Development of Dental Resinous Systems Composed of Bisphenol A Ethoxylated Dimethacrylate and Three Novel Methacrylate Monomers: Synthesis and Characterization

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ABSTRACT: Three novel monomers with a methacrylate unit, different chain lengths, and functional groups were synthesized and proposed as possible diluent monomers in dental resinous systems containing bisphenol A ethoxylated dimethacrylate (BisEMA) aiming at their use in dental resin mixtures. The monomers were mixed with BisEMA and photopolymerized in the presence of a photoinitiator system. The unfilled formulations were evaluated regarding their degree of conversion, thermal properties, Vickers microhardness, water sorption, water solubility, and surface morphology. The monomers presented a high conversion degree compared to control groups and have affected the glass transition temperature of the samples. Their hardness values were similar to or higher than the value found for the control group. The specimens evaluated presented a homogeneous matrix and stability throughout the water sorption and solubility tests. Considering their simplicity and effective application in synthesis, as well as the results obtained for the polymerized formulation groups, the new monomers presented here represent promising photocurable dental monomers. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 000: 000–000, 2012

INTRODUCTION

The restoration of carious or damaged teeth usually involves the attachment of an artificial material to the remaining tooth structure. Gold alloys or amalgams were successfully used for many years, but due to esthetic concerns composites based on a resin matrix with ceramic fillers have attracted the attention of patients and dentists, because these materials present characteristics such as color and mechanical strength, similar to teeth.[1] Many approaches have been studied and suggested for the treatment of carious teeth,[2] one of which is the etch and rinse technique, a reliable and effective way of achieving efficient and stable bonding to tooth structures. This technique involves a separate etch and rinse phase and is composed of three steps: (i) the conditioning step, when a strong acid such as phosphoric acid (30–40%) is used to demineralize the dentin. The acid is rinsed after a few seconds, removing the smear layer and exposing the collagen network and dentinal tubules; (ii) the priming step, when hydrophilic methacrylate resins are applied and infiltrate the collagen matrix and tubules; and finally, (iii) application of a hydrophobic resin monomer mixture that is subsequently polymerized, resulting in the adhesion of the monomers to the infiltrated primer.[3,4]

Composite resins usually consist of a mixture of dimethacrylate and methacrylate monomers, inorganic particles (fillers), stabilizers, and a photoinitiator system.[5,6] Despite the importance of methacrylate and dimethacrylate monomers in a dentinal system, the major component of most dentinal composites is the inorganic filler, a relatively inert substance that provides better resistance and elastic modulus, reduced polymerization shrinkage and water sorption.[7] The organic part represents 10–30% by weight of the composite, and it is mainly composed of polymerizable molecules.[8]

To improve the performance of dental composites and adhesives, extensive investigations have been carried out, mostly related to the synthesis of new methacrylate and dimethacrylate
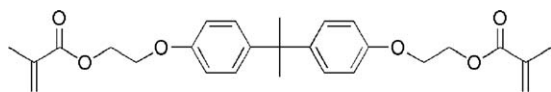
Figure 1. Molecular structure of BisEMA.

Figure 3. Molecular structure of CMEE.

monomers.[2,9,10] Several new monomers have been suggested for application in this area, in particular the dimethacrylates, which facilitate the formation of densely crosslinked networks.[11,12] The hydrophobic monomer bisphenol A ethoxylated dimethacrylate (BisEMA) (Figure 1) was synthesized and is widely used in the composition of etch and rinse adhesives[13,14] and resinous composites[4] as a base monomer mixture with diluent monomers. This monomer contains no free OH groups in its structure, a characteristic that leads to reduced viscosity of the system.[13] This is a great advantage of BisEMA when compared to hydrophilic dimethacrylate monomers, because a dental resinous system presenting lower viscosity permits a higher filler loading, favoring the mechanical properties of the resin. Despite its lower viscosity, BisEMA still presents a low double bond conversion,[13] mainly due to steric hindrance.

As previously mentioned, in the field of dental resinous systems, numerous studies have focused on the synthesis and application of dimethacrylates, and, therefore, the current market has good examples of this type of monomer. Nevertheless, the methacrylate monomers, which are also an important part of these systems, remain less explored in the literature. The methacrylate molecules generally have a smaller hydrocarbon chain, lower molecular weight, lower viscosity, and higher hydrophilic behavior than dimethacrylates. Therefore, these monomers can infiltrate into the dentinal tubules (microchannels crossing the dentin from enamel to pulp) leading to a bigger resin tag, resulting in a system with greater anchorage capacity when the monomer used is hydrophilic.[15] Furthermore, these monomers can dilute the dimethacrylate monomer improving system mobility, which leads to a higher degree of polymerization and, generally, to greater hardness of the system. 2-Hydroxyethylmethacrylate (HEMA; Figure 2) is a methacrylate monomer widely used for this purpose. The disadvantages of using this diluent monomer in dental systems are higher polymerization shrinkage, lower system hardness,[11] and its ease of leaching from dental resin systems.[4] Therefore, new diluent monomers must be developed to overcome these problems.

The degree of conversion (DC) of monomers to polymers is an important factor, because it is known that monomers with methacrylate groups are toxic, mutagenic, and allergenic.[16,17] Precautions should be taken to minimize the elution of these compounds into the patient's oral cavity, either through the presence of noncured monomers in the resin, or as a result of the hydrolysis of monomers polymerized by only one active chain end of the methacrylate. The release of compounds such
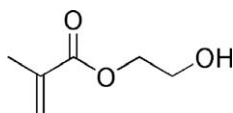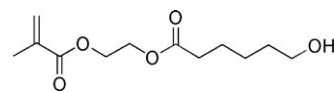

Figure 2. Molecular structure of HEMA.

as methacrylic acid may be observed when such a hydrolysis reaction occurs. In addition, low degrees of conversion are usually related to low values for material hardness[18,19] and to the formation of empty voids, leading to high water sorption values or limited reactivity of diluent monomers.[20] Such factors may lead to biocompatibility problems in the application of the dental resinous system due to the leaching of molecules and low wear resistance of the composite resin. Aiming to improve factors such as the low DC and low hardness of dental resinous systems, monomers containing one methacrylate group and hydrophilic groups in the monomer chain, to increase the reactivity, are suggested herein.

Two new monomers derived from caprolactone 2-(methacryloyloxy) ethyl ester (CMEE) (Figure 3) with different alkyl chain lengths were easily and efficiently synthesized and evaluated for their hardness, thermal properties DC, water sorption and solubility, and surface morphology when used in dentin bonding systems as diluent monomers. A third monomer containing an acid group was also synthesized and evaluated following the same procedures. Acid groups apparently interact with hydroxyapatite and can demineralize the dentin.[2,21,22] Studies have shown benefits in the use of acid monomers, but the advantages of better adhesion and conditioning should be combined with the achievement of higher conversion degrees, satisfactory hardness, and low water sorption.

EXPERIMENTAL

Materials
CMEE (Sigma–Aldrich), methylene chloride (CH_2Cl_2, anhydrous, 99.8%, Sigma–Aldrich), chromium oxide (CrO_3, 99%, Merck), acetone (99.8%, Sigma–Aldrich), and isopropanol (99.5%, Merck) were used as received. The acid chlorides chloroacetyl chloride (98%, Sigma–Aldrich) and 4-chlorobutyryl chloride (98%, Sigma–Aldrich), as well as triethylamine (Et_3N, 99.5%, Sigma–Aldrich), were distilled prior to use.

Synthesis of Chloroacylated Derivatives of CMEE (CMEE-2 and CMEE-4)
Triethylamine (3.4 mL, 24.5 mmol) was added dropwise to a stirred and cooled (0°C) solution of CMEE (5 g, 20.5 mmol) in dichloromethane (75 mL). After addition, the acid chloride (22.5 mmol) was added slowly and the reaction remained under the same conditions for 1 h. The ice bath was then removed, and stirring was continued for 4 and 24 h at room temperature for chloroacetyl chloride and 4-chlorobutyryl chloride, respectively. Subsequently, the organic layer was washed with water, $1M$ aqueous NaOH and $0.5M$ HCl. Finally, the organic layer was stirred for 5 h with activated carbon, dried over anhydrous sodium sulfate (Na_2SO_4), filtered through Celite and evaporated to obtain CMEE-2 and CMEE-4. Figure 4 represents the reactions described in this experiment.
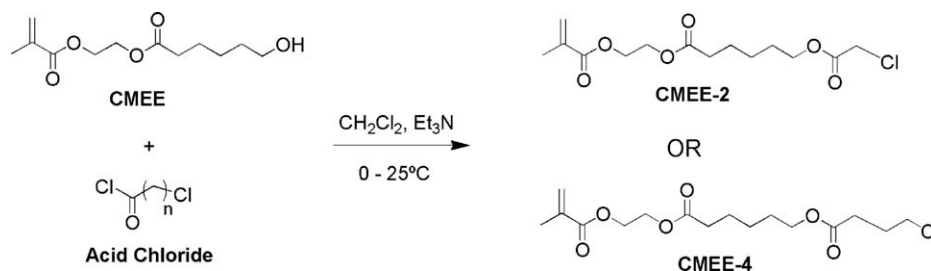
Figure 4. Preparation of chloroacylated derivatives of CMEE.

Synthesis of Acid Derivative of CMEE (CMEE-H)

The acid derivative of CMEE was prepared using Jones reagent, a well-known and traditionally used reagent for the oxidation of primary alcohols to carboxylic acids and secondary alcohols to ketones. Jones reagent consists of a mixture of $2.67M$ CrO_3 in $4.3M$ sulfuric acid. To a stirred and cooled (0°C) solution of CMEE (4.63 mL, 20.5 mmol) in acetone (46 mL), Jones reagent was added slowly. The solution turns from yellow to green during the reduction of Cr (VI) to Cr (III). The end point of the reaction is defined by the presence of a yellow coloration of the solution, indicating that Cr (VI) is no longer being reduced to Cr (III). To destroy the unreacted Jones reagent in the solution, isopropyl alcohol was added dropwise, until the disappearance of the yellow color. The solvent was then evaporated and the resulting transparent oil was taken up in diethyl ether (15 mL), and the organic layer was washed with water and evaporated. The resulting oil was treated with saturated aqueous Na_2CO_3 solution, and the aqueous phase was extracted with ethyl acetate. The aqueous layer was acidified with aqueous HCl to pH 2 and extracted with diethyl ether (3 × 10 mL). The combined organic layer was dried over Na_2SO_4, filtered, and evaporated. Figure 5 shows the reaction described in this experiment.

Characterization of Methacrylates

Each sample, prior to characterization, was analyzed and confirmed as homogeneous by thin layer chromatography (TLC) performed on silica gel plates (Kieselgel 60 254-Merck, Darmstad, Germany) visualized with UV light. The derivatives prepared were characterized using Fourier transform infrared (FTIR) spectroscopy and nuclear magnetic resonance (NMR) spectroscopy techniques. The FTIR spectra were recorded on an ABB Bomen FTLA 2000-100 instrument (Quebec, Canada). NMR spectra were recorded at 20°C using a Varian AS-400 NMR spectrometer (Palo Alto, CA) operating at 400 MHz for ^{1}H and 100 MHz for ^{13}C. Chemical shifts (δ) are presented in parts per million (ppm) and were determined using residual $CHCl_3$ and tetramethyl silane as internal standards.

Curing Procedure

In the photopolymerization, a photoinitiator system was added to the monomers, forming the dental resinous system that was subsequently irradiated by blue light for a specified period of time. In this study, the formulations used consisted of 49.4% experimental monomers and 49.4% BisEMA (forming a 50/50 w/w blend of the experimental and commercial monomers), with addition of 0.43% camphorquinone (CQ) as a photoinitiator and 0.8% N, N-dimethylaminobenzoic acid (DAB) as a coinitiator. BisEMA was used as a model base crosslinking monomer due to its wide application in composite resin formulations and in the bonding of dental adhesives. This system was irradiated for 20 s using a blue light source of 1250 mW/cm^2 (Kerr, Demetron LC, Orange, CA), and subsequently characterized. As control groups, formulations containing 49.4% HEMA/ 49.4% BisEMA and 98.8% BisEMA were prepared following the same procedure.

Characterization of Polymers

To determine the DC of the formulations, FTIR spectra of all systems, before and after irradiation with the light source, were recorded on an FTIR-8300 Shimadzu spectrophotometer (Kyoto, Japan). The FTIR spectrum obtained for the polymerized system was compared with that for the nonpolymerized system in each formulation, and the intensity of the C=C peak (~1640 cm^{-1}) relative to the C=O peak (~1730 cm^{-1}) was evaluated. The C=O absorption band remains constant during polymerization and serves as an internal standard. To evaluate the efficiency of the double bond conversion in each experimental system, the results were compared with the DC values obtained for control samples using eq. (1), where A represents the surface area of the absorption bands analyzed:

$$\%DC = 100 \times \left(1 - \frac{\left(A1630 / A1730 \right) polymer}{\left(A1630 / A1730 \right) monomer} \right) \quad (1)$$

Differential scanning calorimetry (DSC) analysis provides information on the thermal properties, such as the glass transition temperature (T_g), melting temperature (T_m), and heat capacity (ΔC_p). Therefore, this technique is important for the determination of possible interactions between the monomers used in the formulations and to evaluate the rigidity of the cured samples.
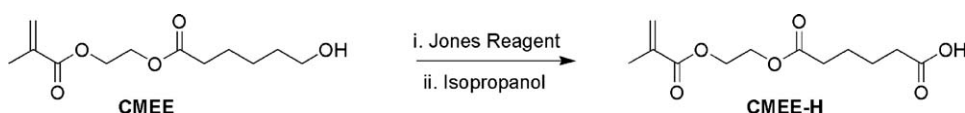

Figure 5. Preparation of acid derivative of CMEE.

A Shimadzu DSC 50 differential scanning calorimeter was used in the analysis. The scans were performed under nitrogen atmosphere (50 cm^3 min^{-1} flow) at a 5°C min^{-1} heating rate. Approximately 8 mg of the samples were heated to 180°C and then quenched. After this step, the samples were heated again from -100 to 200°C, and this second scan was used to determine the T_g values.

The samples were evaluated in terms of their Vickers microhardness, which measures the material microhardness based on the resistance that the material provides to the penetration of a pyramid diamond point under a given load. Hardness is used as an indicator of important parameters of materials such as durability. Formulations prepared with experimental monomers and BisEMA mixed with a photoinitiator system were polymerized in circular disk shapes, and their Vickers microhardness values were determined in triplicate using a 10 gf indenter load. Three indentations were made on each specimen, and the mean values and standard deviations were calculated.

The morphology of the polymerized formulations was evaluated through analysis of the materials surfaces and cross-sections using scanning electron microscopy (SEM). The samples were analyzed using a Philips XL 30 microscope. Prior to the analysis, all samples were coated with gold by sputtering with a Polaron E 5000 vacuum unit. When necessary, the energy dispersive X-ray (EDS) technique was used to identify the surface composition.

The formulations were also tested for water sorption and water solubility. The samples were weighed and maintained in a vacuum oven until the attainment of constant weight (m_1). After the weight stabilization, the specimens were placed in test tubes containing 5 mL of distilled water in a Dubnoff bath at 37°C. A bath temperature of 37°C was used to accelerate the aging of the specimens and thus allow an assessment of the behavior of the specimens over a prolonged period of time. Once a week, the specimens were removed from the bath, blotted to remove the water present on the surface, and their weights were recorded for 4 weeks (m_2, m_3, m_4, and m_5). After this 4-week period of water sorption tests, the specimens were once again placed in a vacuum oven and weighed regularly until constant weight (m_6). Equations (2)–(4) were used to determine the values for mass change (W_{mc}), water solubility (W_{sl}), and water sorption (W_{sp}). All values were considered on a percentage basis.

$$W_{mc}(\%) = \left(\frac{m_2 - m_1}{m_1}\right) \times 100 \qquad (2)$$

$$W_{sl}(\%) = \left(\frac{m_1 - m_6}{m_1}\right) \times 100 \qquad (3)$$

$$W_{sp}(\%) = W_{mc}(\%) + W_{sl}(\%) \qquad (4)$$

The tests to determine the DC, Vickers microhardness, and water sorption and solubility were performed in triplicate. The mean values and standard deviations were calculated, and multiple-comparison analysis of variance (ANOVA) and the Tukey test were applied, considering statistical significance at $P < 0.05$.
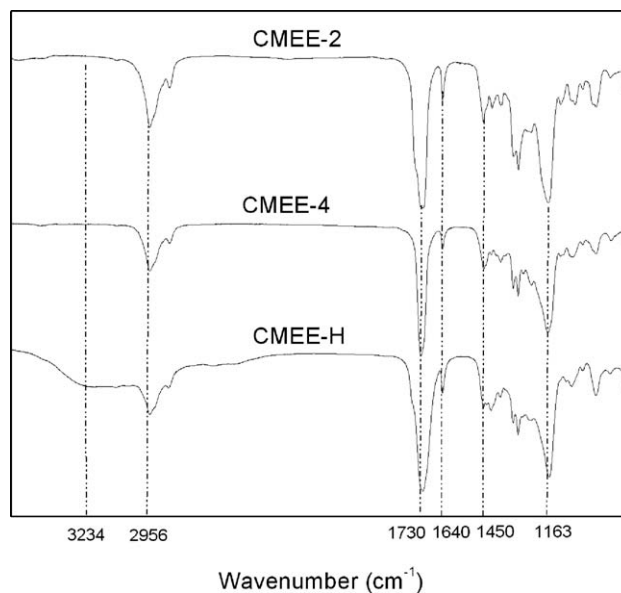

Figure 6. FTIR spectra obtained for the synthesized monomers.

RESULTS AND DISCUSSION

Synthesis of Methacrylates

The monomers CMEE-2, CMEE-4, and CMEE-H were chosen due to their ease of preparation, and present some characteristics that may be beneficial to a dentinal system. It is expected that interaction between the monomers and dentin occurs based on a Lewis acid–base interaction between the electron donor species, the experimental monomers, and hydroxyapatite that is present in dentin, which is an electron acceptor.[23]

The monomers were obtained with simplicity and effectiveness, and the reactions were monitored by TLC using silica as the stationary phase. These reactions provided high yields, were reliable, and the use of laborious purification steps were not necessary, leading to fast synthesis procedures. The experimental monomers required only simple extraction procedures and posterior use of activated charcoal to remove any impurities that may be present in the reaction medium. After the purification step, the samples were analyzed once more by TLC, which indicated that the material was pure. The yields obtained were 93% for CMEE-2, 95% for CMEE-4, and 52% for the CMEE-H.

Characterization of Methacrylates

Figure 6 shows the FTIR spectra obtained for the new synthesized monomers. The CMEE-H monomer presents a broad absorption band at 3234 cm^{-1} due to the hydroxyl group of the carboxylic acid. Although the starting reagent also has a hydroxyl group in its structure, it is possible to conclude that the CMEE-H monomer was formed with the aid of the ^{13}C NMR results, shown later. As expected, the infrared spectra of the monomers CMEE-2 and CMEE-4 showed no typical ─OH absorption, due to the structure of these monomers. Additionally, the three monomers showed absorption bands between 3050 and 2800 cm^{-1} (related to the stretching vibration of CH$_2$ and CH$_3$), the carbonyl stretching vibration at 1730 cm^{-1}, absorption of aliphatic C═C at 1640 cm^{-1}, stretching vibration bands related to CH$_2$ molecules around 1450 cm^{-1}, and C─O

Figure 7. ^{1}H NMR spectrum for CMEE-2.

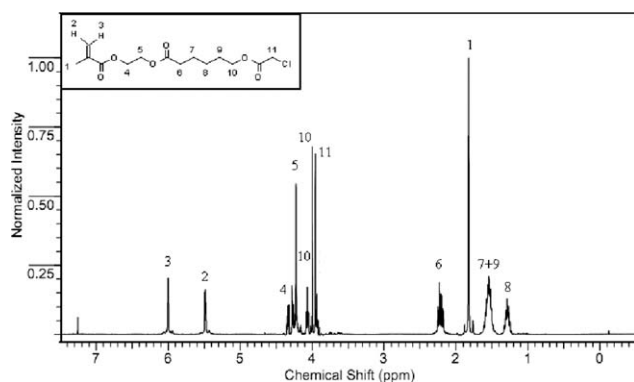**Figure 9.** ^{1}H NMR spectrum for CMEE-H.

stretching vibrations at ∼1163 cm⁻¹. The FTIR spectra obtained indicate that the reactions were carried out successfully.

The ^{1}H NMR spectra obtained for the synthesized compounds (Figures 7–9) confirm the proposed structures for CMEE-2, CMEE-4, and CMEE-H. Each spectrum shows the chemical shift displacements obtained with the corresponding hydrogen atoms. These assignments were made with the aid of two-dimensional NMR spectra (COSY).

The ^{1}H NMR spectrum of CMEE-2 showed three singlet peaks: at 6.00 and 5.49 ppm related to the hydrogen atoms of the vinyl group, and at 1.82 ppm, associated with the methyl of the methacrylate group. The areas of all peaks obtained were proportional to the amount of hydrogen atoms represented by each peak and overlapping of two CH_2 groups that are part of the aliphatic chain of this molecule was observed, represented here by the numbers 7 and 9. The ^{13}C NMR spectrum of CMEE-2 had the following chemical shift displacements (CDCl₃, 100 MHz): δ 18.31 (C-1), 24.57 (C-7), 25.54 (C-8), 28.40 (C-9), 33.98 (C-6), 41.01 (C-11), 62.14 (C-4), 64.13 (C-5), 66.00 (C-10), 126.04 (C-2/3, vinyl group carbon), 136.05 (quaternary carbon, which participates in the double bond), 167.06 (methacrylate group carbonyl), 167.40 (acetyl group carbonyl), and 173.18 (caprolactone carbonyl). These assignments were made with the aid of the two-dimensional NMR technique (HETCOR) and distortionless enhancement by polarization transfer (DEPT) technique, not presented herein.
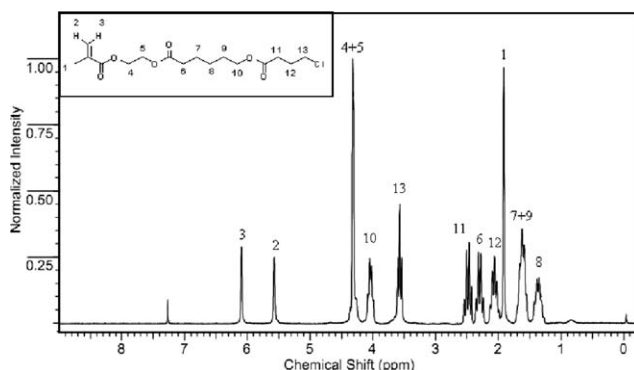
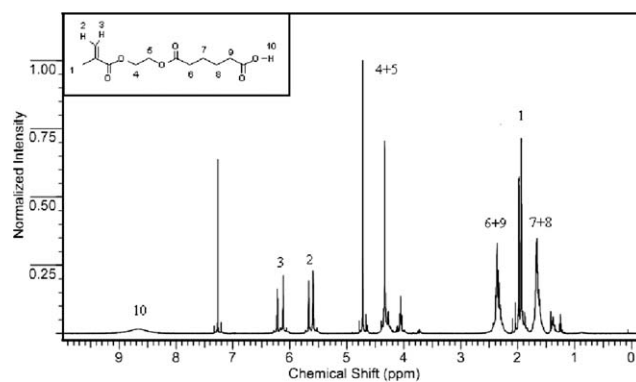The ^{1}H NMR spectrum shown in Figure 8 confirms the suggested structure for CMEE-4. As in the case of CMEE-2, the peak areas were used to calculate the number of hydrogen atoms represented by each peak, and the results are consistent with the molecule shown. In addition to the overlap between peaks 7 and 9, as observed for the CMEE-2 monomer, this molecule also showed overlapping of peaks 4 and 5. The overlap was confirmed by the number of hydrogen atoms represented by each peak. The chemical shifts of ^{13}C NMR (CDCl₃, 100 MHz) found for these molecules were the following: δ 18.49 (C-1), 24.69 (C-9), 25.71 (C-8), 27.83 (C-11), 28.48 (C-12), 31.39 (C-6), 34.13 (C-11), 44.33 (C-13), 62.20–62.63 (C-4 and C-5, which appear overlapped), 64.57 (C-10), 126.30 (C-2/3, vinylic carbon), 136.12 (quaternary carbon belonging to double bond), 167.31 (methacrylic group carbonyl), 172.94 (acetyl group carbonyl), and 173.78 (caprolactone carbonyl). Once more, the assignments presented here were defined based on HETCOR and DEPT spectra obtained for this monomer.

Finally, Figure 9 confirms the proposed structure for the CMEE-H monomer. It was possible to observe a broad peak at δ 8.66 ppm, characteristic of hydroxyl groups. This spectrum also presented a peculiar duplicity of the peaks assigned to the hydrogen atoms of the methacrylate group (1–3 hydrogen atoms). This duplication may be explained by the presence of conformers that easily interconvert at room temperature. The peak ratio indicates that the relation between these two structural forms is approximately 62–38%. This spectrum also shows overlapping between the hydrogen groups 4-5, 6-9, and 7-8. The assignment of the specific peaks to these hydrogen atoms was only possible with the aid of two-dimensional NMR spectroscopy (COSY), which elucidated the interaction between neighboring hydrogen atoms. The ^{13}C NMR chemical shifts found for this molecule were also evaluated, and assignments were made using HETCOR and DEPT techniques (CDCl₃, 100 MHz): δ 18.41 (C-1), 24.39 (C-7), 25.66 (C-8), 28.48 (C-9), 34.08 (C-6), 60.66–62.65 (C-4 and C-5 overlapped), 127.30 (C-2/3, vinylic carbon), 136.08 (quaternary carbon in the methacrylate group), 167.43 (methacrylate group carbonyl), 173.38 (caprolactone carbonyl), and 179.53 (carboxylic acid carbonyl).

Characterization of Polymers

As detailed in "Experimental" section, the monomers were cured and characterized according to their DC, Vickers microhardness,

Figure 8. ^{1}H NMR spectrum for CMEE-4.

Table I. Mean and Standard Deviation for DC, Vickers Microhardness, Water Sorption, and Solubility for the Studied Formulations

Formulation	Methacrylate molar masses (g mol^{-1})	DC (%)	T_g (°C)	Vickers microhardness (HV)	Water sorption (%)	Water solubility (%)
BisEMA/CMEE-2	320.75	65.10 ± 2.43a	10.76	6.40 ± 1.33b	3.27 ± 0.94a	4.31 ± 0.53a
BisEMA/CMEE-4	348.71	63.36 ± 2.78a	−13.47	3.09 ± 0.42c	1.65 ± 0.93a, b	2.40 ± 1.06b
BisEMA/CMEE-H	258.29	54.12 ± 0.59b	75.79	11.82 ± 2.03a	3.10 ± 0.60a	3.49 ± 0.27a, b
BisEMA/HEMA	130.14	46.40 ± 3.05c	_a	_a	_a	_a
BisEMA	–	38.90 ± 2.93d	83.33	5.81 ± 0.21b, c	−0.51 ± 1.02b	−0.35 ± 0.76c

Values followed by the same letters on the same column are not statistically different (α = 5%).
^{a}The measurements in this formulation could not be carried out due to the formation of a specimen with insufficient integrity.

thermal properties surface and cross-section morphology, and water sorption and solubility.

The formulations prepared in this study contained photoinitiator systems that absorb luminous energy reaching excited states. This step is responsible for the formation of free radicals or other initiator species that convert the monomers present in the dentinal system into a crosslinked polymer network.[24,25] The ketone CQ was chosen as the photoinitiator in this study due to its maximum light absorption at 468 nm, the same wavelength of conventional dental curing units. Along with this ketone DAB was used as a coinitiator molecule. This secondary amine effectuates the transfer of an electron to the excited ketone and then the transfer of a hydrogen to the ketone structure, forming an aminyl radical that is responsible for initiating the polymerization reaction.[2]

The DC of a dental system is an important factor, because the greater the conversion degree of a given system the lower the risk of the release of unreacted monomers into the patient's oral environment, also leading to the occurrence of a cohesive polymer matrix. The experimental systems studied showed an easy polymerization reaction and postcuring procedures were not necessary. However, the double bond conversion of methacrylates is not totally complete due to effects such as immobilization, gelification, vitrification, and steric hindrance.

Table I shows the DC values obtained for the formulations studied. As expected, the lowest value was observed for the control group composed entirely of BisEMA. As this monomer contains two methacrylic groups, its mobility decreases with the enhancement of polymerization. Formulations composed of monomethacrylated monomer and dimethacrylate tend to exhibit higher degrees of conversion, due to the greater mobility of methacrylates in the medium during polymerization. However, the control group BisEMA/HEMA showed only 46.4% of conversion of their double bonds into single bonds (generating the polymer), though this formulation was composed of a short-chain methacrylate monomer, which has greater mobility in the polymer network and consequently presents a greater possibility of polymerization. This suggests higher reactivity of the synthesized monomers when compared with the diluent model monomer HEMA.

The DC values obtained for the formulations containing the novel monomers were very satisfactory when compared with

the control groups, especially in the case of the BisEMA/CMEE-2 and BisEMA/CMEE-4 formulations. The BisEMA/CMEE-2 group presented 65.1% of conversion, a clearly superior value when compared to the BisEMA/HEMA formulation, commonly used in commercial dental systems. The BisEMA/CMEE-4 formulation followed the same trend and the BisEMA/CMEE-H presented a slightly lower double bond conversion in relation to the other formulations tested, but this value was still higher than that obtained for the commercial monomers. The results suggest that the presence of the monomers synthesized in this study led to a greater reactivity of the system, reflecting in the increased DC found for these samples.

The ANOVA of the DC results confirmed that the population means are statistically different, and the Tukey test indicated that, among the groups studied, the results obtained for the formulations BisEMA/CMEE-2 and BisEMA/CMEE-4 are statistically similar, which suggests that the chain length of these monomers had little effect on the DC. In general, the formulations evaluated showed a trend of increasing DC with increasing molar mass of the methacrylate monomer, and this may be one of the factors that led to the low double bond conversion observed for the BisEMA/HEMA formulation. Additionally, the introduction of a hydrophilic group into the monomer chain, like the ester group in CMEE-2 and CMEE-4, could contribute to a higher reactivity. Similar behavior was observed in a series of monomers containing ethyleneglycol units compared with monomers without these hydrophilic groups.[20]

The results obtained for the glass transition temperatures for the systems studied are also presented in Table I. The T_g of a material is the temperature at which a relaxation in the polymer chain occurs and is generally observed for the amorphous regions of polymers. Materials with higher rigidity present higher glass transition temperatures. Of the monomers tested the system composed entirely of BisEMA had the highest stiffness. This result may be explained by the structure of BisEMA, which presents two methacrylate ends and therefore can have both terminals polymerized forming a densely crosslinked network, resulting in a system with low mobility of polymeric chains.

Table I shows significant differences on the T_g values of the systems studied in comparison with the control groups, indicating that very pronounced interactions occur between the proposed

monomers and BisEMA. It can be observed that the lower the molecular weight of the monomers involved in the system the higher the T_g of the system, that is, an increase in material stiffness is suggested. Of the monomers synthesized CMEE-H presented the highest T_g, followed by CMEE-2-and CMEE-4. The same pattern was observed for the Vickers microhardness, as described later. It was observed that the systems comprising the CMEE-2 and CMEE-4 monomers had a greatly reduced stiffness in relation to the system prepared with CMEE-H. This effect is observed mainly due to the CMEE-H structure, which can form intermolecular hydrogen bonds contributing to the low mobility of the system.

The Vickers microhardness of a specimen is related to the mechanical properties of polymers generated and may be used as an indication of the stiffness of the materials formed. Low values for Vickers microhardness may indicate the formation of polymers with a low elastic modulus or the occurrence of phase separation of the components of the adhesive system.[20] It was not possible to determine the Vickers hardness for the formulation BisEMA/HEMA, because the indentation diagonals of this material were not visible, probably due to the generation of a polymer with low elastic modulus. This conclusion is corroborated by the visual aspect of the specimens prepared with the BisEMA/HEMA formulation immediately after the curing procedure, which were very soft and lacked the integrity required for hardness measurements. It is worth noting that in commercial dental systems, the percentage of HEMA used is lower than that used in this study. However, to better visualize the effect of the novel monomers, the amount of diluent monomer used to prepare the samples was increased. This was especially important when we compare very similar chemical structures like CMEE-2 and CMEE4.

The polymer prepared only with BisEMA presented a Vickers microhardness of 5.81 HV. Among the materials tested only BisEMA/CMEE-4 showed a microhardness value slightly lower than that reported for the control group, whereas the BisEMA/CMEE-2 formulation showed a slightly higher value than the control group. The BisEMA/CMEE-H formulation showed the significant microhardness result of 11.82 HV. Comparing the three novel synthesized monomers, only CMEE-H is able to interact with BisEMA through hydrogen bonds. This strong chemical interaction is probably responsible for the higher microhardess of the final polymer of BisEMA/CMEE-H.

The analysis of variance shows that the population means obtained are statistically different. The Tukey test results revealed that the pure BisEMA formulation is statistically similar to BisEMA/CMEE-2 and BisEMA/CMEE-4, although the latter two are different in relation to one another. Therefore, the statistical analysis performed in this study indicates that the BisEMA/CMEE-H formulation is the only one that really showed a greater hardness in comparison with the commercial formulation, whereas BisEMA/CMEE-2 and BisEMA/CMEE-4 are statistically equivalent. This result, together with the data obtained in the DSC analysis, suggests that the formulations prepared with the CMEE-2 and CMEE-4 monomers have matrices with high elastic modulus values, because their microhard-

ness values are comparable to that observed for the formulation containing BisEMA, despite the fact that they present a much lower T_g value. This result also suggests that the monomer CMEE-H is a potential substitute for HEMA in dental systems, because although a direct comparison between these formulations was not possible, one can assume that the hardness value of the BisEMA/HEMA formulation would be below the value for BisEMA/CMEE-H, because the former presented a pellet sample that did not have sufficient hardness to allow the marking of the indentation diagonal after its cure stage.

Figure 10 shows the micrographs of surfaces and cross-sections obtained for the studied systems. Once more, it was not possible to analyze the formulation BisEMA/HEMA due to the poor integrity of the specimen generated. Both the surface and the cross-section presented here were taken at 100× magnification, but micrographs obtained at other magnifications (not shown) were also evaluated and considered in the assessment of the matrix characteristics.

All of the formulations had a homogeneous matrix, and domains or phase separations were not observed, indicating good compatibility among the formulation components. The cross-section micrographs corroborate this conclusion. Furthermore, the cross-section micrographs of all samples also revealed the absence of air bubbles within the material, a factor that could increase the water solubility of the resinous material.[26] In the case of the BisEMA/CMEE-2 and BisEMA formulations some microparticles were present on the surface. These particles were analyzed by the EDS technique, which indicated the presence of calcium chloride at the specimen surface, probably added during the manipulation of the samples.

The aqueous behavior of the formulations studied is an important parameter in the preparation of dental resinous systems, because water is constantly present in the patient's oral environment. There are several studies in the literature focusing on the effects of water in a variety of physicochemical processes in the polymeric matrix. Such processes lead to biological implications and may be responsible for negative effects associated with the structure and behavior of this matrix.[27–29] When a polymer is placed in water, interactions between polymer chains are broken and hydrogen bonds are formed between the water and polar groups of the polymer network ($—OH$, $—C=O$, etc.), changing the molecular structure and increasing the mobility of polymer chain segments.

Table I shows the results obtained for the formulations studied after 4 weeks of water sorption. Unfortunately, the BisEMA/HEMA formulation is not represented due to the impossibility of attaining a cohesive matrix with the curing time used in this study.

Water sorption in polymer networks is controlled mainly by two factors: the polarity of the material, that is, the presence of polar groups available to form hydrogen bonds with water,[30,31] and the topology of the polymer network, which is related to the cohesive energy density of the polymer network.[32,33] Besides these factors, one should take into account that dental resinous systems usually have incomplete polymerization. When partially
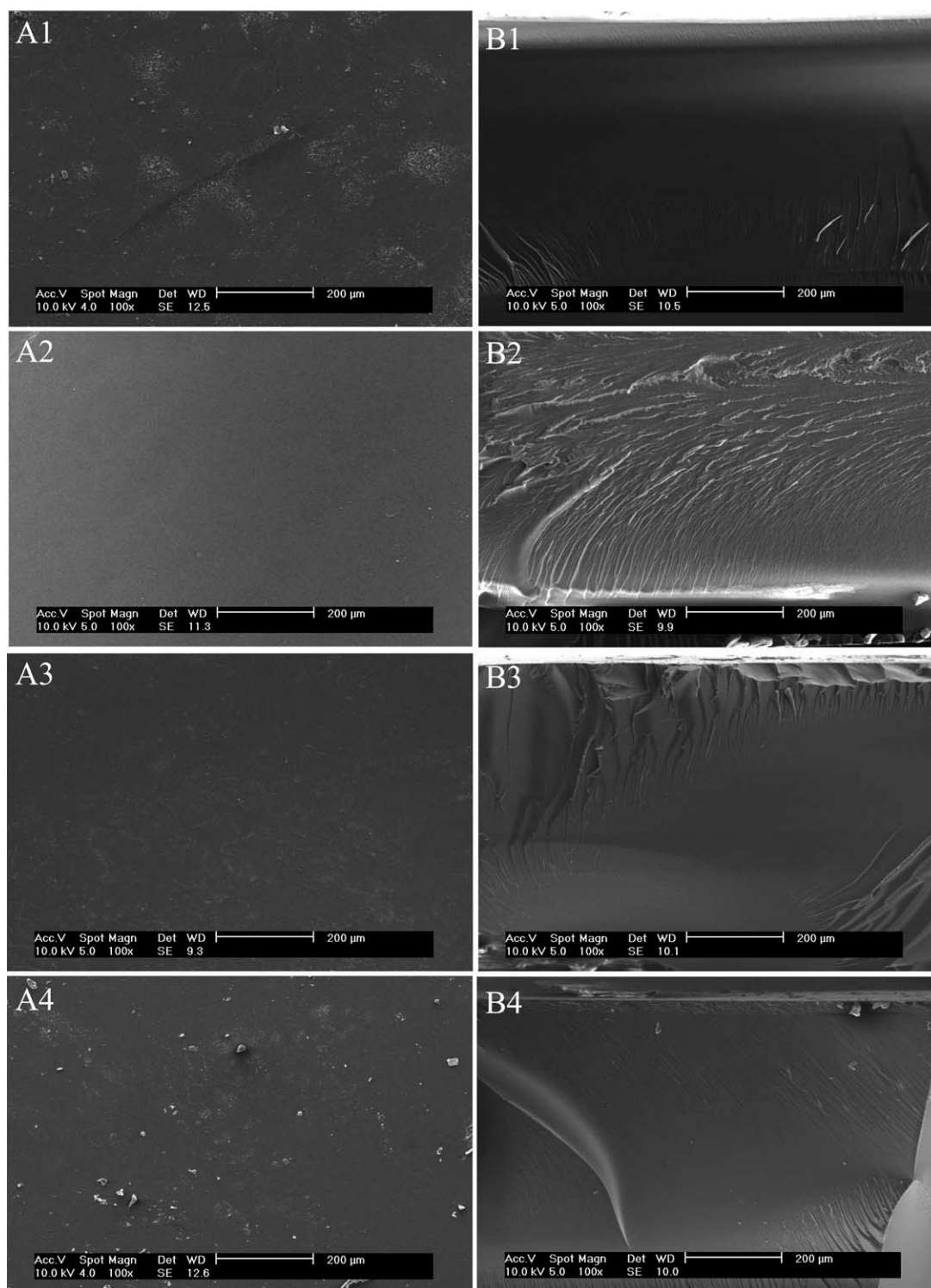
Figure 10. SEM of the (A) surface and (B) cross-section for the formulations: (A1,B1) BisEMA/CMEE-2; (A2,B2) BisEMA/CMEE-4; (A3,B3) BisEMA/CMEE-H, and (A4,B4) BisEMA. All micrographs were taken at 100× magnification.

polymerized samples are stored in water, the water infiltrates the material, increasing its weight. However, unreacted monomers trapped between the polymer chains or micropores can be released, reducing the sample weight.[14,29]

A similar behavior was observed for all experimental formulations, that is, there was a relatively high water uptake during the first week of tests followed by a reduction in the water sorbed the following week. The decrease in water sorption

observed may be related to two different factors: elution of uncured monomers trapped in the polymer matrix and the material's solubility in water, which act in conjunction with water sorption in the polymeric matrix. However, after the second week, it is highly unlikely that there are still unreacted monomers in the polymer matrix due to the prolonged immersion of the sample in water. In fact, after the second week, there was no significant variation in the water sorption values, which indicates that the water sorption equilibrium was reached. This observation is consistent with earlier studies,[34,35] which indicated a reduction in the rate of water sorption of a polymer matrix with increasing storage time. The formulation comprising only the commercial and hydrophobic monomer BisEMA absorbed almost no water during the first 2 weeks of tests and underwent a slight reduction in weight in the third week. This result was expected due to the hydrophobic character of BisEMA, whereas the other monomers tested had hydrophilic characteristic.

The analysis of variance indicated that the population means are statistically different. The Tukey test results ($P < 0.05$) were used to evaluate the difference between the groups and indicated that there was a difference between the results found for the BisEMA group compared with the other formulations. The BisEMA/CMEE-2, BisEMA/CMEE-4, and BisEMA/CMEE-H formulations, according to the Tukey test, are statistically similar. These results may primarily be due to the fact that the experimental monomers that composed the BisEMA/CMEE-2 and BisEMA/CMEE-4 formulations are structurally similar, and therefore their behaviors and interaction with water are similar. As the molecule used in the BisEMA/CMEE-H formulation is more hydrophilic than CMEE-2 and CMEE-4, it was expected that this characteristic could have increased the water sorption due to its polarity. Nevertheless, we must bear in mind that this formulation has a lower DC value when compared to the BisEMA/CMEE-2 and BisEMA/CMEE-4 formulations and thus, the effect of the elution of unreacted monomers from this sample is greater than for the other formulations, reducing the weight of the specimen.

The analysis of variance was also used to compare the relative sorption characteristics of each formulation during the 4-week period. In this case, all population means were significantly similar, which indicates that there is no statistical difference between the water sorption of pellets of the same formulation during this period, with the exception of the sorption between week 0 and week 1. This result suggests that after the first week of tests, where there was a relatively significant water sorption for all experimental formulations (between 3 and 6%), water sorption for all samples remained relatively stable until the end of week 4.

After the water sorption analysis, the pellets were placed in the vacuum oven and weighed daily until they reached constant weight. Using this value, it was possible to determine the solubility of the specimens in water by determining the difference between the initial mass of the specimen and the value after 4 weeks of testing. The results obtained are also presented in Table I.

The BisEMA/CMEE-2 formulation showed the greatest solubility in water, followed by BisEMA/CMEE-H. Taking into account

the DC values obtained for these formulations, which were 65.1% for BisEMA/CMEE-2 and 54.12% for BisEMA/CMEE-H, a lower weight loss for the former may be expected in comparison to the latter. However, besides the DC, the difference in the relative molecular size and hydrophilic/hydrophobic character of the monomers must be taken into account. The monomers in the BisEMA/CMEE-2 formulation have a higher molar mass than those in BisEMA/CMEE-H. Therefore, the elution of unreacted monomers from the former causes a greater reduction in the specimen weight than the elution of the same amount of unreacted monomers from the latter. Additionally, the monomers in the BisEMA/CMEE-2 and BisEMA/CMEE-H formulations are more hydrophilic than those in the pure BisEMA and CMEE-4.

The BisEMA/CMEE-2 group clearly showed a higher solubility than BisEMA/CMEE-4 group, despite the similar DC values found for the two formulations (65.1 and 63.36%, respectively). This result suggests that a monomer with a longer hydrocarbon chain would lead to a more flexible polymeric matrix, as suggested by the T_g values found for the samples analyzed, which is consistent with the lower microhardness of the BisEMA/CMEE-4 group. It is also worth noting that the increase in the hydrocarbon chain makes the CMEE-4 monomer less hydrophilic when compared to CMEE-2, which can also explain the lower solubility of CMEE-4 in water and reduces the water sorption capability of the BisEMA/CMEE-4 group. The analysis of variance results indicate that the population means are statistically different, and thus the Tukey test was performed to assess which of these results were different. There are statistical similarities between the results found for the BisEMA/CMEE-H group relative to the BisEMA/CMEE-2 and BisEMA/CMEE-4 groups, although these formulations were considered to be statistically different.

As BisEMA is a highly hydrophobic monomer, it was expected that this group would have lower solubility values when compared to the experimental monomers synthesized in this study, which are hydrophilic. However, the results obtained for the BisEMA/CMEE-2, BisEMA/CMEE-4, and BisEMA/CMEE-H formulations are considered satisfactory. It is worth noting that Table I shows a negative solubility for the BisEMA formulation, which probably indicates that this sample was not completely dry when the dry weight was recorded, that is, it still contained water molecules in its matrix.

The values for the water sorption and water solubility obtained in this study can be improved by varying factors such as the light irradiation time of the specimens and the addition of inorganic fillers to the adhesive system.[26,35,36] The addition of inorganic fillers to dental resinous systems usually results in improved hardness of the system, decreased water sorption, and reduced solubility.[23,26,35] These factors should be taken into account and investigated in future studies.

CONCLUSIONS

The results obtained suggest that the monomers synthesized in this study are promising diluent monomers and offer the possibility of replacing commercially used methacrylate monomers in

dental resinous systems. For this to be achieved, some aspects regarding their cytotoxicity and mechanical properties should be evaluated. The DC values obtained show that the double bond conversion is more efficient in the case of CMEE-2, CMEE-4, and CMEE-H in comparison with the control groups, allowing the formation of a denser crosslinked matrix. The values for the glass transition temperature indicate the formation of specimens with increasing flexibility as the molecular mass of the methacrylate monomer increased. Regarding the hardness results, the value obtained for the CMEE-H monomer was very satisfactory, indicating the formation of a matrix with a high elastic modulus. Despite the good hardness result obtained, BisEMA/CMEE-H formulation showed a lower DC value when compared to the other experimental monomers. This problem can be overcome by increasing the time of exposure to the light source. The scanning electron micrograph results provided some evidences to confirm the miscibility among the components for all formulations, with the absence of specific domains and phase separation. Tests for water sorption and solubility showed that after elution of the nonpolymerized monomers, the matrices were stable in aqueous solution.

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