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THE MODULUS OF ELASTICITY AND FLEXURAL STRENGTH OF SOME ACRYLIC BONE CEMENTS

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The modulus of elasticity and flexural strength were measured for three bone cements, CMW Bone Cement, Surgical Simplex, and Palacos R, with various additions and prepared as in actual use. A distinct afterpolymerization was demonstrated in all three brands. The addition of blood lowered the E-modulus whereas radio-opaque media seemed to render them somewhat stiffer. The rupture values demonstrated the inhomogeneity of the final product in all three brands. The possible clinical significance of the findings is discussed.

Key words: bone cement; E-modulus; flexural strength

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The use of polymethylmethacrylate as a means of fixation of total joint replacements has become an established procedure. The present study was intended as a contribution to the understanding of the nature of some of the bone cements available. A comparative study of variations in the modulus of elasticity and the flexural strength as a result of the addition of various substances was carried out as a preliminary analysis.

MATERIAL AND METHODS

In order to get an impression of the physical characteristics of the substance, as used in surgery, it was decided to use a preparation technique resembling as closely as possible that of actual use, i.e., manual mixing, stirring, and handling. Three brands of cement were tested: CMW Bone Cement®, Surgical Simplex®, and Palacos R®. All test samples were prepared from packages from the same production batch as indicated by the numbers on the packages. The cement was in each case mixed according to the instructions of the manufacturer described in the directions accompanying the packages. In each case a whole package of bone cement powder (40 g) and a vial of monomer of about 20 g were mixed. All additions of dry substance, i.e. $BaSO_4$, or gentamicin, were made to the powder and mixed well with this before adding the liquid monomer.

As it is not possible to measure the amount of blood added to cement during actual use in surgery it was chosen to investigate the effect of the addition of two quantities, 1 ml and 3 ml, of heparinized whole blood to the cement. The amount of blood was measured with a standard injection syringe; the blood was added to the cement as soon as the powder-monomer mixture had become liquid and was mixed into the cement by stirring. It was possible to mix the blood into the cement quite evenly without stirring more vigorously than usual.

After mixing, the cement was pressed manually into an open mould. The mould was closed and held together with clamps during polymerization in order to obtain complete filling of the mould. Each package yielded eight test samples measuring $4 \times 10 \times 110$ mm. After polymerization the test bodies were removed from the mould and excess cement was machined off so as to obtain the exact thickness of 4 mm. In order to minimize the risk of early rupture

originating from surface cracks during testing, the machining was done lengthwise on an automatic lathe.

The samples were then tested in bending, to rupture, in a Zwick Z 1–3D test rig. The samples were loaded centrally with a deformation speed of 6 mm per minute. The modulus of elasticity (Young's modulus), hereafter called E-modulus was determined from two readings on the ascending part of the curve obtained. The E-modulus was calculated from the readings using a nomogram constructed for the purpose according to the formula:

$$E = \frac{L^3}{4 \times bh^3} \times \frac{\triangle F}{\triangle Y} \text{ kp/cm}^2$$

(Weast 1968)

L = distance between supports.
b = width of sample.
h = height of sample.
$\triangle$ F = increase of blood.
$\triangle$ Y = deformation.

The samples were then further loaded until rupture and the flexural stress was read directly from the graphs obtained from the test rig. The flexural strength was calculated from the formula:

$$S_{max} = \frac{3}{2} \times \frac{F_{max} \times L}{b \times h^2}$$

F_{max} = stress at rupture.

The experiments were made at room temperature (22° C). However, E-modulus and flexural strength were also determined at 38° C for all three brands of cement. CMW and Simplex P were tested without any additions, but Palacos was only available as Palacos R ®, i.e., with Zirconiumdioxide as radio-opaque substance already added. CMW was tested with the addition of 2.5 and 5 g of barium sulphate as indicated by the manufacturer while Simplex was tested both pure and in the form of Surgical Simplex R, Radioopaque ® which also contains $BaSO_4$. Macroscopically the $BaSO_4$ was difficult to distribute evenly in the CMW. There was a tendency for small clumps of the substance to stick together and they were visible on the surface of the test samples. All brands of cement were tested with gentamicin added, as this antibiotic might have clinical relevance as a cement additive. In the case of Palacos the ready-mixed preparation of Refobacin-Palacos R ® was used. A further package of each brand was prepared and tested after the gentamicin had been washed out at body temperature in human plasma as indicated by Holm & Vejlsgaard (1976). Also the three types of cement were tested for possible changes of values due to afterpolymerization. Samples were tested 8 h after mixing and others at 24 h and 1 week after initial polymerization. All other samples were stored for at least 3 weeks at room temperature to eliminate any effect of afterpolymerization on the results. A total of 376 tests were made.

RESULTS

E-modulus

The measured values were treated statistically by parametric variance analysis and the Student-Newman-Keul procedure. These analyses showed for all types of cement that the variation between the eight determinations of E-modulus obtained from each portion of cement was significantly smaller than the variation between the portions of cement prepared in different ways ($P < 0.01$). The standard deviations of the eight measurements per package were for CMW 1.54, for Simplex P 1.16, and for Palacos R 1.15. Standard deviations between different portions of cement were two to four times larger.

The values of the E-moduli in each type of cement fell into 3–5 groups that were significantly different whereas the values within each group did not differ significantly from each other. In the case of CMW the groups were not sharply delineated statistically speaking, but overlapped somewhat. This means that for some factors significant differences cannot be demonstrated with certainty; however indicative tendencies were found. Where percentages are given in the following they are only to be taken as approximations. Mean values are given in Table 1.

For CMW the E-modulus calculated from the results for the portions of cement without additions was found to be 26,000 kp/cm²; Simplex P showed a value of 24,600 kp/cm², and Palacos R (Zirconium dioxide added) was found to have an E-modulus of 23,900 kp/cm².

The E-modulus showed a statistically significant increase for all three brands during the first week after polymerization as indicated by the values obtained at 8 hours, 24 hours, and 1 week after initial polymerization. The increase amounted to 5 per cent for Simplex, 7 per cent for CMW, and 8 per cent for Palacos.

Table 1. Modulus of elasticity; mean values of eight determinations per package of cement ($n \times 10^3$ kp/cm^2).

Addition	CMW	Simplex	Palacos R
None, 8 h	24.4	23.8	22.2
None, 24 h	25.9	24.2	23.8
None, 7 days	26.5	25.3	24.4
None, 3 weeks	26.7	24.1	24.4
do	25.3	24.4	23.1
$BaSO_4$, 2.5 g	28.0	25.1	
do	27.0	26.7	
do	27.4		
do	29.8		
$BaSO_4$, 5.0 g	26.3		
do	25.6		
Gentamicin, 1.0 g	26.9		
do	25.5		
Gentamicin, 0.5 g		22.5	23.9
do			23.9
Blood, 1 ml	21.8	25.6	25.3
do	23.9	26.7	24.3
Blood, 3 ml	20.1	24.1	23.3
do	20.8		23.2
Gentamicin eluted	23.0	23.6	23.3
None, 38° C	26.9	24.7	22.5

Adding 2.5 g $BaSO_4$ to one portion of CMW increased the E-modulus in all tests though only one test showed values that were with certainty statistically increased (about 10 per cent). The radiopaque Simplex also showed a tendency towards greater stiffness than the pure preparation, but only one determination was significantly increased (8 per cent).

Adding blood to CMW decreased the E-modulus; 1 ml of blood caused a decrease of about 12 per cent. This change was further augmented by adding 3 ml per portion, a decrease of 21 per cent giving the lowest value recorded in the series. In the case of Simplex, the results were somewhat different, showing a slight increase in the E-modulus after addition of 1 ml of blood, but the values are only statistically significant in one case. Adding 3 ml of blood again gave lower values. In the case of Palacos R the results of adding 1 and 3 ml of blood fell into separate statistical groups, the smaller amount of blood showing no change of E-modulus whereas the larger amount decreased the E-modulus by about 3 per cent which is statistically significant.

Adding a soluble substance such as gentamicin sulphate to CMW in an amount of 1 g per portion of cement tended to decrease the E-modulus a little, though the values are not statistically significant, but when the antibiotic had been washed out the E-modulus decreased about 11 per cent, this figure being statistically significant. Surgical Simplex showed a similar pattern with a decrease in E-modulus of about 8 per cent in spite of the fact that only 0.5 g of gentamicin was added in this case. Refobacin-Palacos R showed values 5 to 6 per cent lower than Palacos R. The elution of the gentamicin from Simplex and Refobacin-Palacos R did not result in any further significant decrease of E-modulus.

The increase of ambient temperature to 38° C gave slightly lower values, but only in the case of Palacos R was the difference statistically significant, about 6 per cent.

Flexural strength

The values of flexural strength, i.e., the maximum stress at rupture of the test sample (expressed in kp/cm^2), were widely scattered. Standard deviations within the groups of eight samples originating from the same portion of cement varied from 4.1 per cent to 10.6 per cent.

Table 2. Flexural strength (stress at rupture). Mean values of eight determinations per package of cement, kp/cm². Figures in brackets indicate the minimum value of each series. Where a time factor is not indicated there was a time lapse of a minimum of 3 weeks between polymerization and test.

Addition	CMW	Simplex	Palacos R
None, 8 h	573 (448)	520 (365)	614 (504)
None, 7 days	678 (562)	547 (381)	601 (558)
None, 3 weeks	612 (500)	564 (503)	488 (454)
do	593 (554)	702 (432)	684 (606)
$BaSO_4$, 2.5 g	599 (409)	503 (299)	
do	544 (395)	577 (386)	
do	594 (396)		
do	592 (430)		
$BaSO_4$, 5.0 g	565 (408)		
do	495 (318)		
do	513 (425)		
Gentamicin, 1.0 g	600 (394)		
do	671 (616)		
Gentamicin, 0.5 g		533 (458)	607 (486)
do			647 (498)
Blood, 1 ml	691 (476)	640 (537)	636 (600)
do	700 (540)	659 (601)	719 (604)
Blood, 3 ml	423 (268)	595 (482)	561 (419)
do	519 (337)		644 (516)
Gentamicin, eluted	650 (587)	476 (395)	571 (528)
None, 38° C	673 (550)	381 (259)	506 (420)

When standard deviations of several portions prepared in the same manner were compared, deviations of as much as 17 to 20 per cent were found. Macroscopic examination of the test samples after rupture showed that in some cases breaking had not taken place in the middle of the sample, i.e., in the area of maximum deformation, but somewhere off to the sides. Occasionally a sample might shatter into three or four fragments indicating high and unevenly distributed intrinsic stresses in the sample. Examination of the rupture surface often revealed extra large air bubbles, grains of radioopaque material or other obvious reasons for local weakening. For this reason only mean and minimum values of flexural strength are indicated in Table 2 in order to demonstrate the order of magnitude of the limiting factor in the load sustaining capacity of the cements.

DISCUSSION

It has been more or less assumed that methylmethacrylate bone cements are rather well defined substances, but differences in handling characteristics seem to indicate that there might be quite substantial differences in mechanical properties depending on the manufacturer and the various additives. Since Charnley did the pioneering work on bone cements in the sixties and published his monograph describing some of the physical properties of CMW bone cement (Charnley 1970), several other investigators have evaluated the physical and chemical aspects of methylmethacrylate cement from a surgical point of view. Methylmethacrylate as used industrially is in each case a rather uniform product, usually heat polymerized and machine mixed. This is not so in surgery. Bone cement consists of polymethylmethacrylate powder plus a liquid consisting of methylmethacrylate monomer. The pow-

der contains an initiator, usually benzoyl peroxide and $BaSO_4$ or ZrO_2 as radio-opacifier and may contain copolymers such as styrene or butylmethacrylate to improve handling (Lautenschlager et al. 1974). The monomer contains a catalyst, mostly tertiary amines, and a stabilizer such as hydroquinone. The cement is mixed manually with a spoon or spatula in a bowl, and polymerization depends on an even distribution in the mixture of catalyst and oxidizer. A varying amount of air is added during the process yielding a very heterogenous substance which is further kneaded, folded and mixed with blood during application. It is not surprising that one often notices that the cement still may be soft in places while other parts have already become hard as an indication of uneven polymerization. This study was aimed at illustrating the variations in physical properties as encountered in surgery and this is the reason why the cement was handled as it is in actual use.

The first question raised by this investigation is the difference between the E-modulus of Palacos R found in the present results and that indicated by the manufacturer in the brochure included in the cement package (15,500 kp/cm^2). The values found in the present investigation correspond well with those of other brands of polymethylmethacrylate investigated and are of the same order of magnitude as values commonly indicated for other commercially available acrylics. However, the values indicated by Buchholz & Engelbrecht (1970) correspond well with the values of the manufacturer. Personal correspondence with the manufacturer (Kulzer & Co.) has given no answer to the question.

An increase in the E-modulus occurred during the first week. This must be interpreted as the effect of afterpolymerization and is caused by an increase in length of the molecular chains and possibly also the polymerization of about 3 per cent of the monomer not polymerized immediately (Haas et al. 1975, Feith 1975, Charnley 1970). With CMW the addition of radio-opacifier is done by stirring the $BaSO_4$ powder into the cement powder. It seemed difficult to distribute the $BaSO_4$ evenly in this way and there was a tendency for small clumps of the substance to stick together. These were visible as little white specks on the surface of the samples. This was not the case with the two other brands where the cement and the radio-opacifier are mixed by the manufacturer. The reduction of E-modulus in CMW mixed with 5 g of $BaSO_4$ cannot be explained with certainty, but it is possible that with increasing amounts of $BaSO_4$ this substance begins to act as a filler and causes a decrease in the amount of acrylic present in the cross section of the test sample.

It is a common experience that cement hardens more quickly when mixed with blood, but the results show a smaller value for the E-modulus which must indicate a lesser degree of polymerization. This could be due to interaction of blood enzymes (catalase?) with the peroxides of the cement, breaking these down so fast that the necessary free radicals to complete polymerization are no longer available. The decrease in E-modulus after the washing out of gentamicin of the cement is in accordance with Grünert & Ritter (1974), who found a change in E-modulus of about 8 per cent, whereas Buchholz & Engelbrecht (1970) found no change in their investigation. However their values are as low as 16,500 kp/cm^2. As regards temperature sensitivity, the slight decrease of the E-modulus at 38° C is to be expected with a thermoplastic substance like polymethylmethacrylate.

The importance of using acrylic cement as a means of fixation in total joint replacement lies in the function of the cement as a filler between bone and prosthesis thereby distributing load and stresses more evenly over the entire con-

tact area. This greatly increases the stability of the prosthesis (Charnley 1965).

During activity when a prosthesis is put under stress an elastic deformation of all components involved takes place at each step. The magnitude of this deformation is dependent on the E-modulus of the substance involved—the smaller the E-modulus the greater the deformation. It is therefore obvious that when two substances of different E-moduli in contact with each other are put under stress in a direction parallel to their common surface, as is the case with cement in contact with bone on one side and the femoral prosthesis on the other, movement will take place between them because one substance will show greater deformation than the other. The phenomenon is called "fretting" and has been described by Charnley (1965) in relation to the anchoring of the femoral stem of the total hip replacement. Charnley considers the cement to be an integral part of the prosthesis. This cannot be entirely true as the cement and the metal of the prosthesis have greatly different E-moduli. As blood and soluble and insoluble additions to the cement may be unevenly distributed throughout the cement the substance will show varying elastic deformations throughout its volume thereby putting greater stress on stiffer areas. The results of the breaking tests where the samples in some cases shattered show that uneven polymerization may give rise to intrinsic stresses in the cement, and such pre-stressed areas further complicate the pattern of stress and deformation throughout the cement. The inclusion of air bubbles and "vacuoles" from dissolved substances will form critical points of weakness from which cracks in the cement may originate. It is thus not uncommon to find fractures of the cement in cases of prosthetic loosening in the absence of infection. Charnley reports such a case in his monograph of 1970. An increased risk of mechanical failure might for the same reasons be encountered in the cement protrusions that interlock with the bony trabecula causing microfractures of either bone or cement and hence loosening.

The most important conclusion must however be that the mixing and the method of application of the cement is the most important factor as regards the strength of the final product. In spite of the fact that careful preparation of all cement was carried out according to the instructions of the manufacturer the end result was extremely inhomogenous and demonstrated how different even portions of the same manufacturing batch may turn out in actual use. The very large standard deviations of the breaking tests with considerable variation even within the same portion of cement underline the problems. It is therefore concluded that careful stirring and mixing of ingredients is important if ready-mixed preparations are not used. It must be considered of importance to have as dry an operating field as can be obtained so as to avoid the decrease in E-modulus resulting from the addition of blood. The use of a cement syringe as advocated by Slooff (1973) would seem a reasonable procedure in order to obtain as homogeneous a cement as possible.

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