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Strength of polymethylmethacrylate increased by vacuum mixing

The mechanical strength of high and low viscosity gentamicin-containing cement was analysed using three different mixing procedures: hand, vibration, and vacuum stirring.
Vacuum mixing improved the flexural and compression strength and the modulus of elasticity by 15–30 per cent, especially for high viscosity cement.

Lars Lidgren
Hassan Drar[1]
Jörgen Möller[1]

University Department of Orthopaedics in Lund,
S-221 85 Lund, Sweden and
[1]Institute for Solid Mechanics in Lund, Sweden

Polymethylmethacrylate (PMMA) strength can be changed by different handling techniques. Rapid stirring by hand will increase the amount of air introduced, resulting in an expansion of the bone cement but a reduction of the mechanical strength. Insertion of the cement stepwise, intermingling with blood, etc. will also substantially decrease the mechanical strength, by 10–20 per cent (Ling 1980). Temperature and humidity will mainly affect the setting characteristics (Krug et al. 1981).

The prosthetic survival will to a large extent depend on the positioning of the prosthesis and, if cement is used, on adequate filling with cement. A stable and lasting fixation with close bone cement contact would reduce movement between the prosthetic compound (prosthesis and cement) and bone and prevent eventual loosening. If the mechanical strength of PMMA could be increased by changing the mixing procedure, the long-term survival of cemented joint prostheses could probably be improved.

The aim of the following study was to analyse three different mixing procedures: hand, vibration and vacuum stirring, with special reference to mechanical strength.

Material and methods

Three different mixing procedures were tested: hand, vibration and vacuum stirring. The temperature in the laboratory was kept at 22°C. The mixing time was 60 s with about 80 stirrings.

Mixing by *hand* was performed in a bowl with a spatula, both of polypropylene.

For mixing by *vibration*, a stainless steel bowl was placed on a vibrating plate (50 vibrations s^{-1}). Stirring was performed with a polypropylene spatula.

For mixing by *vacuum*, 0.2 bar absolute pressure was applied. Stirring was carried out by hand through the top of a stainless steel bowl, with a polypropylene spatula.

The monomer was poured into the bowl and the PMMA powder added. Two types of cement were tested: low viscosity cement (not registered, EMD 42522) and high viscosity cement Palacos cum gentamicin (Refobacin-Palacos) (both types of cement were supplied by Merck, Darmstadt, West Germany) The cements were equal apart from the relation of polymer to monomer, and the diffusion of gentamicin which was less for EMD 42522 than for Refobacin-Palacos. The amount of gentamicin was 1.0 g base/40 g polymer powder in EMD 42522 and 0.5 g/40 g in Refobacin-Palacos.

A cartridge was filled with the cement and a cement gun was used to pressurize the cement into a hollow oak bar (12 × 12 × 120 mm^3). The bar was plugged distally.

The cement was allowed to harden at room temperature (20–25°C) for 48 h before testing.

Testing procedures

The flexural properties were tested by two methods: the three- and four-point bending tests. In the former, a cement bar with a rectangular sectional cross area was tested in bending, while resting on two supports with a loading nose midway between the supports. In the second method the cement bar was loaded at two points, which were equidistant from the adjacent supports.

Table 1. Number of PMMA specimens that did not fail at the line or at the area of maximum stress (rejected), average specimen thickness and rate of strain.

Cement type/ test type	Mixing procedure	Rejected specimens/ total number	Average thickness mean ± SD (mm)	Rate of strain (10^{-2} × mm/mm min)
EMD 42522/3-point	Hand	1/6	10.4 ± 0.75	1.25
	Vibration	0/5	10.4 ± 0.27	1.24
	Vacuum	0/5	10.5 ± 0.76	1.26
Refobacin-Palacos/ 3-point	Hand	1/6	11.3 ± 0.25	1.36
	Vibration	0/5	11.3 ± 0.43	1.35
	Vacuum	1/6	10.8 ± 0.50	1.30
Refobacin-Palacos/ 4-point	Hand	1/6	11.3 ± 0.29	1.07
	Vibration	2/5	11.3 ± 0.31	1.08
	Vacuum	1/5	11.0 ± 0.42	1.05

The bar was deflected until rupture occurred, using the Instron mechanical testing device (model TT-D). The applied load and the beam deflection were measured simultaneously. The deflection was measured by the motion of the loading nose relative to the supports. The basic difference between the two methods was in the location of the maximum bending moment and maximum axial fibre stresses. The maximum axial fibre stresses occurred on a line under the loading nose in method one and over the area between the loading noses in method two. Specimens with large voids which did not fail at the line or area of maximum stress were rejected (Table 1).

The rate of crosshead motion of the machine was constant for all specimens (2 mm/min). However, due to the variation in the specimens (4 per cent at the most), a difference in the rate of straining of the outer fibre was obtained. The rate of strain (Z, see appendix) was calculated according to ASTM D790 (Annual Book of ASTM Standards 1980).

The load-deflection data were used to calculate the maximum flexural strength (S) and the maximum strain (ε) in the outer fibres of the specimens of different mixing procedures, according to ASTM D790.

The maximum deflection at rupture (D) was mea-

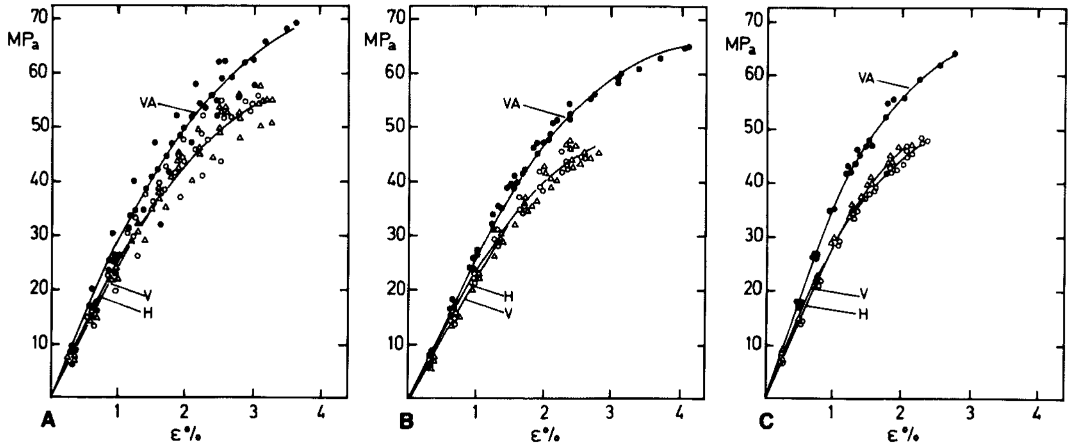

Figure 1. Maximum flexural strength in the outer fiber of the specimens of different mixing procedures against the maximum strain in the same fiber.

	Type of cement	Bending test
A	EMD 42522	3-point
B	Refobacin-Palacos	3-point
C	Refobacin-Palacos	4-point

Mixing by hand (H), vibration (V) and vacuum (VA).

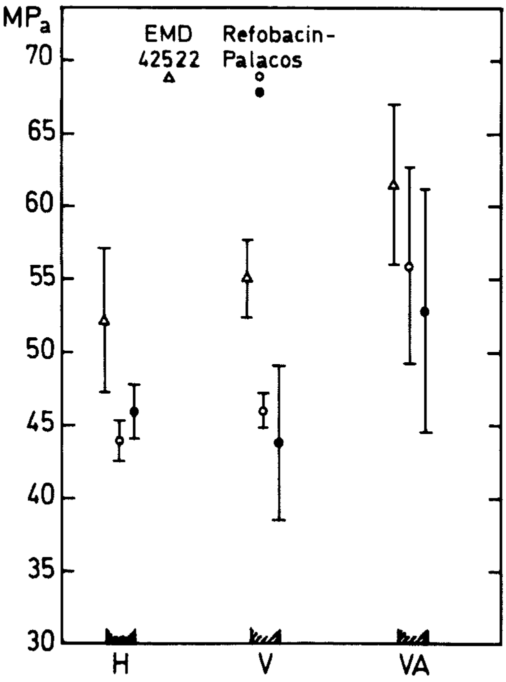

Figure 2. The flexural strength (S) of the specimens of EMD 42522 and Refobacin-Palacos cements.
Symbols △ and ○ for 3-point test and ● for the 4-point bending test. Mixing by hand (H), vibration (V) and vacuum (VA). Mean ±SD.

sured for all specimens. The same data were also used to determine the tangent modulus of elasticity in bending (E_B).

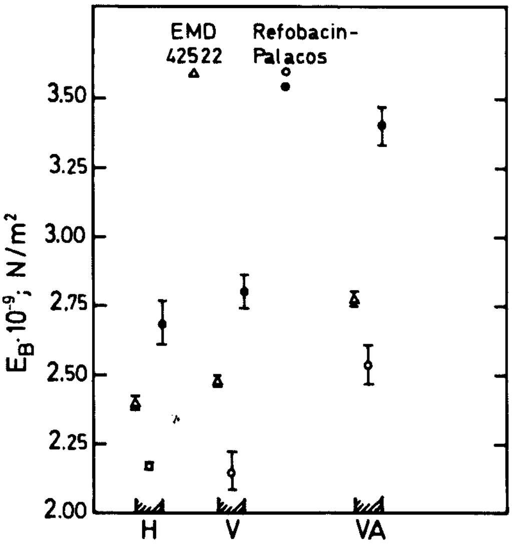

Figure 4. The tangent modulus of elasticity in bending (E_B). The same symbols as in Figure 2.

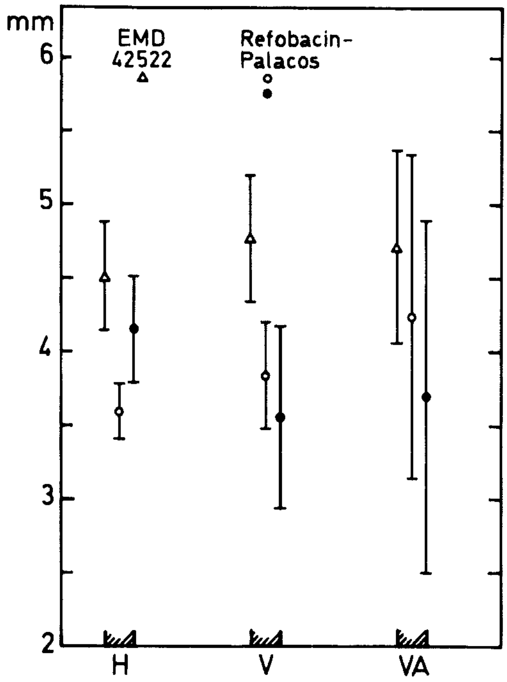

Figure 3. The maximum deflection (D) of the outer fibers of the specimens at the moment of rupture. The same symbols as in Figure 2.

The hardness according to the Rockwell L scale (HRL) of at least three bars of each mixing procedure was measured at random on a surface approximately 5 mm from the outer fibre of the bars.

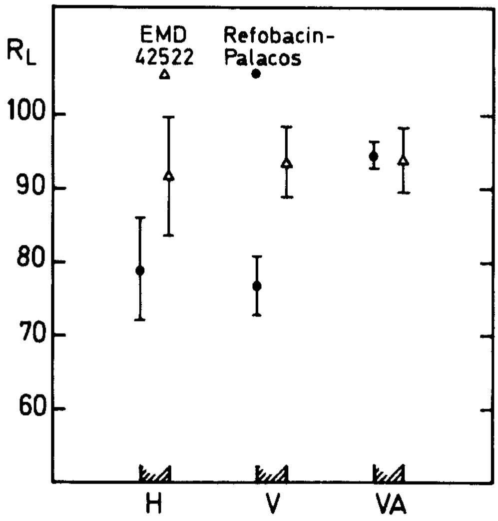

Figure 5. The hardness of the investigated cements according to the Rockwell L scale. The same symbols as in Figure 2.

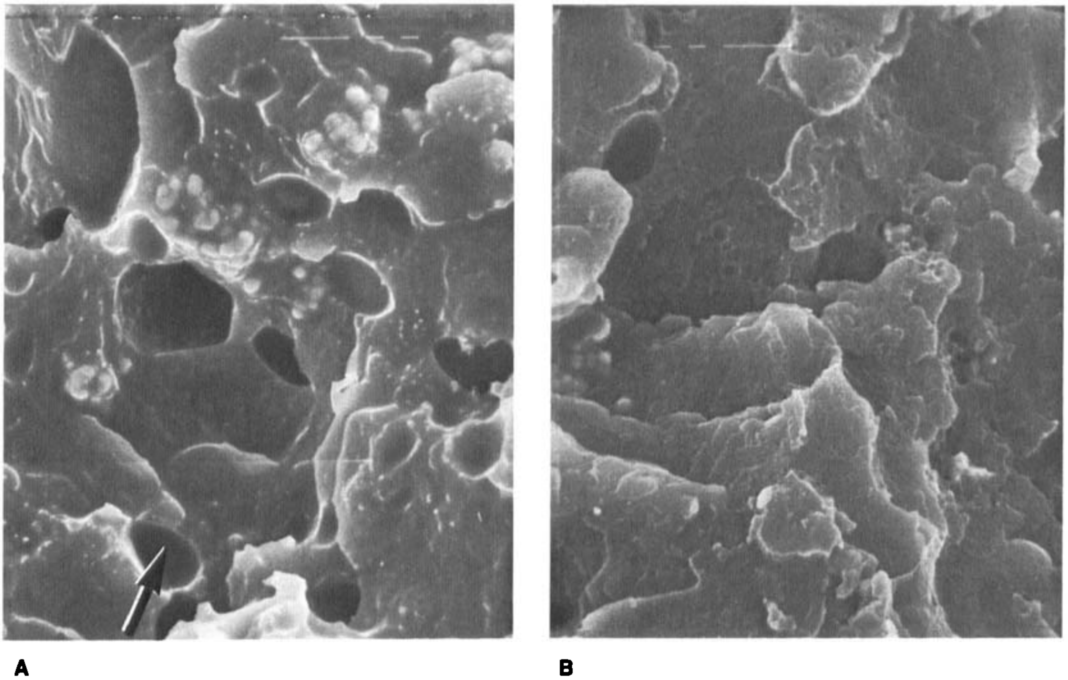

Figure 6. SEM showing large air voids (arrow) in hand mixing (A) compared to vacuum mixing (B). (×1 000).

Each specimen was examined for large voids or inhomogeneities. Scanning electron microscopy (SEM) was used to illustrate variations in porosity related to handling methods.

Results

Table 2 shows that for a given cement and test type, the rate of strain for the specimens produced by the three mixing procedures tested was approximately constant.

In Figure 1 the maximum flexural stress and the maximum strain in the outer fibre of each specimen are plotted from the start of the bending test to the moment of rupture. All the data belonging to one mixing procedure and to one type of cement were plotted on a separate sheet and a curve was drawn by hand. The data and the curves of all mixing procedures for each cement were then superimposed for comparison.

The flexural strength (S), maximum deflection (D) and tangent modulus of elasticity (E_B) are given as means with standard deviations (Figures 2–4). The results show that the flexural strength, the maximum deflection and the modulus of elasticity were especially increased with the vacuum mixing technique, by 15–30 per cent compared to hand mixing.

The hardness according to the Rockwell L scale for each mixing procedure is shown in Figure 5. The hardness (compressive strength) of the inner surface chosen at random was improved mainly by vacuum mixing.

SEM investigations at magnification ×100 and ×1 000 (Figure 6) showed a greater number of air voids in the cement with hand mixing than with vacuum mixing.

Discussion

PMMA has been used in prosthetic surgery for more than 30 years (Kiaer 1951, Habousch 1953) but gained international recognition through Charnley's publications (Charnley 1970). From the beginning, the cement was introduced into bone cavities by finger pressure. However, several reports on pressurization of cement have shown improved fixation (Halawa et al. 1978, Miller et al. 1979), suggesting a longer prosthetic survival, and low viscosity cements have been introduced for better cement penetration with this new technique (Miller et al. 1979). Practical handling of low viscosity cement causes some difficulties, especially in the acetabulum (Ling 1980). Hierton et al. (1983) reported that the use of low viscosity cement was positively correlated to loosening of the femoral component if conventional cementing was performed without pressurization. Only long-term controlled clinical studies will determine whether low viscosity cement is an improvement on high viscosity cement when using the same technique of prosthetic insertion and cementing.

When it sets, the cement shrinks onto the prosthesis and away from the surrounding bone. If this process is hindered, cement stress will occur but relaxation will take place mainly during the first months (Holm 1980 ab, Schreyer 1972). Volume changes, i.e. PMMA thermal expansion and contraction and porosity-related air expansion, have been thoroughly described by Debrunner et al. (1976).

The heat generated by the cement on setting will probably be reduced below the coagulation temperature of living bone by bleeding and heat absorption to metal, especially for the femoral component (Masaru et al. 1974, Ohnsorge 1971. However, thermal necrosis and thus fixation vary significantly in relation to the amount of cement used, the anatomic location and the type of prosthesis.

The shear strength has not been analysed in this study; Charnley emphasized in his monograph (1970) that mechanical strength, i.e. compressive strength, is the most important cement factor. Flexural strength would, however, also correlate well to the loading environment *in vivo* (Bargar et al. 1983).

In this study two types of PMMA have been analysed. The flexural and compressive strengths were higher with low viscosity cement for all types of handling (Figures 1–5). Rapid stirring by hand introduces much air into the cement and increases expansion but decreases mechanical strength (Debrunner et al. 1976). It was shown that if the amount of air could be reduced by applying a vacuum during mixing, the flexural and compressive strengths and the modulus of elasticity would be increased, especially for high viscosity cement. Vibration mixing improved the mechanical properties of both cement types only slightly.

The reduction of porosity by vacuum stirring was clearly illustrated by the SEM investigation (Figure 6 A, B). The pores in the cement are caused not only by air inclusion but also by monomer evaporation, which forms small cavities during setting (Debrunner et al. 1976). As porosity was decreased and the mechanical strength slightly increased by vibration, but mostly by vacuum stirring (15–30 per cent), the effect must have been due to a reduction of the air inclusions. The low viscosity cement was more easily mixed, which could account for there being less air in the cement and could to some extent explain the better strength regardless of the handling method. A relatively small overpressure has been reported to give better strength and a clearer, more transparent cement (Debrunner et al. 1976, Lee et al. 1977, Ling 1980). If pressurization is used during insertion of the prosthesis, this would mainly reduce monomer porosity.

Commercial acrylics, such as Plexiglas®, change by creeping about 1 per cent per year (Holm 1980b). Increased humidity and higher temperature will speed this process. If the initial mechanical cement properties can be improved, prosthetic failures may be postponed.

Acknowledgements

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Appendix

List of the equations and symbols used:

For the 3-point bending test:

$Z = 6Rd/L^2$

$S = 3\ PL/2\ bd^2$

$\varepsilon = 6\ Dd/L^2$

$E_B = L^3m/4\ bd^3$

For the 4-point bending test:

$Z = 4.76\ Rd/L^2$

$S = PL/bd^2$

$\varepsilon = 4.7\ Dd/L^2$

$E_B = 0.21\ L^3m/bd^3$

Z = rate of strain of the outer fiber.
R = rate of crosshead motion.
d = depth of beam tested.
L = support span.
S = stress in the outer fiber at midspan (method one) or throughout load span (method two); M Pa (N/mm^2).
P = load at a given point on the load deflection curve.
b = width of beam tested.
ε = maximum strain in the outer fibers.
D = maximum deflection of the beam tested.
E_B = tangent modulus of elasticity in bending.
m = slope of the tangent to the initial straight-line portion of the load-deflection curve.