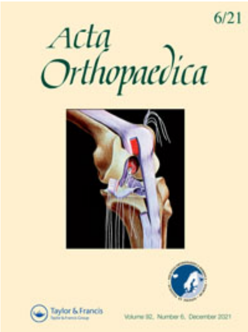

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The dynamic volume changes of polymerising polymethyl methacrylate bone cement

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ABSTRACT – The Swedish hip register found an increased risk of early revision of vacuum-mixed cemented total hip replacements. The influence of cement mixing technique on the dynamic volume change in polymerising PMMA is not well understood and may be relevant to this observation.

Applying Archimedes' principle, we have investigated the dynamic volume changes in polymerising cement and determined the influence of mixing technique. All specimens showed an overall volume reduction: hand-mixed 3.4% and vacuum-mixed 6.0%. Regression analysis of sectional porosity and volume reduction showed a highly significant relationship.

Hand-mixed porous cement showed a transient volume increase before solidification. However, vacuum-mixed cement showed a progressive volume reduction throughout polymerisation.

Transient expansion of porous cement occurs at the critical time of micro-interlock formation, possibly improving fixation. Conversely, progressive volume reduction of vacuum-mixed cement throughout the formation of interlock may damage fixation. Stable fixation of vacuum-mixed cement may depend on additional techniques to offset the altered volumetric behaviour of vacuum-mixed cement.

The importance of the cement interfaces was appreciated early in the evolution of modern cemented total hip arthroplasty. Cement-bone micro-interlock of more than 3 mm is considered essential to achieve stable cement mantle fixation (Krause et al. 1982, Macdonald et al. 1993). Attempts to improve micro-interlock using techniques such as endosteal preparation, retrograde cement insertion and cement pressurisation improve implant survival (Malchau et al. 1994).

In vitro studies clearly show a relationship between cement mantle voids and fatigue fracture (Topoleski et al. 1990, James et al. 1992). Unfortunately, void reduction techniques have had a limited impact on implant survival. The Swedish hip register found an increased risk of early revision of vacuum-mixed cement-inserted prostheses. The increased risk of revision persisted for 3 years, thereafter an improvement in the survival rate was observed. The proposed explanation was technical inexperience with a new mixing system (Malchau et al. 1994).

Theoretical calculations predict that the molecular rearrangement occurring during polymerisation will produce a volumetric shrinkage of 7.6% (Haas et al. 1975). Lower observed shrinkage of porous cement is explained by void growth during polymerisation. Void elimination by vacuum mixing increases cement shrinkage, possibly compromising the mantle interfaces. The dynamic volumetric behaviour of polymerising PMMA cement may explain the apparent poor clinical performance of vacuum mixing techniques.

Methods

We employed Archimedes' water displacement theory to calculate the relative density of cement specimens. An apparatus was designed that would permit measurement of the weight of a suspended mass of cement in water (Figure 1). Polyethylene

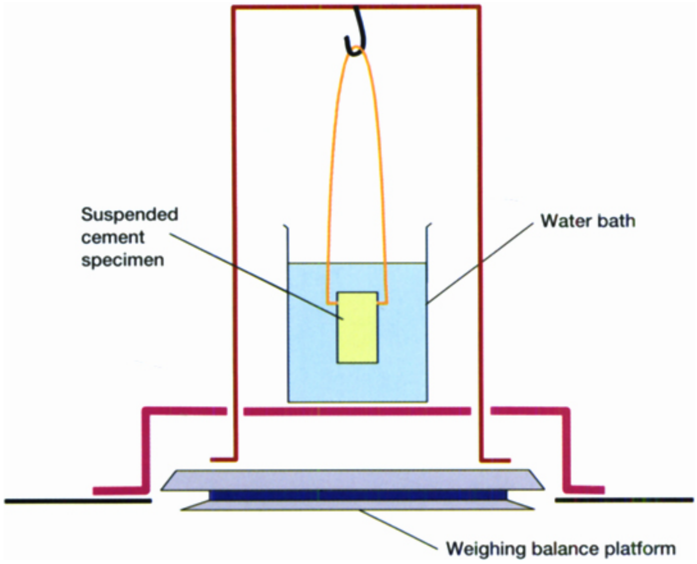

Figure 1. Apparatus used in experiment.

tubes of 19 mm in diameter, closed inferiorly, were modified by placing three longitudinal slits extending 75% of the length of the tube to allow radial expansion/contraction. The initial dry and submerged weights of the tube were measured, the tube was then filled with cement, and suspended in the water bath. Hand- and vacuum-mixed CMW1 (Depuy, Blackpool UK) cement was blended using the recommended timings, but was rapidly transferred to the tube as soon as mixing was complete, in order to detect any early changes in volume.

The first recording occurred approximately 1 minute after the start of mixing. Sequential weight measurements were made at 1-minute intervals until no further change in weight was recorded (30 mins). The specimen was then thoroughly dried and weighed again.

6 hand-mixed and 6 vacuum-mixed specimens were made. The specimens were then sectioned (Beuhler-Krautkramer, Isomet 2000) into 6 3 mm disks and each surface was stained with acrylic dye and examined using image analysis (Beuhler-Krautkramer, Omnimet 3) to assess porosity.

Calculations

The dry weight of the cement specimen is known (W_{dry}). The submerged weight of the cement ($W_{immersed}$) in water varies with the volume of the specimen. From this one can calculate the relative volume of the specimen using:

$$\frac{v_t}{v_o} = \frac{W_{dry} - W_{immersed\,(t)}}{W_{dry} - W_{immersed\,(0)}}$$

v_t = volume at time t
v_o = volume at time 0
$W_{immersed(t)}$ = weight immersed at time t
$W_{immersed(0)}$ = weight immersed at time 0

The derivation of this equation is based on the density of the immersion fluid remaining constant. A volume of water sufficiently large was used that could absorb the liberated thermal energy of cement polymerisation without causing a significant change in temperature. Calculations based on the enthalpy of polymerising PMMA reveal that for the given volume of cement (~10 g), the liberated thermal energy will generate a maximum 0.7 °C temperature rise of 250 mL water. The effect of density change over this temperature range will be extremely small and can be neglected. Furthermore, as all samples had the same dimensions, any change in the density of water will be equal in all specimens.

Results

All hand-mixed specimens showed greater porosity than vacuum-mixed specimens. All vacuum-mixed specimens showed greater overall shrinkage than hand-mixed ones. In no specimen was it possible to show overall expansion (Table).

Porosity and associated volume change

Hand-mixed cement		Vacuum-mixed cement	
Porosity	Volume change	Porosity	Volume change
9.0	–2.9	0.25	–6.91
6.5	–3.59	1.19	–6.01
4.24	–3.7	3.47	–4.42
6.76	–3.28	1.43	–5.68
7.62	–2.92	0.16	–7.35
5.88	–4.2	1.22	–5.95
Mean 6.67	–3.43	1.28	–5.99

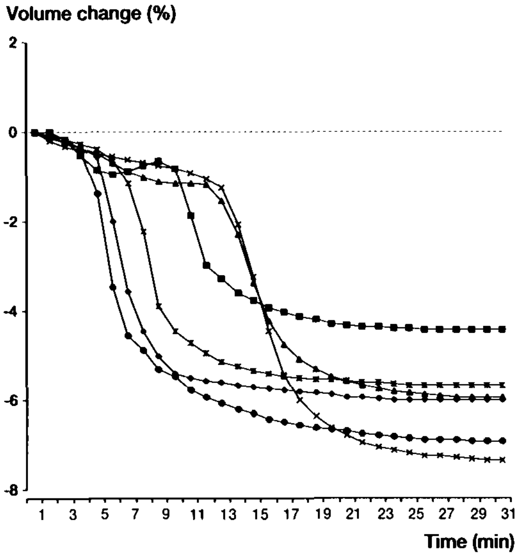

Figure 2. Volumetric profiles of vacuum-mixed cement.

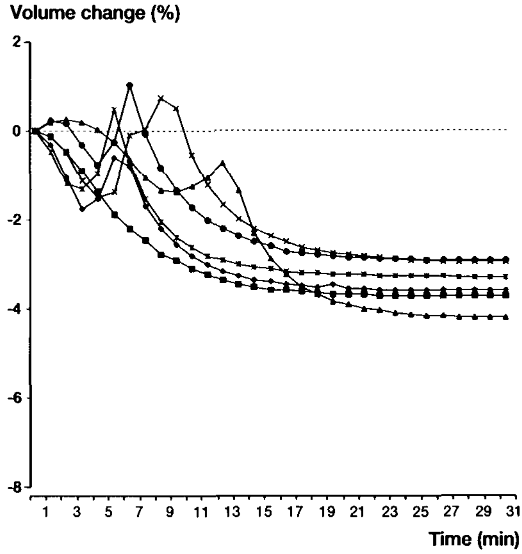

Figure 3. Volumetric profiles of hand-mixed cement.

The vacuum-mixed cement did not expand even during the period of rapid polymerisation (Figure 2). Although all hand-mixed specimens showed an overall net volume reduction, all samples demonstrated a tendency to expand immediately before solidification (Figure 3). In several samples a positive expansion was temporarily recorded. Linear regression analysis of porosity and contraction shows a highly significant relationship (Figure 4).

The vacuum-mixing system used (CMW vacumix plus) is designed to cause a 'moderate' reduction in porosity. If the technique is changed slightly by prevacuuming the powder and exercising care to avoid cement occlusion of the vacuum holes, cement of very low porosity will be obtained. The effectiveness of this technique varied. This accounts for the variability observed in porosity and contraction of vacuum-mixed specimens. Very low porosity cement (~ 0.1%) shows a volume reduction of approximately 6.7%.

We found a variable delay in the onset of maximum shrinkage (Figures 2 and 3). The rate of polymerisation depends on the ambient temperature, however, the ambient temperature throughout the experiments was 19.0 (18.2–21.3) °C. Furthermore, the specimens were polymerised in water of constant temperature. The delay observed in onset of polymerisation is frequently encountered clinically and appears unrelated to ambient conditions. This finding remains unexplained.

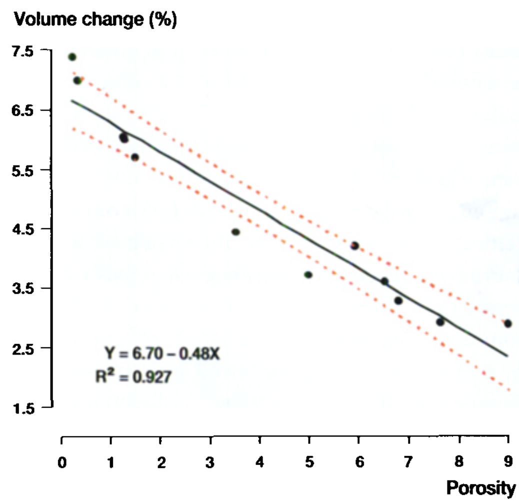

Figure 4. Regression plot of contraction versus porosity (black) + 95% Confidence Interval of line (red).

Discussion

A clear relationship exists between porosity and the biomechanical performance of the cement (Jasty et al. 1990). The performance of the implant-mantle construct depends on the intrinsic strength of the cement and the stability of the interfaces. While vacuum-mixing techniques improve the strength of the cement, the changes in the dynamic volumetric behaviour of the polymerising cement may have a detrimental effect on the interfaces. Gradual cement shrinkage may result in retraction from the bone interface or from the prosthesis interface or from both. Successful implementation of void reduction techniques may depend on additional efforts to lessen the impact of cement shrinkage on the interfaces.

The polymerisation process of PMMA cement can be divided into two periods: before and after solidification. During the time before solidification, cement has fluid-like properties which permit it to flow. Any change in volume will result in expansion or contraction of cement in all directions—true volumetric change. In a clinical perspective, this is the critical period of cementing technique and component insertion, during which stable implant fixation must be achieved.

Adequate cement-bone micro-interlock is essential to implant survival. Interlock is created by pressure-driven penetration of dough stage cement into the trabecular structure of cancellous bone. Transient expansion (0.63–2.34%) of porous cement during this crucial process would enhance interdigitation. Conversely, the progressive volume reduction of low porosity cement would impede interdigitation. Inadequate pressurisation of low porosity cement will therefore favour cement retraction from cancellous bone.

Progressive cement shrinkage may also result in retraction from the prosthesis cement interface compromising implant stability. Techniques such as component heating are known to reverse the direction of polymerisation possibly eliminating interface retraction, at the expense of increased retraction at the bone interface (Bishop et al. 1996).

Polymer manufacturing techniques are available to eliminate polymerisation-induced shrinkage by controlled void formation or by including low shrinkage polymer additives. Deliberate void growth techniques were not investigated because of concerns regarding detrimental effects on mechanical performance of highly porous cement. Attempts to change the cement formulation were also deliberately ignored to avoid the numerous pitfalls regarding changes in bone cement formulation, problems exemplified by Boneloc cement.

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