Rheological Characterization of Acrylic Bone Cements Used in Total Hip Replacement

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The paper presents the results of rheological tests for three commercial acrylic bone cements currently used in total hip replacement . Moreover, twelve experimental formulations of acrylic bone cements were realized, by partially replacing the methyl methacrylate (MMA) from the classical liquid monomer phase with a new monomer and their rheological properties were evaluated and compared with the commercial bone cements. Thus, the efficacy of acrylic bone cements as anchoring materials as well as their handling and curing properties were estimated. The new formulations exhibited higher elasticity, lower dynamic moduli and clear shear-thinning behavior proving to be potential replacements for classical acrylic based bone cements.

Keywords: structural stability, viscoelastic properties, rheological behavior, acrylic bone cements

The development of acrylic bone cements played a key role in the improvement of surgical techniques for joint replacement, making this type of intervention one of the most successful procedures in orthopedic surgery since firstly reported by Charnley [1]. The acrylic bone cements are the only biomaterials prepared in the operating room strictly before being used, allowing a more personalized treatment.

Together with the use of adequate surgical techniques and pre- and post-operatory treatment corresponding to the disease and the patient, the use of biomaterials adequate to the case, allows a faster recovery of the tissue and physiological function, decreasing patient inactivity period. The success of total hip arthroplasty as a treatment method in degenerative diseases of the hip lead to a pronounced increase in the demand for specific materials (prosthetics, cements, adhesives) and extended the indications for this type of procedure from elder to younger patients in need of hip prosthetics. Furthermore, the development of new cementing materials, like blends and polymeric composites, offered not only solutions for the improvement of fixing endoprosthetics, but also efficient therapeutic solutions In this regard, one example is offered by the decrease of infections caused by cemented endoprosthetics that can be attributed to the use of antibiotic loaded cements [2-7].

The diversity of biomaterials used in the preparation of implants and medical devices makes it difficult to select the optimal option that will ensure the highest chance for the success of the surgery. The use of bone cements allows a better distribution of the forces between the bone and the implant. Furthermore, if a new intervention is needed to revise the hip prosthesis, the ablation of the prosthetic material can be performed easier and with less damage.

The increasing use of biomaterials in orthopedic surgery imposes the evaluation of advantages and disadvantages that could rise from the use of implants and synthetic devices [8]. The lack of knowledge regarding the proprieties and purpose of the biomaterials used during surgical treatment makes their selection extremely difficult.

The present study was intended to establish and compare the rheological properties of three commercial acrylic bone cements with experimental formulations obtained by adding a new monomer in the liquid phase, immediately following the preparation. One of the main purposes was to estimate the influence of the newly added monomer on the shear-thinning behavior of samples as an indication of their injectability. The rheological properties allowed the estimation of the efficacy of acrylic bone cements as anchoring materials, as well as their handling and curing properties [9]. Important information regarding the ability of the cement dough to flow and penetrate the voids and irregularities in/between the bone and implant were also obtained. Moreover, it was observed that rheological properties may influence the porosity of the bone cements and, consequently, their fatigue performance, the loosening of prosthesis and ultimately patient wellbeing [10].

Experimental part

Materials and methods

Three commercial acrylic bone cements, i.e. Tecres Medical Advancing High Technology S.p.A., Verona, Italy, Depuy International Ltd., Blackpool, UK, Howmedica International Ltd., London, UK were rheologically tested. It is well-known that commercially available bone cements are two phase system based on polymethymethacrylate (PMMA). The powder phase of the bone cement contains mainly PMMA beads or beads of methyl methacrylate (MMA) containing copolymers, such as methyl methacrylate – styrene copolymer (MMA-co-St), as well as an inorganic radiopacifying agent (barium sulfate or zirconia), and small amounts of polymerization promoter (benzoyl peroxide (BPO)).The main component in the liquid phase is methyl methacrylate (MMA), but this phase also contains an accelerator of the polymerization reaction N,N-Dimethyl-*p*-toluidene (DMPT) and hydroquinone (Hy) to

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avoid premature polymerizatiom and to prolong *shelf-life.* The experimental cements used in this study were prepared based on commercial materials and a monomer, butyl acrylate (BuA), usually not found in the formulation of commercial cements. The powder of commercial bone cements was used as the solid phase, while MMA and BuA (Merck) were used after vacuum distillation as the liquid phase.

Cement preparation - Three series of samples (CS, CC, CP) with different compositions were prepared (table 1). The index 1 in each series stands for the commercial cement, the reference samples CC1, CP1 and CS1 being prepared using only the commercial formulation with no further physical or chemical treatment performed. The new experimental bone cements had as starting point a standard formulation for acrylic bone cements obtained by adding the MMA liquid phase to the solid phase (PMMA), in a typical solid/liquid ratio of 2:1. The polymeric powder from the commercial products was used as the solid phase of each cement from the CS, CC, CP series. For the new formulations, different amounts of MMA (the base monomer) have been partially replaced with the new BuA (co)monomer in 1:1 and 1:4 ratios. All formulations contain DMPT (activator) in the liquid phase and BPO (polymerization initiator) in the solid phase in the amounts given in table 1. All cements were prepared manually, following the same procedure, at 23°C ± 1°C, the temperature recommended by orthopedic cements manufacturers. Briefly, the polymer powder was placed in a glass crucible and the monomer/monomers was/were added in preset quantities to obtain the desired composition (table 1). The mixture was homogenized until the powder was completely wet. Homogenization duration varied from sample to sample, but it was always less than 50 seconds. Each sample was prepared just prior the rheological tests. After preparation, the samples were placed between the plates of the rheometer in order to evaluate their properties. The 100 s time represents the time elapsed between the beginning of cement mixing and the first readings on the rheometer and stands for the time allowed to the operator for sample preparation and handling.

The rheological measurements were performed on a Physica MCR 501 rheometer (Anton Paar, Austria) equipped with a Peltier system for the temperature control. All measurements were carried out in a stainless steel parallel-plate geometry with a diameter of 50 mm, and a gap of 2 mm. To avoid sample slippage, serrated plates were used [9, 11]. Two types of oscillatory rheological tests were performed: amplitude sweeps and frequency sweeps. The amplitude sweep was carried out keeping the oscillation frequency constant (ω= 10 s^{-1}) while the oscillation amplitude was varied between 0.001 and 1%. This test is mainly used to determine the limits of the viscoelastic region (LVR), indicating the maximum deformation tolerated by the sample before destroying the internal super-structure [11, 12], but, in our case, it also allowed useful information on structure development and the mechanical stability of the samples. The frequency sweep is widely used as a standard test in polymer rheology. In this test, a sinusoidal strain with a constant amplitude (γ = 0.1 %) was applied and the oscillation frequency was varied between 10^{-1} and 10^{2} rad/s. All the measurements were carried out at 37°C [11]. Three specimens of each sample

Table 1
THE COMPOSITION OF THE PREPARED CEMENTS

Sample	Powder phase	Liquid phase	
		Components	MMA/BuA ratio (v/v)
1	2	3	4
CC1	PMMA - 85 % $BaSO_4$ - 12 % POB - 3 %	MMA - 98,2 % DMPT - 1,8 % Hy - 75 ppm	1 / 0
CC2		MMA - 50,7 % BuA - 48,3 % DMPT - 1,0 %	1 / 1
CC3		MMA - 20,6 % BuA - 78,4 % DMPT - 1,0 %	1 / 4
CP1	P(MMA-co-S) - 21.1 % PMMA - 67.05 % $BaSO_4$ - 10 % POB - 1.85 %	MMA - 98 % DMPT - < 2 % Hy - 75 ppm	1 / 0
CP2		MMA - 50,7 % BuA - 48,3 % DMPT - < 1 %	1 / 1
CP3		MMA - 20,7 % BuA - 78,3 % DMPT - < 1 %	1 / 4
CS 1	P(MMA-co-S) - 75 % PMMA - 15 % $BaSO_4$ - 8,3 % POB - 1,7 %	MMA - 97,5 % DMPT - 2,5 % Hy - 80 ppm	1 / 0
CS2		MMA - 50,3 % BuA - 48,3 % DMPT - 1,4 %	1 / 1
CS 3		MMA - 20,4 % BuA - 78,2 % DMPT - 1,4 %	1 / 4

PMMA= poly (methyl methacrylate), P(MMA-co-S) = poly (methyl methacrylate-co-styrene), BPO= Benzoyl peroxide, MMA= methyl methacrylate, DMPT = N,N-Dimethyl-p-toluidene, Hy = hydroquinone.

were analyzed to check the reproducibility of the results. All rheological characteristics were determined in dynamic oscillation mode (DSO) [13]

Results and discussions

The analysis of the rheological behavior of commercial and modified bone cements offers useful information on their structural stability, but more importantly about the flow and deformation as a result of the applied mechanical stress. In this way it is possible to estimate both the handling and curing characteristics as an implant fixing material. Oscillatory tests were used for the rheological characterization. The typical measured parameters were the storage modulus G' (a measure of the deformation energy stored by the sample during the shear process, representing the elastic behavior of the material), loss modulus G" (a measure of the deformation energy used by the sample during the shear process, representing the viscous behavior of the material) and complex viscosity |η*| [11]. These types of tests are used to study all types of viscoelastic materials – from polymer solutions to pastes, gels, elastomers or even solid samples. The basic conditions for a correct measurement are (a) the sample should adhere to both plates, without local displacements or slippage occurring, and (b) the sample is deformed homogeneously in the whole shear area. It is known that the acrylic bone cements are viscoelastic thus both elastic and viscous components of the materials were studied. When the two phases of the cements are mixed both physical and chemical processes are involved. Firstly, the polymer or copolymer beads in the solid powder swell in the liquid phase, a slow viscosity increase being noticed [9, 14]. Moreover, the polymerization starts with a free radical reaction immediately after consumption of the low Hy amount. At the beginning, at room temperature, the reaction is slow. During this working time period the polymerization has an insignificant influence on the rheological properties, as proved by the first experiment comparing two samples: one using standard liquid phase for the preparation of the cement, and the second one using a liquid phase without activator (fig. 1). At the physiological temperature the polymerization reaction accelerates and the dissolution process becomes less important. Thus, the mixture cures and the cement solidifies [15]. As seen in figure 1for sample CC2, an almost perfect superposition of the complex viscosity curves occurs for samples with and without activator for the first 6 min. The same situation is characteristic for all the analyzed cements with only small differences in the recorded time. For this reason, one should consider interesting to investigate the rheological properties of the acrylic bone cements starting from the point where the polymerization reaction has a significant influence on the rheological properties, supposing no difference exists in the mechanical properties of the samples in the first six minutes after mixing, in agreement with literature data [16].

The amplitude sweep tests presented in figure 2 give useful information regarding the structural and mechanical stability of the commercial and newly formulated bone cements First, one can analyze the influence of P(MMA-co-St) copolymer presence on the rheological behavior of the analyzed cements. The samples are grouped as follows: low amount of copolymer (a), high amount of copolymer (b) and compared to cements without copolymer (c). Moreover, each series contains samples in which MMA was partially replaced with BuA. As can be easily seen from figure 1, the curing process is fast for all samples, but the addition of the BuA slightly delays the

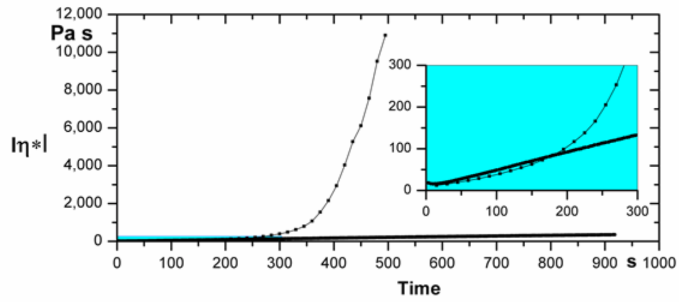

Fig. 1. Time test showing the influence of polymerization on complex viscosity of an experimental acrylic bone cement

process, giving the physician more time to handle the cement. . A stable, solid-like structure is characteristic for all samples with G' > G" for the whole experimental domain.

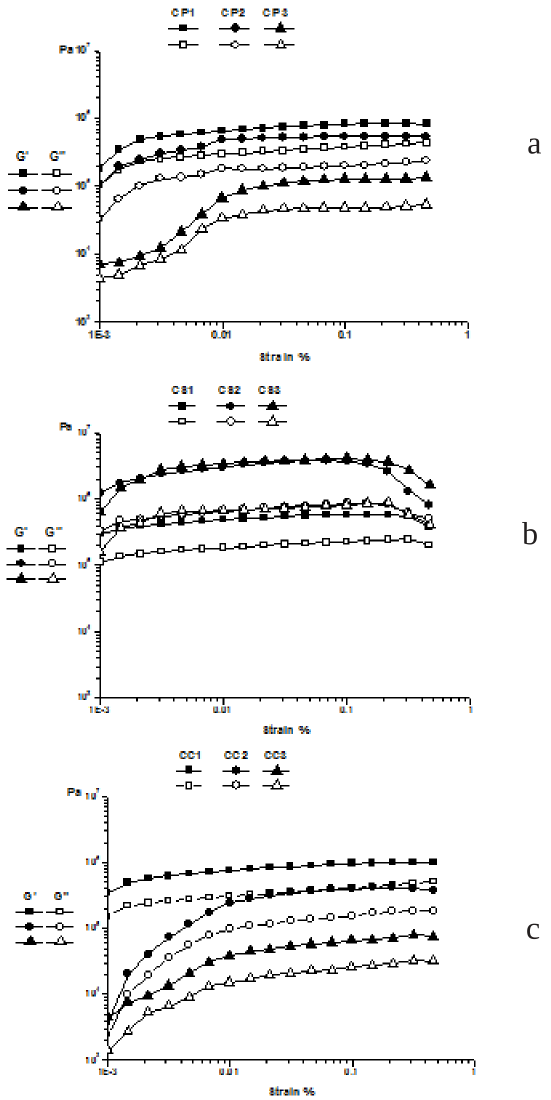

Fig. 2. Amplitude sweep results for acrylic bone cements: (a) low amount of P(MMA-co-S) copolymer; (b) high amount of P(MMA-co-S) copolymer; (c) without P(MMA-co-S) copolymer

The LVR does not significantly differ for all the analyzed samples. The samples with the highest amount of P(MMA-co-S) copolymer exhibit higher structural and mechanical stability. This observation is also valid when the rheological behavior of the commercial cements is analyzed. Adding different amounts of BuA decreases the stiffness of the bone cements making them more flexible as suggested by lower values for the dynamic moduli. It is known that usual acrylic bone cements have a storage modulus [17, 18] higher than the storage modulus of bones [19-21], the risk of accidental fractures being thus increased. Low-modulus cements characterized by lower stiffness can reduce this disadvantage. It can be also supposed these cements are easier to inject and are able to form stable and flexible structures resistant to mechanical solicitations.

To obtain a complete image of the rheological behavior for both commercial and experimental acrylic bone cements a frequency sweep test was carried out for all samples. In this test a sinusoidal strain with a constant amplitude (γ_L = 0.1%) is applied and the oscillation frequency is varied between 10^{-1} and 10^{2} rad/s. All measurements were carried out at 37°C. In figure 3, the storage modulus G' and the loss modulus G" variation with frequency for the same cements as previously discussed is presented. The influence of the P(MMA-co-St) copolymer and added BuA on the rheological behavior of the analyzed samples is obvious. From these graphs one can notice that the addition of the copolymer reduces to some extend the stiffness, but in some cases it can also increase the brittleness. When part of MMA in the liquid phase is replaced with BuA, a more pronounced stiffness decrease can be obtained for all series of samples. This effect could be beneficial if one takes into consideration that the acrylic cements usually act as an elastic buffer between the prosthesis and the bone. A more elastic material may reduce the concentration of stresses and ensure long term stability as well.

For all types of acrylic bone cements their injection ability at the place of intervention is of great importance. Moreover, the cements must have a high enough viscosity to withstand the bleeding pressure avoiding blood lamination in the cement. Cement handling and operation conditions are also influenced by its viscosity. Therefore, following preparation the cements must be liquid enough to be delivered with a suited device and to flow under pressure to the place of application [22]. For this reason, figure 4 depicts the variation of the complex viscosity with frequency, the shear-thinning behavior of all samples being thus estimated.

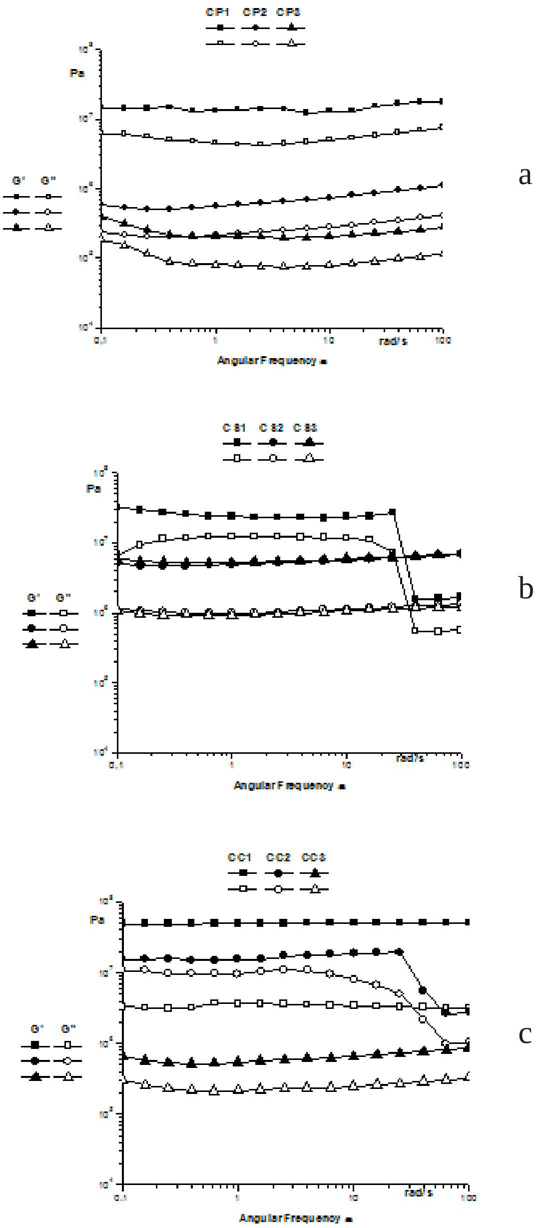

Fig. 3. Frequency sweep tests for acrylic bone cements: (a) low amount of P(MMA-co-S) copolymer; (b) high amount of P(MMA-co-S) copolymer; (c) without P(MMA-co-S) copolymer

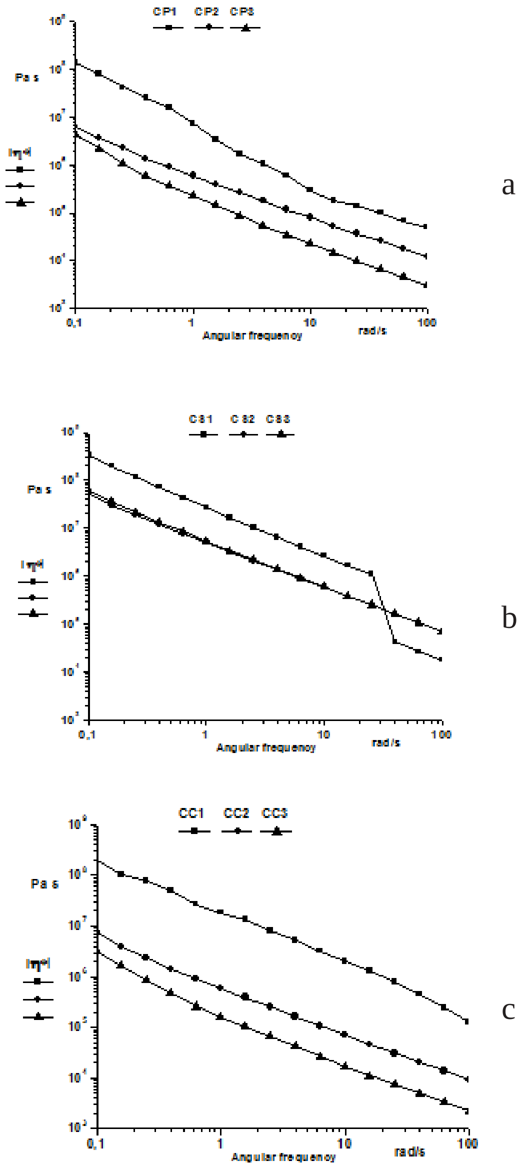

Fig. 4. Complex viscosity curves for acrylic bone cements: (a) low amount of P(MMA-co-S) copolymer; (b) high amount of P(MMA-co-S) copolymer; (c) without P(MMA-co-S) copolymer

All analyzed samples are highly pseudoplastic, this making them injectable. Moreover, adding the new BuA monomer in the liquid phase decreases the viscosity of the cements for all the analyzed systems. The lower viscosity of the acrylic cements with BuA immediately after preparation avoids air incorporation in the mixture and appearance of micro-cracks after curing.

Conclusions

The oscillatory rheological test evidenced a higher structural and mechanical stability of acrylic bone cements with P(MMA-co-St) copolymer in the powder phase. Twelve experimental formulations of acrylic bone cements were realized by partially replacing MMA from the classical liquid monomer phase with BuA monomer. The presence of BuA units in the acrylic bone cements composition decreased to some extent the viscosity in the working phase, and improved the flexibility and injectability of the resulted materials. The new compositions exhibited higher elasticity, lower dynamic moduli and clear shear-thinning behavior proving to be potential replacements for classical PMMA based cements.

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