

Conclusions

Both MFR and SEM were found to be useful methods in the study of the bone-cement interface. Both methods show the effect of vibration in improving the interlock between bone and cement at microscopic level.

Acknowledgements

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Discussion with Reviewers

I.G. Turner: Please discuss the validity of your results in view of the fact that the Keil bone used experimentally will differ in terms of structure and properties from the bone normally encountered in the clinical situation.
Authors: The Keil bone used in the experiments has had all the marrow, fat and a lot of its protein removed and it is thus different to normal human bone. However, during joint replacement surgery, it is now routine to clean the patients bone using Pulsed Lavage and the patients bone is, therefore, rendered into a condition much more like the Keil bone than normal.

L.D.T. Topoleski: Vibration appears to enhance PMMA penetration into cancellous bone. The observation that the "ends" of the PMMA streams penetrating the interstices are "flat" for the vibrated bone and "rounded" for the non-vibrated bone suggests, however, that the penetration enhancement may not be due to "shear thinning" but by reducing surface tension or somehow mechanically disturbing the fluid to eliminate the menisci. Have you considered alternate explanations? Suppose that vibrating the bone did nothing to the apparent viscosity of the PMMA, could enhanced penetration still occur?

Authors: The flattening of the ends of the PMMA streams and consequent improved coating of the interstices of the cancellous bone are, we think, caused by a combination of localised shear thinning of cement, acting at a microscopic level, and by a mechanical disturbance of the cement stream causing the cement to slosh from side to side within the interstice of the trabecular bone. We can think of no method of measuring surface tension in PMMA, because the PMMA, as it sets, tends to acquire a surface skin which is thought to occur because the surface of the cement is cooler than the centre of the cement and is thus of lower viscosity. It is difficult to be sure whether improved cement penetration would occur if cement did not exhibit shear thinning behaviour as there are no non-Newtonian fluids of appropriate viscosity to assess. If one places a droplet of water on to Keil bone, penetration of the water is enhanced by vibration, this is probably caused by altering the surface viscosity.

L.D.T. Topoleski: Why were the experiments performed on low viscosity cement and not "standard" viscosity cements right from the start?
Authors: Low viscosity cement was used partly because of ease of testing and partly because it has been shown in previous studies to provide optimal cement penetration. Blood contamination at the interfaces is thought to be an important factor clinically and for this reason, in clinical practice, we used Pulsed Lavage which removes most of the blood and marrow from the bone interface.