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Effect of pressure on bone cement stiffness

An *in vitro* study

Twenty-two canine femora were injected with PMMA cement at pressures varying between 0.2 and 1.3 MPa. Sections cut from the femora were tested in bending in several planes and under axial loading. Cement penetration was determined for each section. The bending and axial stiffness values were correlated with the cement penetration values. Both bending and axial stiffness were related linearly to penetration and nonlinearly to the cement intrusion pressure. The stiffness values increased with the intrusion pressure: slowly at low pressures, rapidly at medium pressures, slowly again at higher pressures, and leveling off at about 1.2 MPa. The 75 per cent of the maximum bending and axial stiffnes values were achieved with a cement intrusion pressure of 0.55 MPa.

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Polymethylmethacrylate (PMMA) cement is an organic polymer that has minimal adhesive or bonding properties. Thus, it is useful only as a space-filling material. Increased mechanical interdigitation of PMMA with bone is thought to improve the mechanical properties of the composite (Halawa et al. 1978, Hayes et al. 1981, Krause et al. 1980, Oh et al. 1983). Consequently, factors that affect the interdigitation of PMMA with the cancellous bone are important in improving the mechanical properties of the bone-cement composite. In recent works, effects of varying pressures on cement penetration (Panjabi et al. 1983) and the bone-cement composite tensile strength have been studied (Askew et al. 1984).

We have examined the change in the physical properties of the bone-cement composite as a function of intrusion pressure and cement penetration. Compression and shear testing alone, as has been done in the past, do not adequately describe all the physical properties that are relevant to the use of this composite. For this reason, we chose to study the physical properties under more complex loading conditions: combined bending and lateral shear; and axial shear.

Material and methods

Cement pressurization and penetration. Eleven pairs of femora were obtained from healthy mongrel dogs weighing 23 to 27 kg. The femoral neck was transected 3 mm proximal to the lesser trochanter. The medullary canal was reamed using a fluted rasp (Richards medium 380166) to a depth of 9.3 cm from the lesser trochanter. An 8.7-mm-diameter hole was drilled through the medial cortex and then tapped transversely 6 cm distal to the lesser trochanter to accomodate a pressure transducer (Sensotec NPT 1/8) (Figure 1). A hole 6 mm in diameter was drilled through the medial and lateral cortices 10 cm distal to the lesser trochanter. Through this hole, a crossbar was placed to anchor the cement pressurization system. The medullary canal was lavaged and a PMMA plug was introduced at a depth of 8 cm distal to the transducer hole and proximal to the crossbar hole. The prepared femora were wrapped in plastic bags and stored at −20°C.

On the day of cement injection, the specimen was thawed to room temperature. The cement was mixed manually for 40 s at 21°C and 50 per cent relative humidity. Methylene blue dye was added to each batch of Howmedica Simplex Cement to enhance the contrast of the cement with respect to the bone. The medullary canal was filled with cement by manual injection, starting from the plug. The pneumatic pressurization system was then assembled over the proximal end of the femur and the cement pressurized within the range 0.21 to 1.30 MPa for 15 s

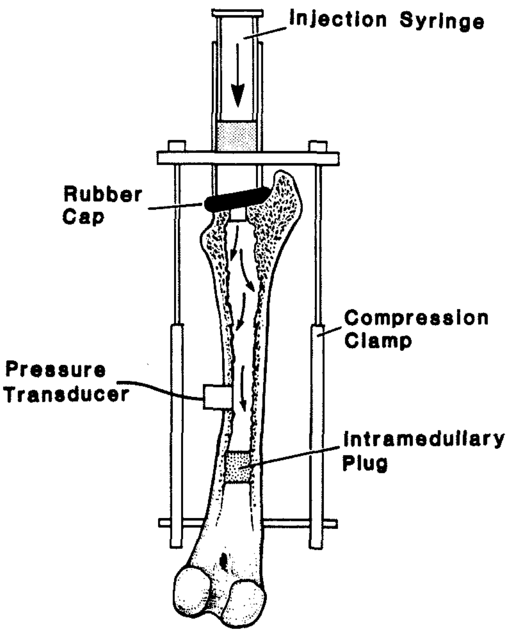


Figure 1. PMMA was pressurized using the apparatus shown. An intramedullary plug was placed into the medullary canal prior to pressurization. Compressin clamp and rubber cap provide a leakage-free medullary cavity. A pneumatic gun was utilized to pressurize the cement. Intramedullary pressures were monitored via the pressure transducer in the diaphysis.

(1 MPa = 7496 mm Hg = 145 psi = 10 atm). Upon completion of the pressurization and after the cement had polymerized entirely, the femora were cut transversally into 10-mm-thick sections starting at the lesser trochanter. The sections were wrapped in plastic bags and stored at −20°C until mechanical testing.

To quantify cement penetration into the bone, the proximal and distal surfaces of each bone section, together with a scale, were photographed in color (Panjabi et al. 1983).

Mechanical testing of bone-cement composite. Metaphyseal sections 1 cm distal to the lesser trochanters were chosen because of the abundance of cancellous bone present and the variability in the penetration of the PMMA into the bone at this level. A 3.0-mm hole was drilled into the approximate center of the PMMA plug. A 6.7-cm-long and 6.4-mm-diameter stainless steel rod with a 25.4-mm-diameter sphere on one end was tapped into the hole. The section was mounted in a specially constructed testing jig. Four arms, located on each side of the jig, helped secure the section by contacting only the cortical edges.

The testing jig was placed into a universal testing machine. A radial load perpendicular to the axis of the femur and not exceeding 25 N was applied to the loading sphere. In order to examine the anisotropy of the PMMA-bone composite, 12 separate radial loads at 30° intervals were applied starting at the anteroposterior orientation. Then, the anteroposterior loading was repeated to confirm the noninvasive nature of the composite and to assess the repeatability of the experiment. After completing the radial bending tests, an axially directed load was applied. Loads were applied at a rate of 10 mm/min. The load-displacement curves were recorded on a strip-chart recorder.

To determine the small amount of give of the test apparatus, the bone-cement specimen was substituted with a steel specimen and the displacement of the steel cylinder subtracted from that of the specimens to obtain the net results.

A Talos Digitizer and a Tektronix 4052 computer were used: (1) to determine the penetration of PMMA into the cancellous bone; and (2) to analyze the load-displacement curves. The maximum load, maximum displacement, and the slope of the middle one-third of the load-displacement curve were determined.

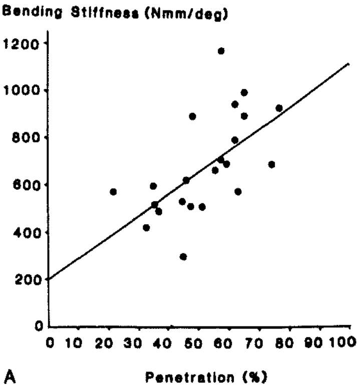
The *cement penetration* was determined using the methods described elsewhere (Panjabi et al. 1983). The outer cortical, cortico-cancellous, cancellous-cement, and the reamer boundaries were digitized. The cement penetration was calculated as the area occupied by PMMA divided by the area of the available cancellous bone. The area of the reamed canal was subtracted from both of these areas. The penetration calculated from the proximal and distal surfaces of the section were averaged to obtain a single penetration value for each section.

The bending stiffness is defined as the resistance of the bone-cement composite to bending. The twelve bending stiffness values, obtained at 30° intervals, were averaged to get a single value for each specimen.

The axial shear stiffness is defined as the resistance of the bone-cement composite to axial loading. Its measure is the ratio of axial force to axial deformation.

Results

The average diameter of 22 metaphyseal specimens was 17.8 ± 1.6 mm (mean ± s.d.). The femora were subjected to an average cement intrusion pressure of 0.51 ± 0.31 MPa, which produced cement penetration of 52 ± 14 per cent. The resulting average bending stiffness and axial stiffness values were respectively



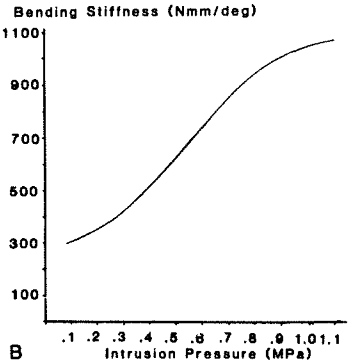


Figure 2. A. Bending stiffness (S_B) plotted against PMMA penetration (P). B. Bending stiffness versus intrusion pressure (P). See text for explanation and Appendix for equations.

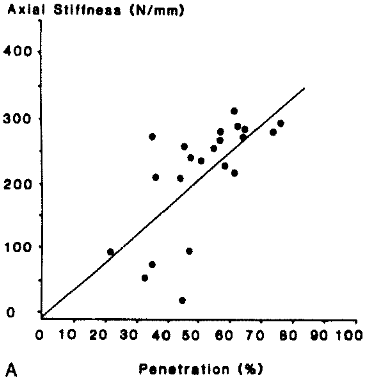
674 ± 214 Nmm/deg and 225 ± 88 N/mm.

The relationship of *bending stiffness* (Nmm/deg) to percentage penetration was linear ($R = 0.60$, $p = 0.003$, Figure 2A). Dividing the bending stiffness values by the corresponding average bone diameter of each section resulted in some improvement of the correlation ($R = 0.64$, $p < 0.001$). Combining these results with those of an earlier study (Panjabi et al. 1983), relationship between bending stiffness and cement pressure is obtained (Figure 2B).

The relationship of *axial stiffness* (N/mm) to cement penetration was also linear ($R = 0.67$, $p < 0.001$, Figure 3A). The relationship between axial stiffness and cement pressurization (Panjabi et al. 1983) leveled off at intrusion pressures of 1.2 MPa, reaching a maximum axial stiffness of 425 N/mm (Figure 3B). Mathematical expressions relating bending and axial stiffnesses to cement penetration and cement intrusion pressure are located in the Appendix.

Discussion

The bending and axial stiffnesses are important mechanical parameters concerning the bone-cement composite *in vivo*. It is probably stiffness, and not the strength, that is a determining factor in the process of adaptation of bone after implantation. The bending loads are the most common physiological load types to which long bones are subjected. Therefore, as a departure from the studies of simple load such as the shear, compression and tension at the interface, we chose to apply a set of complex loads, i.e., combined bending and radial compression in different radial planes of the test specimen. As a base line, we also performed



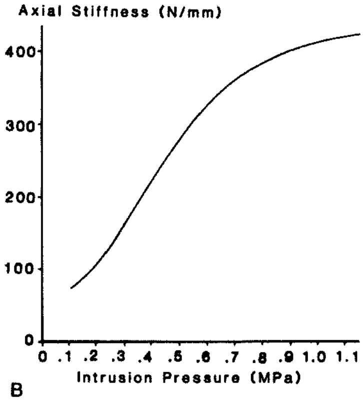


Figure 3. A. Axial stiffness (S_A) plotted against PMMA penetration (P). B. Axial stiffness versus intrusion pressure (P). See text for explanation and Appendix for equations.

shear, axial stiffness tests. Further, we chose to utilize whole-bone sections for the mechanical tests, in contrast to the machined specimens of defined geometric shape, again to reflect more closely the *in vivo* situation.

Our study was designed to provide a quantitative relationship between the amount of cement penetration into the cancellous bone, and the stiffness of the bone-cement composite so produced. When combined with our previous work (Panjabi et al. 1983), in which we determined the relationship between the cement penetration and the cement intrusion pressure, the study provides a set of relationships between the cement injection pressure, the cement penetration, and the resulting bone-cement composite axial and bending stiffness values. Therefore, it now seems possible to either predict the stiffness of the bone-cement for a given intrusion pressure or to determine the necessary intrusion pressure to obtain a certain bending or axial stiffness value for a mechanically optimum bone-cement interface. The results of our study, however, must be taken together with their limitation. A canine femur is quite different from that of the human; moreover, our study did not include the effects of muscle loads, long-term fatigue, and biomechanical adaptation.

In that the specimens were sections of whole femurs with variation in size and geometry, the correlation between the bending stiffness and cement penetration (R = 0.6) was respectable. The linear relationship implies that the curve becomes discontinuous at 100 per cent penetration. Since the upper limits of the curve were not well explored, the true behavior of the curve as the penetration approaches 100 per cent is not well described. At the other extreme of the curve, the bending stiffness at zero penetration was 197 Nmm/degree. The positive stiffness intercept represents the stiffness of the cancellous bone alone. The calculation, using this stiffness value, yields Young's Modulus of 13 MPa. Although the lower end of the curve was better described as compared to the upper end, with several low penetration specimens being tested, the lowest penetration, however, was 22 per cent. This extrapolation may account for a 30 per cent discrepancy between our modulus value and that of the cancellous bone alone reported by Carter et al. (1977). In contrast to the bending stiffness tests, the axial compression testing (sometimes also referred to as the shear test, because of the stresses generated at the interface) has been utilized by several researchers (Greenwald & Wilde 1974, Halawa et al. 1978). The correlation of axial stiffness with cement penetration was linear (R = 0.67) and highly significant. The axial stiffness at zero penetration was about 6.5 N/mm. This is equivalent to the shear stiffness of the cancellous bone alone. The shear modulus calculated from this value was about 14 MPa. Greenwald and Wilde (1974) reported the modulus of rigidity of human femoral sections to be 46 MPa. It should again be emphasized that this comparison is based on an extrapolation beyond our experimental data.

In a recent study, the effect of intrusion pressure on bone-cement composite was determined *in vitro* using methodology quite different from that of ours (Askew et al. 1984). Specimens were made from flat-faced cancellous bone sections penetrated by circular cylinders of PMMA under varying pressures. Tensile failure loads were used for testing. In spite of the major differences in the methodologies of the two studies, the results are in good agreement. Penetration, as well as strength, was found to have a nonlinear relationship to the intrusion pressure, first increasing at almost a constant rate and then reaching a plateau qualitatively similar to our Figures 2B and 3B. It is to be noted that in clinical simulations intrusion pressures of 0.3 MPa for low viscosity and 1.1 MPa for normal viscosity cements have been recorded (Drinker et al. 1981).

Acknowledgments

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Appendix

Linear regression of the data depicted in Fig. 2A, provides the expression relating bending stiffness (S_B) and cement penetration (P): (1) $S_B = 197.0 + (9.1 \times P)$, where S_B is in Nmm/deg and P is in percentage. The latter is defined in the body of the paper.

Relationship between cement penetration (P) and cement intrusion pressure (p) (Panjabi et al. 1983), and is as follows: (2) $P = 100/(K)$, where $K = \mathrm{EXP}\ (2.255 - 5.643 \times p)$.

Combining equations (1) and (2) results in a direct relationship between S_B and p, depicted in Fig. 2B: (3) $S_B = (1107.0 + 197.0 \times K)/(1 + K)$, where $K = \mathrm{EXP}\ (2.255 - 5.643 \times p)$.

The axial stiffness (S_A), which produces shear stress at the bone-cement interface, versus the cement penetration (P), is linear (Fig. 3A): (4) $S_A = 6.5 + 4.2 \times P$, where S_A is in N/mm.

Again combining this relationship with results of our previous study, Panjabi et al. (1983), we obtain a direct relationship between the axial stiffness (S_A) and the cement intrusion pressure (p) (Fig. 3B): (5) $S_A = (426.5 + 6.5 \times K)/(1 + K)$, where $K = \mathrm{EXP}\ (2.255 - 5.643 \times p)$.