Effects of lamination on the strength of bone cement

Gunnar Flivik, Xunhua Yuan, Leif Ryd, Rigmor Juliusson and Lars Lidgren

To improve cement penetration into the cancellous bone of the acetabulum in hip arthroplasty, sequential cementation of each anchoring hole may be feasible. Since this procedure creates laminations in the cement, we have determined the conditions under which such laminations affect the strength of the cement.

Cement bars made at 2, 3 or 4 minutes after the start of cement mixing and with either dry laminations or laminations including blood or saline were tested for tensile strength. Solid unlaminated bars were used as references. Dry and saline laminations made up to 4 minutes after the start of cement mixing did not reduce the strength of the cement. However, there was a time-dependent decrease in cement strength if blood was entrapped in the interface. In such cases, there was a decrease in strength for laminations made at 4 minutes, at 3 minutes this was less pronounced and at 2 minutes no weakening at all was noted.

Our findings indicate that a sequential cementation procedure is permissible as regards cement strength, provided it is performed within 2–3 minutes after the start of cement mixing. If the cement area is kept free from blood, the time may be prolonged up to 4 minutes, without the risk of weakening the cement strength.

Department of Orthopedics, University Hospital, S-221 85 Lund, Sweden. Tel +46 46-171510. Fax -130732
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Increased interdigitation of bone cement into cancellous bone leads to improved long-term stability of the cement-bone interface, since micromovement between cement and bone is minimized and, furthermore, the migration of debris along the cement-bone interface is impeded (Eftekhar and Nercessian 1988, Schmalzried et al. 1992).

The long-term results of cemented total hip arthroplasty have improved substantially, by using better surgical and cementing techniques (Malchau et al. 1993). Late loosening of cemented acetabular components is nevertheless still a problem (Eftekhar and Nercessian 1988, Garcia-Cimbrelo and Munuera 1992, Schmalzried et al. 1992, Mulroy et al. 1995, Ranawat et al. 1995). As we have pointed out in previous studies, a main reason for this loosening may be insufficient penetration of the cement into the anchorage holes and the cancellous bone, since it is difficult to attain adequate cementation pressure in the entire acetabulum (Juliusson et al. 1994, 1995). One way of achieving the desirable penetration depth could be to cement, under pressure, each anchoring hole individually with sealing nozzles. Subsequently, the rest of the acetabulum would be filled with cement in a sequential cementation procedure. However, this procedure may create laminations in the cement, some of which might include blood. Experiments have shown that bleeding from the bone bed during cementation reduces the strength of the cement-bone interface (Benjamin et al. 1987, Bannister and Miles 1988, Majkowski et al. 1994). It has also been demonstrated that, under certain circumstances, inclusion of blood in the cement mass or in laminations appearing during cementation reduces the mechanical strength of the bone cement (Gruen et al. 1976, Holm 1977, Lee et al. 1978, Saha and Pal 1984).

We analyzed the conditions under which laminations in the cement affect its strength.

Material and methods

Pre-chilled Palacos® (4 °C) was used for all the tests. Mixing was performed in an Optivac vacuum-mixing system (Mitab) according to the manufacturers' instructions. The mixing time was 30 seconds, with about 15 stirrings. A 300 mm long plastic tube with an inner diameter of 9 mm was divided into 6 parts, each 50 mm long, and all were patched together with an external adhesive. The tube was attached to the cement gun and filled with cement. Immediately after the introduction of cement, the 6 parts were separated with a scalpel. At 2, 3 and 4 minutes, respectively, after the start of mixing of powder and liquid, the ce-

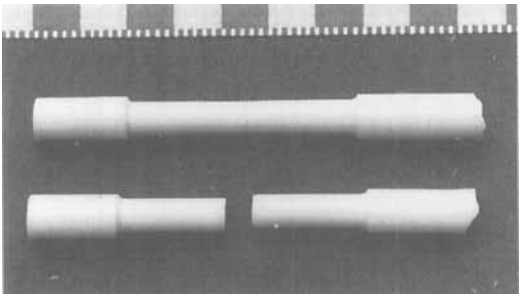

Figure 1. One cement bar before and one after fracture in the tensile strength test. Note the vaguely visible line in the middle of the upper bar indicating the lamination interface.

ment-filled tubes were brought together two-by-two, so that the cement surfaces met under manual pressure and thus formed a lamination interface. The cement surfaces were either dry or floaded with fresh venous blood or with saline, before being brought together. Thus 3 types of laminations were made, each at 3 different points in time, and 6 solid bars with no interface served as references. All specimens were made in a laboratory at room temperature (21 °C).

After curing, the approximately 200 specimens made were radiographed to exclude all bars with voids bigger than 1 mm as well as all with visual voids in the interface. Thus, about half of the specimens were excluded. The remaining specimens were machined to achieve a middle portion of 7 mm in diameter and 50 mm in length (Figure 1).

The tensile strength was tested in an Instron testing-machine by loading the bars in tension to the point of fracture. The rate of crosshead motion of the machine was 5 mm/min. The average ultimate tensile stress, σ (MPa), was calculated by dividing the ultimate tensile force, F (N), by the cross-sectional area, A (mm^2), of the fracture surface. If there were any internal voids in the fracture areas, the specimens were discarded. 25 specimens with cement fracture at load in any part of the bar other than in the lamination area were also excluded, since in such cases the actual strength of the interface could not be established. The ANOVA test was used for statistical analysis.

Results

The solid unlaminated bars had a mean tensile strength value of 52 (47–62) MPa (Table). Dry lamination and laminations including saline showed no statistically significant decrease in strength for any of the time groups. At 4 minutes a slight, statistically insignificant decrease by approximately 10% was found. Blood laminated bars showed no decrease in strength compared to solid unlaminated bars, when made at 2 minutes after starting the mixing. However, at 3 minutes the strength had decreased by about 30% ($p < 0.0001$), and at 4 minutes by more than 50% ($p < 0.0001$) (Figure 2).

The slopes of the curves on the X-Y recordings from the Instron machine were almost identical, indicating no effect on stiffness from the different laminations.

Discussion

There is one study similar to ours in which Gruen et al. (1976) tested specimens with either dry or blood-laminated interfaces for tensile and shear strength. Their testing conditions corresponded to ours, except that they used Simplex P cement and mixed it by hand. This may explain why our cement was about 70% stronger at comparable times. Their laminations were formed at times ranging from 4 to 6.5 minutes after the beginning of mixing. For dry lamination, they found a steady decline in tensile strength down

The tensile strength of the different groups of laminated cement bars and the unlaminated reference bars

Lamination type	No. of specimens	Lamination time (min)	Mean strength (N/mm^2)	SD (N/mm^2)	SE (N/mm^2)
Unlaminated	6	–	52	6.3	2.8
Dry	7	2	48	5.1	1.9
Dry	6	3	49	6.8	2.8
Dry	7	4	46	4.9	1.9
Saline	6	2	53	5.1	2.1
Saline	6	3	53	3.9	1.6
Saline	8	4	49	5.0	1.8
Blood	9	2	47	4.6	1.5
Blood	8	3	36	1.5	0.5
Blood §	7	4	24	9.3	3.5

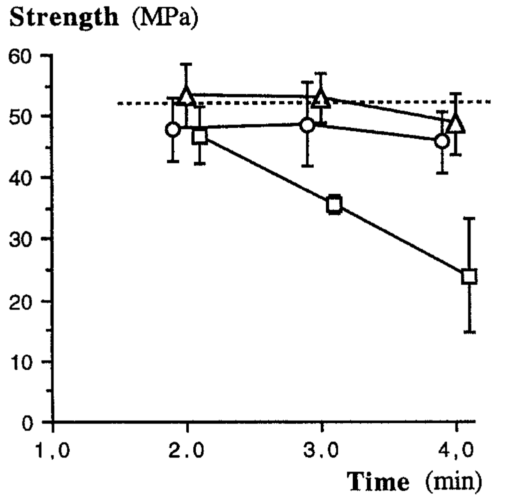

Figure 2. The relation between interfacial cement strength (mean ± SD) and the time elapsed from start of cement mixing up to lamination for 3 different kinds of cement-cement interface (Δ saline, O dry, □ blood). Dotted line refers to the reference strength of solid bars.

to 46% of that of the unlaminated material at 6.5 minutes. This finding may be due to time-dependent loss of monomer by evaporation and initial polymerization, whereby less monomer would be available on the interface surface for dissolution and bonding of the PMMA powder surfaces. The results of our dry lamination tests at 2, 3 and 4 minutes, as well as their 4-minute specimens, indicate that within 4 minutes this effect has not started to influence the bonding capacity and thereby the strength. Our results also clearly show that saline, which is used for pressure lavage in cleaning the bone-bed from debris and blood, does not affect the interface strength, if it is entrapped in the interface up to 4 minutes after the beginning of cement-mixing. The fact that the laminations were created under only slight pressure strengthens our conclusion; if anything, higher pressure should increase the lamination strength. For blood-laminated specimens, Gruen et al. (1976) showed a more marked reduction in interface strength compared to their dry laminations. They demonstrated a 75% reduction in tensile strength and a 62% decrease in shear strength after 6.5 minutes, which was only slightly weaker than their starting values at 4 minutes. They did not test the interval between 2 and 4 minutes, where we found a clearly time-dependent decrease. Their tests for shear strength all showed a less pronounced decline than in the tensile tests, whereas the same pattern of reducing strength by increasing time was demonstrated.

Tests with blood mixed into the actual cement mass have also demonstrated a weakening effect on the cement. Holm (1977) reported that the flexural modulus of elasticity of CMW cement was reduced by up to 21% by the addition of 3 mL of blood, but that the same amount of blood reduced the strength of Palacos by only 3%. Lee et al. (1978) mixed 1 mL of blood in the cement mass (Simplex P) and showed a reduction in ultimate compressive strength between 8% and 16%. The experiment revealed rather high standard deviations, indicating unpredictable behavior.

Cement acts by three-dimensional interdigitation with cancellous bone. It has been shown that bleeding from the bone surface during cementation will reduce the strength of the crucial cement-bone interface (Benjamin et al. 1987, Bannister and Miles 1988, Majkowski et al. 1994). In addition, we have demonstrated that the penetration of cement is diminished by the presence of blood in the cancellous bone (Juliusson et al. 1995). Finally, if cement is inserted early in a low viscosity state or not kept under pressure during the early stage the cement may be extruded by the rather low intraosseous blood pressure (Benjamin et al. 1987). These facts all emphasize the importance of keeping a dry and thoroughly cleaned bone-bed prior to cementation, which must be performed under pressure to achieve adequate cement penetration. This has been shown to be around 3 mm (Huiskes and Sloof 1981, Krause et al. 1982, Noble and Swarts 1983, Askew et al. 1984, Majkowski et al. 1993). Previously we have shown that a pressure of at least 0.3 MPa seems to be needed to achieve such penetration in arthrotic bone (Juliusson et al. 1995). The acetabulum raises special difficulties regarding pressurization, since the cavity is difficult to seal in order to achieve containment (Charnley 1979). Furthermore, the desired pressures would create a counter-force on the pressure instrument of 400–600N, which is difficult to counteract during the required period of time. If each anchoring hole is cemented individually using sealing nozzles, adequate pressures can more easily be reached. In a second step, the cementation may be completed by the use of a full-size pressurizer to counteract the blood pressure. During this procedure, laminations are created, which might include blood.

The results of this study suggest that a sequential cementation procedure may be used as regards cement strength, provided that it is performed within 2–3 minutes after the start of cement-mixing. If the cement area is kept free from blood or cleansed with saline, the procedure may be feasible up to 4 minutes with the tested cement. With modern cement delivery systems, there is little problem in early handling of the cement. The penetration requirements necessitate the maintenance of adequate pressure on the cement, until increased viscosity can resist displacement

(Krause et al. 1982, Benjamin et al. 1987, Rey et al. 1987, MacDonald et al. 1993). If this cannot be achieved, the cement should be delivered as late as possible and in one stage. With adequate sealing, staged cementation of first the anchoring holes and subsequently the cavity may be one way to achieve better cementation of the acetabulum in hip arthroplasty and thus reduce the risk of late loosening.

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