Effect of Acidic Comonomers on Methacrylate Conversion and Mechanical Strength of Bioactive Composites Based on Amorphous Calcium Phosphate

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INTRODUCTION

Amorphous calcium phosphate (ACP) is a postulated precursor in the formation of biological hydroxyapatite (HAP) - the structural prototype of the mineral component of bones and teeth. Relative to HAP, ACP is more soluble and readily transforms into HAP. Recently, ACP has been evaluated as a filler phase in bioactive dental composites that utilize typical photocurable dental monomers, e.g., 2,2-bis[p-(2'-hydroxy-3'-methacryloxypropoxy) phenyl] propane (BisGMA), triethylene glycol dimethacrylate (TEGDMA) and 2-hydroxyethyl methacrylate (HEMA), to form the resin matrix binder phase (1-3). Mechanical properties of these remineralizing composites are somewhat inferior compared to conventional, bioinert glass-filled dental composites. In an effort to better understand how mechanical strength depends on the structural elements comprising these bioactive composites, previous studies have investigated the effects of chemical structure and monomer compositional variation on the mechanical strength and ion-releasing properties of the composites (4-6). In addition, the effects of variations in the type of ACP used as the filler have been evaluated for their effect both on mechanical strength and ion-release.

Most recently we have evaluated the effects of chemical structural variations in the neutral hydrophilic monomeric components of a BisGMA/TEGDMA ternary resin system on the degree of methacrylate conversion (DC) and on the biaxial flexure strength (BFS) (6) of the composites based on zirconia-hybridized ACP (Zr-ACP). The aim of this study was to formulate with Zr-ACP ternary BisGMA/TEGDMA/X resins where X was a surface-active acidic comonomer and assess the effect of the acidic comonomer on DC and strength of these potentially bioactive composites.

EXPERIMENTAL

Formulation of Photoactivated Matrix Resins. Four ternary photoactivated resins based on mixtures of BisGMA/TEGDMA (1:1 mass ratio) with four types of acidic monomers (**Fig. 1**) were formulated along with a control resin based only on BisGMA/TEGDMA (BT; **Table 1**).

**Table 1. Composition of the Resin Systems Used for the Preparation of ACP Composites (mass fraction, %).**

Resin/component	BT	BT/VPA	BT/MA	BT/MaA	BT/4MET
BisGMA	49.50	45.00	45.90	45.90	46.57
TEGDMA	49.50	45.00	45.90	45.90	46.57
VPA	-	9.00	-	-	-
MA	-	-	7.20	-	-
MaA*	-	-	-	7.20	-
4MET*	-	-	-	-	4.90
CQ	0.20	0.20	0.20	0.20	-
4EDMAB	0.80	0.80	0.80	0.80	-
PbTMBPO	-	-	-	-	1.96

* Incorporated levels controlled by solubility constraints.

The acidic monomers, vinyl phosphonic acid (VPA), methacrylic acid (MA) or maleic acid (MaA) were added to BisGMA/TEGDMA along

with a visible light photoinitiator system consisting of camphorquinone (CQ) and ethyl-4-N,N-dimethylaminobenzoate (4EDMAB). For mono-4-(methacryloyloxy) ethyltrimellitate (4MET), phenylbis(2,4,6-trimethylbenzoyl)phosphine oxide (PbTMBPO) was utilized as photoinitiator because of storage stability problems encountered with the use of CQ and 4EDMAB and the 4MET resin.

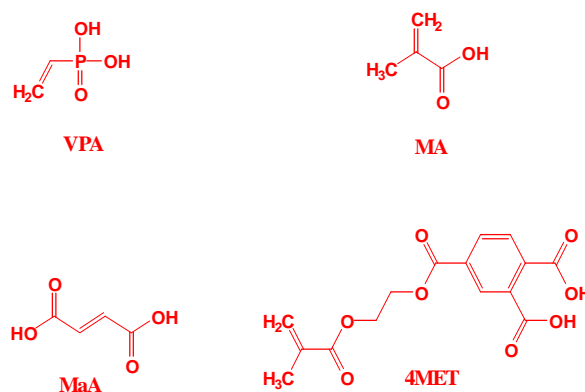Base Monomers:
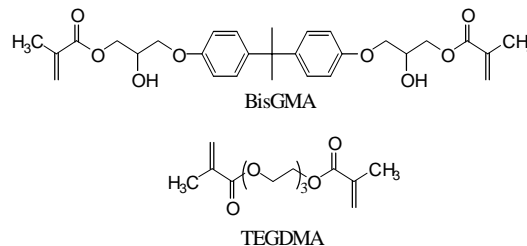
Acidic Comonomers:

Figure 1. Chemical structures of the monomers used in the study.

Composite Preparation. Zr-ACP precipitated instantaneously in a closed system at 23 °C upon rapidly mixing equal volumes of a 800 mmol/L Ca(NO$_3$)$_2$ solution, a 536 mmol/L Na$_2$HPO$_4$ solution that contained a molar fraction of 2 % Na$_4$P$_2$O$_7$ as a stabilizing component for ACP, and an appropriate volume of a 250 mmol/L ZrOCl$_2$ solution (mole fraction of 10 % ZrOCl$_2$ based on Ca reactant) (7). The reaction pH was between 8.6 and 9.0. The suspension was filtered, the solid phase washed with ice-cold ammoniated water and lyophilized. The ACP powder, shown to be amorphous by X-ray diffractometry and Fourier-transform infrared spectroscopy (FTIR), was then utilized as a filler in the composites at a mass fraction of 40 %. The photoactivated resins and their composite disks were polymerized with the aid of visible light (470 nm) in Teflon molds (15.8 mm to 19.6 mm in diameter and 1.55 mm to 1.81 mm thick). Each face of the mold assembly was irradiated with a visible light source for 120 s (Triad 2000, Dentsply, York, PA).

Copolymer and Composite Evaluation. Mid-FTIR was used to determine the DC of the unfilled resins and their ACP-filled composites by monitoring changes in the 1637 cm^{-1} absorption band for the vinyl group against that of the phenyl ring at 1582 cm^{-1} (used as internal standard) 24 h at 23 °C after photo-curing. FTIR spectra were acquired by collecting 64 scans at 2 wavenumber resolution (wavenumber relative uncertainty of 0.5 cm-1). Triplicate measurements were performed for each experimental group.

BFS values of the dry and wet (after 2 weeks of immersion in HEPES-buffered, pH = 7.40, saline solutions) composite disk specimens (three or more specimen per group) were determined by using a computer-controlled Universal Testing Machine (Instron 5500R, Instron Corp., Canton, MA) operated by Testworks4 software.

The BFS was calculated according to mathematical expressions given in ref. (8).

Experimental data were analyzed by multifactorial ANOVA (α = 0.05). Significant differences between specific groups were determined by all pairwise multiple comparisons (Tukey test).

RESULTS AND DISCUSSION

The DC after 24 h attained with copolymers was practically unaffected by the resin composition for all but MaA formulations (average DC for VPA, MA and 4MET = 72.33 ± 2.11 vs 65.26 ± 2.11 for MaA; **Fig. 2**). Introduction of Zr-ACP filler reduced the DC of all the composites compared to corresponding unfilled resins. The effect subsided in the following order: VPA (14.5 %) > (Control (7.8 %), MA (5.8 %), MaA (5.5 %)) > 4MET (0.6 %). As discussed previously (7), the observed reduction in DC in going from unfilled polymer to composite is most likely due to the reduction in the exotherm of resin polymerization by the ACP filler phase. Other factors such as greater air entrapment and light scattering by ACP cannot, however, be discarded as possible contributing factors to this reduction. Generally, the extent of DC reduction of unfilled polymers vs composites observed with acidic, carboxylate-containing comonomers (with exemption of VPA) was lower than previously reported (7) for a series of non-acidic hydrophilic monomers with the base BT resin.
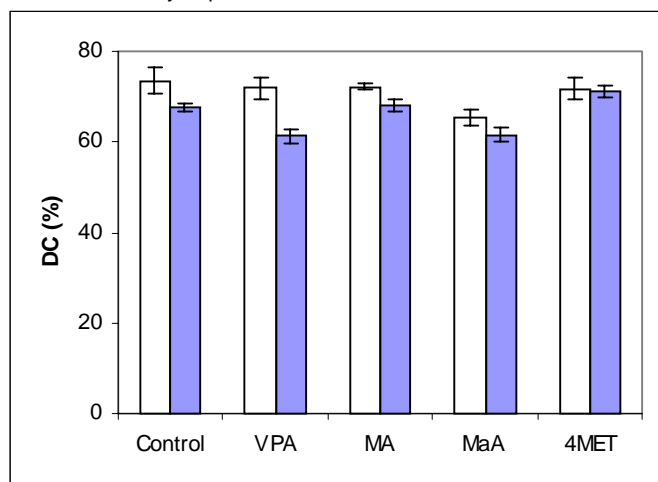

Figure 2. Degree of methacrylate conversion (DC; mean ± SD (indicated by bars) of unfilled (unfilled columns) and ACP composites (filled columns) attained at 24 h after photo-curing. Standard deviation (SD) is taken as a measure of the standard uncertainty.

BFS values of dry and wet composites are given in **Fig. 3**. The BFS of dry composite specimens declined in the following order: (4MET, MA, control) > (MaA, VPA). The strength of specimens upon aqueous immersion decreased in the following order: (4MET, control) > (MA, VPA, MaA). Differences in the BFS for the matrices indicated within parentheses were found statistically insignificant. No apparent correlation between the DC and the BFS of either dry or wet specimens could be established. Although exposure of composite specimens to aqueous environment generally reduced their mechanical strength differences in the BFS between the dry and wet samples were found significant only for the MA, MaA and 4MET formulations. Compared to the dry specimens, the BFS values of the wet MA, MaA and 4MET composite specimens decreased 51 %, 53 % and 25 %, respectively. This reduction in mechanical strength is plausibly caused by a) a reduction in ACP intactness and rigidity at the ACP-matrix interface due to the chemical and/or spatial changes that occurred during the loss of ACP and/or internal conversion to HAP, or b) excessive water absorption. To determine if there is a positive correlation between the observed strength reduction and polymer matrix plasticization by water, extensive water sorption/desorption studies are in progress.
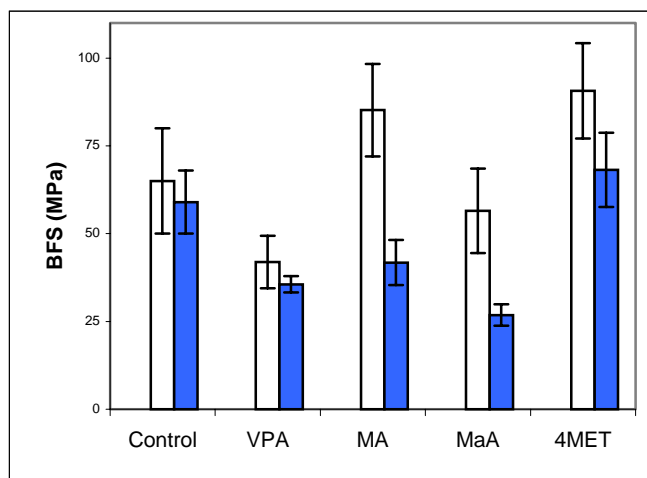

Figure 3. Biaxial flexure strength (BFS; mean ± SD (indicated by bars)) of dry (unfilled columns) and wet (filled columns) BTX composite specimens. The SD is taken as a measure of the standard uncertainty.

CONCLUSIONS

The DC of BT/acidic copolymers examined in this study showed practically no dependence on structural variations of the carboxylate comonomers. While the addition of ACP resulted in a reduction of DC, the differential in conversion for polymer and composite was generally smaller than for the ternary BT resins containing comonomers with hydroxyl or ether functionalities. No correlation could be established between DC and the BFS values of the composites, dry or wet. Despite moderate weakening of its composites upon soaking, 4MET seems to be a promising surface-active monomer for ACP composites.

DISCLAIMER

Certain commercial materials and equipment are identified in this article to specify the experimental procedure. In no instance does such identification imply recommendation or endorsement by the National Institute of Standards and Technology or the American Dental Association Health Foundation or that the material or equipment identified is necessarily the best available for the purpose.

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