CLINICAL ORTHOPAEDICS AND RELATED RESEARCH
Number 299, pp. 293–297

The Effect of Bleeding on the Cement–Bone Interface

An Experimental Study

R. S. Majkowski, F.R.C.S.(Orth.),
G. C. Bannister, M.Ch.(Orth.), F.R.C.S.Ed.(Orth.), F.R.C.S.,
and A. W. Miles, M.Sc.Eng., M.B.E.S.

A model was developed to simulate bleeding from cancellous bone at the physiologic pressures and flow rates that can occur during total hip arthroplasty. The consequences of simulated bleeding on the penetration of bone cement into cancellous bone, the shear strength of the cement–bone interface, and the shear strength of bone cement were investigated. In the presence of active bleeding, the shear strength of the cement–bone interface was reduced significantly in 50% of interfaces in which cements of lower viscosity were used. The simulated bleeding did not exert a detrimental effect on the depth of cement penetration.

The clinical results of total hip arthroplasty have only become consistent since the adoption of polymethylmethacrylate bone cement, and long-term results support its continuing use.[1,8,9,13,14] The main late complication of cemented hip arthroplasty is aseptic loosening, which occurs predominantly at the cement–bone interface.[15] For this reason, modifications in cementing techniques during the past two decades have been directed toward enhancing the strength of the cement–bone interface.

During hip arthroplasty, cement is inserted into bleeding bone. Intramedullary bleeding pressures of up to 27.7 mm Hg and flow rates of up to 70 ml/minute have been recorded.[4,10] Active bleeding may have a number of potentially damaging consequences. Contamination of the bone surface with blood before cement insertion may reduce the shear strength of the cement–bone interface by up to 50% when cements of lower viscosity are used.[2] Blood has been shown experimentally to create voids within the main body of cement, producing laminations in cement handled during surgery and thus weakening the cement mantle.[3,7] Theoretically, the pressure of back bleeding could drive bone cement back from the bone, reducing penetration. Therefore, it is important to investigate the effects of active bleeding from cancellous bone during cement insertion and polymerization on the shear strength of the cement–bone interface, the shear strength of bone cement, and the penetration of bone cement.

A model was developed to compare the effect of simulated bleeding from cancellous bone on cements of differing viscosities.

MATERIALS AND METHODS

Cancellous bone was obtained from the distal metaphysis of paired bovine femora. Right and left femora from the same animal were used to standardize the mechanical and morphologic properties. Matched transverse sections, 10-mm thick, were heated to 37° in an incubator. The surfaces of each section were prepared by scrubbing with a nylon brush 60 times followed by pulsed lavage at 50 psi (Micro Aire Surgical Instruments, San Fernando, California) using 1 L of normal saline at

From the Department of Orthopaedics, University of Bristol, and the Department of Mechanical Engineering, the University at Bath.

Reprint requests to R. S. Majkowski, F.R.C.S. (Orth.), 12 Archer Crescent, Wollaton, Nottingham NG8 1HB, United Kingdom.

This work was funded by the John Charnley Trust.

Received: April 29, 1992.
Revised: February 4, 1993.
Accepted: February 10, 1993.

21°. Sixteen disks of bone, 30-mm thick, were cut from identical areas of each matching pair of bone sections using a crown drill and embedded in a circumferential collar of polymethylmethacrylate bone cement (Fig. 1) to provide a watertight seal.

The experimental model (Fig. 2) consisted of a bone disk clamped between two cylindrical aluminium chambers. The lower chamber was connected to a water reservoir of adjustable height with an inlet valve to control fluid pressure and flow. The upper chamber provided access for insertion of bone cement that could be pressurized using compressed air applied to a thin rubber diaphragm inside a screw-on cap.

Back bleeding was simulated using water. Conditions representing the worst extremes of pressure and flow recorded clinically were reproduced.[4,7] The height of the reservoir was adjusted to 37.4 cm above the bone surface, giving a pressure of 27.7 mm Hg. The surface area of the bone disk was 700 mm^2, compared with the internal surface area of the reamed proximal femoral medullary cavity in an anatomic specimen that was approximately 7000 mm^2. The flow rate was reduced proportionately to 7 ml per minute.

Simplex P (Howmedica, London, United Kingdom) and low-viscosity bone cements (LVC; Zimmer, Warsaw, Indiana) were used. Simplex P was mixed at 1 Hz for one minute and LVC for two minutes, according to the manufacturers' instructions. Immediately after mixing, the cements were poured into a wide-bore syringe. The Simplex P was injected into the upper chamber at three different intervals after the start of mixing, 90 seconds (early), three minutes 40 seconds (dough stage), and five minutes 20 seconds (late). The LVC was injected after two minutes 30 seconds. Immediately after injection, cement was pressurized for 30 seconds using compressed air at 25 psi.

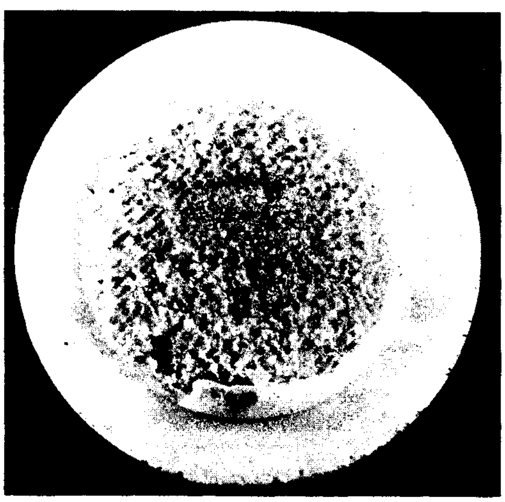

FIG. 1. Cancellous bone disk with a surrounding collar of bone cement.

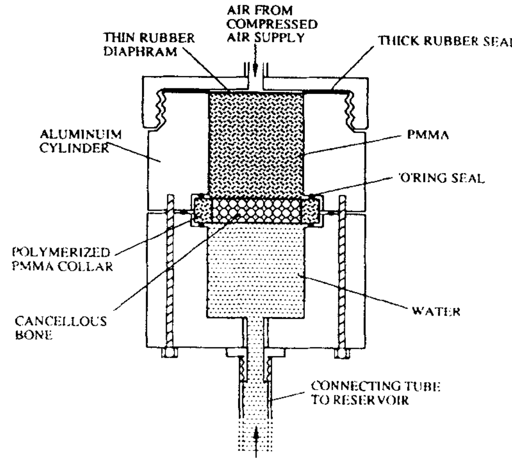

FIG. 2. Experimental model.

Experiments using each cement of the above type/stage of polymerization were performed twice under dry and simulated bleeding conditions on a matching pair of bone disks. In bleeding tests, flow was initiated before cement insertion and maintained until polymerization was complete. The specimens were removed from the model and cut into rectangular struts perpendicular to the original bone surface with a transverse section 6 mm × 6 mm. Between eight and ten struts were obtained from each specimen. The struts were examined radiographically at an exposure of 30 mvs for 60 seconds (Faxitron 438 55 A, Vinter Analytical, Bedfordshire, United Kingdom), and cement penetration in each strut was measured from the radiographs to the nearest 0.5 mm. The shear strength of the cement–bone interface at the original cut surface of the bone and the cement was tested in a single-face shear jig mounted on a Hounsfield Tensometer (Tensometer, Croydon, United Kingdom) at a strain rate of 20 mm/min.

Statistical analysis of the data was performed using Student's t test and Spearman rank correlation. The shear strength of the cement–bone interface and penetration were compared only in matching sections of bone.

RESULTS

The mean shear strength of the cement–bone interface ranged from 20.4 to 35.4 MPa.

When Simplex P was inserted at the dough stage or later, simulated bleeding did not affect the shear strength of the cement–bone interface. However, Simplex P, when inserted at 90 seconds, and LVC produced significantly weaker interfaces in two of the four experiments ($p < 0.05$), with reductions in shear strength of 14% and 20%, respectively.

Mean penetration varied from 2.9 to 9.2 mm and appeared to be determined by the morphology of cancellous bone rather than cement viscosity. This was particularly noticeable in the experiments where Simplex P was used early. Simulated bleeding exerted no effect. At the penetration levels observed, there was no correlation between the depth of penetration and the strength of the cement–bone interface.

Mean shear strength of bone cement ranged from 40.0 to 48.2 MPa. Cement strengths were comparable whether polymerization occurred under dry or simulated bleeding conditions. Fluid-filled voids were not observed in any of the preparations. There was no difference between Simplex P and LVC (Table 1).

DISCUSSION

The results obtained using this experimental model cannot necessarily be applied to femoral component implantation *in vivo* because of the difference in materials. However, bovine cancellous bone has mechanical and morphologic properties that are comparable with those of bone from the human femur.[2,18] As far as possible, the authors standardized the cancellous bone used because regional variations have been shown to affect the strength of the cement–bone interface by a factor of three.[5] Bone surfaces were subjected to prolonged pulsed lavage to maximize removal of surface debris and marrow within the interstices, thereby minimizing their detrimental effect on the shear strength of the cement–bone interface.[11] Bone cement was pressurized at 25 psi because this is representative of the pressures obtained by finger

TABLE 1. The Shear Strength of the Cement–Bone Interface and the Shear Strength and Penetration Into Cancellous Bone of PMMA Under Dry and Stimulated Bleeding Conditions

Bone Cement	*Cementing Conditions*	n	*Shear Strength Cement–Bone Interface (MPa)*	*Shear Strength PMMA (MPa)*	*Penetration (mm)*
Simplex P (early)	Dry	10	27.0 ± 5.0	45.2 ± 3.6	3.0 ± 0.3
	Wet	10	27.3 ± 4.8	45.5 ± 5.5	3.2 ± 0.4
	Dry	9	31.0 ± 1.9	42.3 ± 1.6	9.2 ± 3.7
	Wet	8	26.6 ± 4.0	45.0 ± 6.6	8.9 ± 3.9
			$p < 0.05$*		
Simplex P (dough)	Dry	10	25.1 ± 5.0	48.1 ± 4.2	3.1 ± 0.6
	Wet	10	23.9 ± 9.0	43.4 ± 4.1	3.3 ± 0.4
	Dry	8	33.1 ± 4.9	47.5 ± 6.3	5.2 ± 0.7
	Wet	10	35.4 ± 4.4	48.2 ± 3.2	6.0 ± 1.1
Simplex P (late)	Dry	9	31.2 ± 3.6	43.4 ± 4.2	3.8 ± 0.3
	Wet	9	30.1 ± 4.7	44.7 ± 7.1	4.2 ± 0.4
	Dry	10	32.9 ± 2.4	47.0 ± 3.4	4.9 ± 0.9
	Wet	8	31.2 ± 3.1	47.0 ± 3.5	5.1 ± 0.6
LVC	Dry	9	25.8 ± 3.6	47.1 ± 4.1	2.9 ± 0.3
	Wet	8	20.4 ± 4.5	44.3 ± 3.8	3.1 ± 0.4
			$p < 0.05$*		
	Dry	9	27.6 ± 3.9	43.2 ± 4.1	3.7 ± 0.4
	Wet	10	25.8 ± 4.4	40.0 ± 3.5	4.1 ± 0.6

* P-values refer to the two values immediately above.

packing in anatomic specimen femora.[6,12,17] Water was used as a substitute for blood, although there are minor rheologic differences between them. To minimize any effect this might have on experimental results, each bone disk was calibrated before cement insertion by adjusting the flow of fluid through the bone, at a known pressure, to the desired rate.

The shear strengths of the cement–bone interface were comparable with those obtained in similarly prepared human bone and much higher than those where pressurized lavage was not used.[2,11] In this study, simulated bleeding had a detrimental effect on the strength of the cement–bone interface when cements of low viscosity were used. Lucencies at the cement–bone interface in radiographs of some intact LVC specimens (Fig. 3) before shear testing suggested that fluid had reached this area. Because penetration of bone cement into bone was not reduced in the presence of simulated bleeding, it would appear that fluid reaches the interface by tracking alongside cement in the cancellous interstices rather than by bulk displacement back into the medullary cavity. This phenomenon has been observed experimentally and is most florid when cement is in a less viscous state.[7] It may explain the early prosthetic migration recorded by Mjoberg *et al.* when LVC is used clinically.[16] Contamination of the bone surface with blood may itself reduce the efficacy of the interlock between cement and bone when LVC is used, as has been observed experimentally,[2] although this effect may only have occurred because the bone was not prepared using pressurized lavage.

The depth of penetration observed in this study was greater than that previously reported and probably reflected the quality of bone cleaning achieved with the duration and pressure of lavage used.[11] The shear strength of cement that polymerized under simulated bleeding conditions in contrast to previous work in this study was not reduced, and no fluid voids were observed, indicating that contamination of the main body of cement with fluid had not occurred.[2,7] This can be partly attributed to the speed of insertion of cement into the model and the lack of handling that produces laminations under operating conditions. The formation of voids depends not only on the viscosity of the cement and the pressure of bleeding but also on the rate of bleeding.[7] The absence of contamination probably occurred because the physiologic flow rates adopted in this study were likely to have been much lower than those used previously.

It would seem that the advantages of LVCs are illusory. Penetration beyond 3 mm does not enhance the strength of the cement–bone

FIG. 3. Radiograph of bone (left)/bone cement (right) strut, before shear testing, obtained after LVC insertion into "bleeding" bone demonstrates lucency at the cement–bone interface. (Original magnification, ×5.)

interface, and such depths can be achieved by using higher viscosity cement, which is less susceptible to contamination by bleeding. Prolonged pressurization of bone cement that has reached dough stage would not seem to confer any additional protection against back bleeding in cancellous bone at physiologic flow rates and pressures. It would appear that the optimum cement technique in bleeding bone involves meticulous cleaning of cancellous bone with pulsed pressurized lavage, rapid application of normal viscosity cement that has reached dough stage and immediate manual pressurization for at least 30 seconds.

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