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Research paper

Comparative study on the mechanical and fracture properties of acrylic bone cements prepared with monomers containing amine groups

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ABSTRACT

In this work, the effect of the incorporation of comonomers containing amine groups on the mechanical and fracture properties of acrylic bone cements was studied. Cements were prepared with either diethyl amino ethyl acrylate (DEAEA), dimethyl amino ethyl methacrylate (DMAEM) or diethyl amino ethyl methacrylate (DEAEM) as comonomer in the liquid phase. It was found that strength and modulus decreased with increasing comonomer content in the bending and compressive tests. It was also observed that fracture toughness (K_{IC}) and the critical strain energy release rate (G_{IC}) increase with increasing comonomer concentration and are significantly higher compared to the control formulation. The mechanical and fracture properties of cements were also evaluated after soaking the specimens in Simulated Body Fluid (SBF) for 3 and 6 months. It was found that the mechanical properties of cements decreased when the samples were stored in SBF, although the impact strength increased in the first 3 months and then decreased. SEM micrographs were in agreement with the results obtained during mechanical characterization as the increase in toughness was confirmed by the appearance of ductile tearing pattern which is associated with plastic deformation.

1. Introduction

Bone cements have been used clinically for a number of years in orthopedic surgery for the fixation of artificial joints with encouraging results (Pascual et al., 1995; Lewis et al., 2007). In this application, the main functions of the cement are to serve as an interfacial phase between the high modulus metallic implant and the bone, and to transfer and distribute body weight loads as well as cyclic loads due to the walking

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movements from the prosthesis to the bone (Pascual et al., 1995; Lewis, 1997).

Despite this relatively good success rate of implant fixation with acrylic-based bone cement, a number of drawbacks are encountered. These disadvantages are related to the exothermic nature of polymerization and, mainly, to the relatively poor mechanical behavior of the cement as compared to the bone and implant performance; for example, an inadequate fracture resistance can lead to cement breakup and subsequent implant loosening. Therefore, improvements in the cement properties are necessary to increase the longevity (performance) of a cemented prosthesis. In this sense, any reduction in the exotherm and/or improvement of the fracture toughness of the commercial bone cement with retention of otherwise satisfactory properties of the bone cement would be highly desirable (Pascual et al., 1995; Lewis, 1997). In this regard, several attempts to improve the mechanical properties of bone cements have been carried out in recent years; one of the methods to reduce the polymerization temperature is to substitute, partially or completely the methyl methacrylate presently used for a methacrylate ester of long alkyl side chain (Pascual et al., 1999; Brauer et al., 1986; Méndez et al., 2002), although the fracture toughness not always is improved.

It has been reported (Pascual et al., 1995, 1999) that the use of hydrophilic monomers in the liquid phase of bone cement formulation may lead not only to lower exotherms but also may introduce significant improvement in toughness of the cements as the last property is influenced by the absorption of low molecules mass species (water) from the environment surrounding the bone cement (plasticizing effect).

In previous papers (Cervantes-Uc et al., 2005; Sabino et al., 2004), it was established that the incorporation of comonomers containing amine groups into bone cement formulations not only promotes a better cell interaction onto the cement surface but also decreases the peak temperature. Also, it was found that bone cements prepared with these comonomers exhibited an increased hydrophilicity with comonomer concentration.

Taking into account the above considerations, the aim of the present study was to evaluate the mechanical properties of acrylic bone cements prepared with comonomers containing amine groups, in particular the impact strength and fracture toughness as it has been reported that these properties are arguably the two most important fracture properties (Lewis and Mladsi, 2000) although they are not included in any bone cement standard. The study of fracture toughness of acrylic bone cements modified with compounds containing amine groups has been reported previously (Deb et al., 2003), but this approach only included the use of these compounds as activators and not as comonomers. It is expected that both properties (impact strength and fracture toughness) could be improved by the use of hydrophilic monomers in the liquid phase of cement formulations. Also, in order to study the plasticizing effect produced by water, specimens of each cement composition were soaked in simulated body fluid (SBF) at 37 °C for 3 and 6 months.

2. Materials and methods

2.1. Materials

Methyl methacrylate (MMA), N-N-Dimethyl-p-toluidine (DMPT), 2-(diethyl amino) ethyl-acrylate (DEAEA), 2-(dimethyl amino) ethyl-methacrylate (DMAEM), 2-(diethyl amino) ethyl-methacrylate (DEAEM), benzoyl peroxide (BPO) and barium sulfate ($BaSO_4$) were purchased from Aldrich Co. and used as received; the chemical structures of monomers containing amine groups are shown in Fig. 1(a). Nictone (PMMA) beads with an average particle size of 60 μm were supplied by Manufacturera Dental Continental, Mexico.

2.2. Bone cement preparation

The experimental bone cements were formulated by adding the liquid component to the solid (powder) component at room temperature (25 °C). The powder component consisted of Nictone (PMMA) beads, benzoyl peroxide (BPO) and barium sulfate ($BaSO_4$) while the liquid component consisted of MMA (as the base monomer), DMPT and either DEAEA, DMAEM or DEAEM at 2, 4, 6 and 10 wt%; these quantities were incorporated by partial replacement of MMA in the liquid phase. BPO and $BaSO_4$ were added to the solid phase at 1% and 10% w/w, respectively. A weight ratio of powder to liquid of 2 was kept in all cases and the cements were prepared by hand mixing without vacuum.

Cements containing only MMA and DMPT in the liquid phase, i.e., without comonomer, were prepared for comparison purposes as control.

2.3. Characterization of bone cements

Bone cements prepared with comonomers containing amine groups were tested under various deformation modes such as tension, compression and bending; impact and fracture properties were also determined. In order to obtain the specimens for mechanical properties, the components (solid and liquid) were mixed and the doughy mixture was placed into a Teflon mold having the dimensions recommended by the ASTM standards. Only those specimens with no visible macropores were included in the study and a minimum of six replicates were used for all mechanical tests. All samples were tested after storing them at 25 °C during at least 1 week.

Compression and bending tests of acrylic bone cements were conducted according to ASTM F451 whereas the fracture and impact tests were carried out according to ASTM-D5045 and ASTM-D256, respectively.

The compression tests were performed on cylindrical specimens (6 mm diameter, 12 mm height) at a cross-head speed of 20 mm/min and compressive strength and modulus were recorded. Bending modulus and bending strength were obtained by means of four-point bending experiments using a crosshead of 5 mm/min. The specimens consisted of rectangular bars (75 mm long, 10 mm width and 3 mm thickness).

For the study of the fracture toughness of bone cements, single-edge-notch bending (SENB) specimens were used. They were machined from the cured bone cements block according