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# Synthesis of Novel Antibacterial Monomers (UDMQA) and Their Potential Application in Dental Resin

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**ABSTRACT:** To prepare antibacterial dental resin, a series of novel urethane dimethacrylates quaternary ammonium methacrylate monomers (UDMQAs) with different substituted alkyl chain length were synthesized, and their structures were confirmed by FTIR and $^1$H-NMR spectra. The obtained UDMQAs were used to replace 2,2-Bis[4-(2-hydroxy-3-methacryloyloxypropyl)-phenyl]propane (Bis-GMA) totally as base monomers of dental resin and mixed with Tri-ethyleneglycol dimethacrylate (TEGDMA) at the mass ratio of 50/50. The properties of these prepared resins like antibacterial activity, double bond conversion (DC), polymerization shrinkage, flexural strength (FS), and modulus (FM), water sorption and sol fraction were investigated. The most commonly used dental resin Bis-GMA/TEGDMA (50wt/50wt) was chosen as a reference. The results showed that UDMQAs could endow dental resin with antibacterial activity. Compared with Bis-GMA-based dental resin, UDMQAs-based resin had the same or higher DC, lower polymerization shrinkage, lower flexural strength and modulus, and higher water sorption and sol fraction. © 2013 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 129: 3373–3381, 2013

**KEYWORDS:** photopolymerization; biomaterials; functionalization of polymers

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## INTRODUCTION

Methacrylate-based dental composites materials have been widely used in dental restorative treatment because of its excellent aesthetic property. However, methacrylate-based composite materials have been reported as accumulating more bacterial or plaque than ceramic or amalgam restorative materials *in vitro*[1] or *in vivo*[2–4] because of their low antibacterial activity. The bacteria survive in the micro gaps between the restorative material and the primed dentin or between the restorative material and the hybrid layer, will lead to bonding failure and generate secondary caries,[5] which has been considered as the most common reason for the replacement of restorations. Therefore, developing methacrylate-based dental restorative materials with antimicrobial properties have driven increasing attention in recent years.

One approach to endowing methacrylate-based restorative materials with antibacterial activity is incorporating methacrylate monomers with antibacterial functional group, such as quaternary ammonium structure. Quaternary ammonium compounds are one kind of well known antibacterial agents, which are widely used in surface coating, water treatment and food industries, for their low toxicity and broad spectrum antibacterial activity.[6–8] 1,2-methacryloyloxydodecylpyridinium bromide (MDPB) synthesized by Imazato and his co-workers, was the first methacrylate quaternary ammonium (MQA) used in dental restorative materials. It has already been reported that incorporating MDPB into restorative materials could decrease the attachment of *Streptococcus mutans* and plaque accumulation,[9–11] which would inhibit the progression of secondary caries.[12] After that, several MQAs were synthesized with the aim of preparing antibacterial dental restorative materials.[13–19] However, all of synthesized MQAs were only used as additional antibacterial agents, and none of them was investigated as base monomer of dental resin.

In this research, a series of dimethacrylates quaternary ammonium (UDMQAs) with different alkyl substituent chain length were synthesized and used to replace Bis-GMA as the base monomer of dental resin, antibacterial activity of obtained

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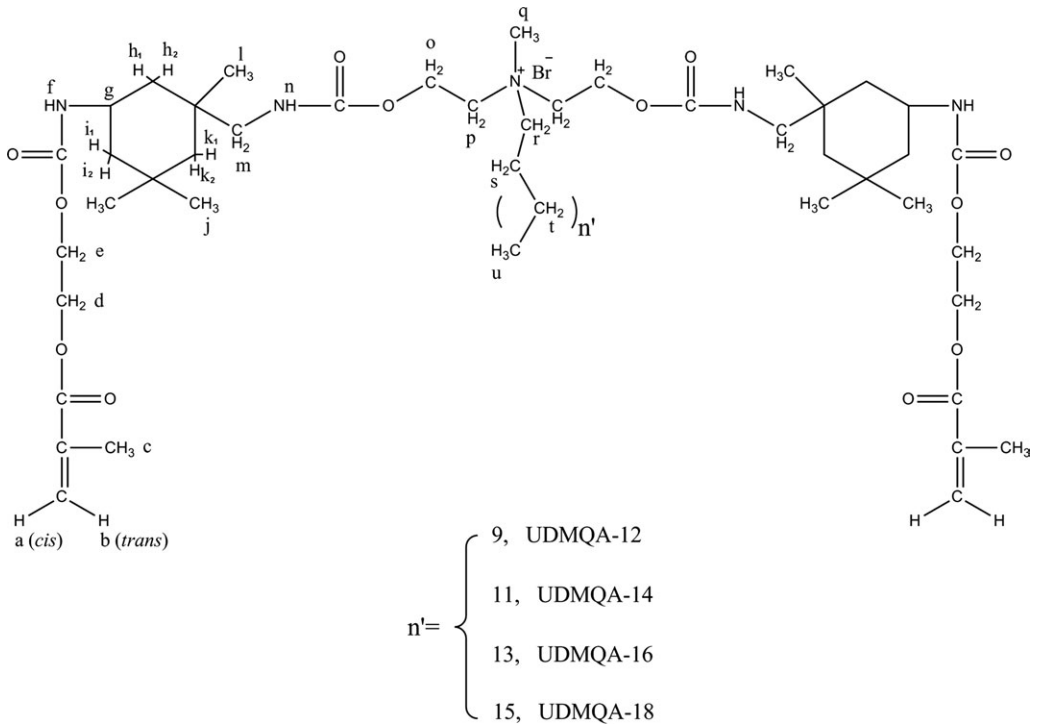


**Figure 1.** Structures of UDMQAs and the position of their protons.

polymer against *S.mutans* was investigated through direct contact test and agar diffusion test. Influence of these monomers on double bond conversion, polymerization shrinkage, mechanical properties, water sorption, and sol fraction were also studied. The most commonly used dental resin system Bis-GMA/TEGDMA (50/50, wt/wt) were used as a reference. The hypothesis is that UDMQAs could endow dental resin with antibacterial activity and decrease polymerization shrinkage of dental resin because of their high molecular weights.

## MATERIALS AND METHODS

### Materials and Instrument

N-methyl diethanol amine (MDEA), isophorone diisocyanate (IPDI), 2-hydroxyethyl methacrylate (HEMA), BisGMA, TEGDMA were purchased from Tokyo Chemical Industry. Dibutyltin dilaurate (DBTDL), hydroquinone, camphorquinone (CQ), 2-(*N*,*N*-dimethylamino)ethyl methacrylate (DMAEMA) were purchased from Energy Chemical. It was reported that quaternary ammonium with long alky chain between 12 and 18 carbon atoms had good bactericidal activity,[20] so 1-bromododecane (Br-12), 1-bromotetradecane (Br-14), 1-bromohexadecane (Br-16), 1-bromooctadecane (Br-18) purchased from Aladdin Chemistry were chosen as the alkyl substituent chain of quaternary ammonium compounds in this work. All of the compounds were used without further purification. FTIR spectra were measured on a Vector33 Model Fourier Transform Infrared Instrument (Bruker, Germany). The samples were in the form of KBr Pellets, and were scanned from 4000 to 400 $cm^{-1}$. $^1$H-NMR spectra were recorded on an Avance AV 400MHz Instrument (Bruker, Switzerland). The chemical shifts were reported in ppm on the $\delta$ scale with tetramethylsilane as the internal reference and $CDCl_3$ as the solvent.

### General Procedure for the Synthesis of Intermediate Product HQA

A mixture of MDEA (0.050 mol), alky bromide (0.052 mol), and 20 ml acetone were stirred at reflux. After 24-h reaction, then the acetone was removed by distillation under vacuum. The obtained raw product was filtered and washed with ethyl ether for several times. Then the white intermediate product HQA was dried under vacuum at 35°C for 48 h. The structure of HQA was investigated by FTIR, and $^1$H-NMR. All FTIR and $^1$H-NMR spectra of HQAs were shown in Figures 4 and 5.

### General Procedure for the Synthesis of UDMQA

IPDI, HEMA, and acetone used here were all dried over 4 Å molecular sieves for 2 weeks. First, a urethane precursor was synthesized via the reaction of 0.030 mol IPDI and 0.015 mol HQA in acetone as solvent and with a few droplets of DBTDL as catalyst. The reaction was carried out at 40°C in a reactor equipped with stirred, heating bath, reflux condenser, and dropping funnel under the $N_2$ blanket. The reaction was continued until the –NCO content, determined by dibutyl amine titration, reached half of the amount of the initial diisocyanate. Then 0.031 mol HEMA and a small amount of hydroquinone were added into the reactor. The reaction was continued under 40°C until the infrared absorbance peak of the –NCO group (2270 $cm^{-1}$) disappeared in the FTIR spectra of the samples taken from the reaction medium every 1 h. After removing the acetone by distillation under vacuum, the product was washed with diethyl ether and centrifuged to remove DBTDL, hydroquinone, and unreacted HEMA. The structure of UDMQA was investigated by FTIR and $^1$H-NMR. The general structure of UDMQA was shown in Figure 1. All FTIR and $^1$H-NMR spectra of UDMQAs were shown in Figures 4 and 6.

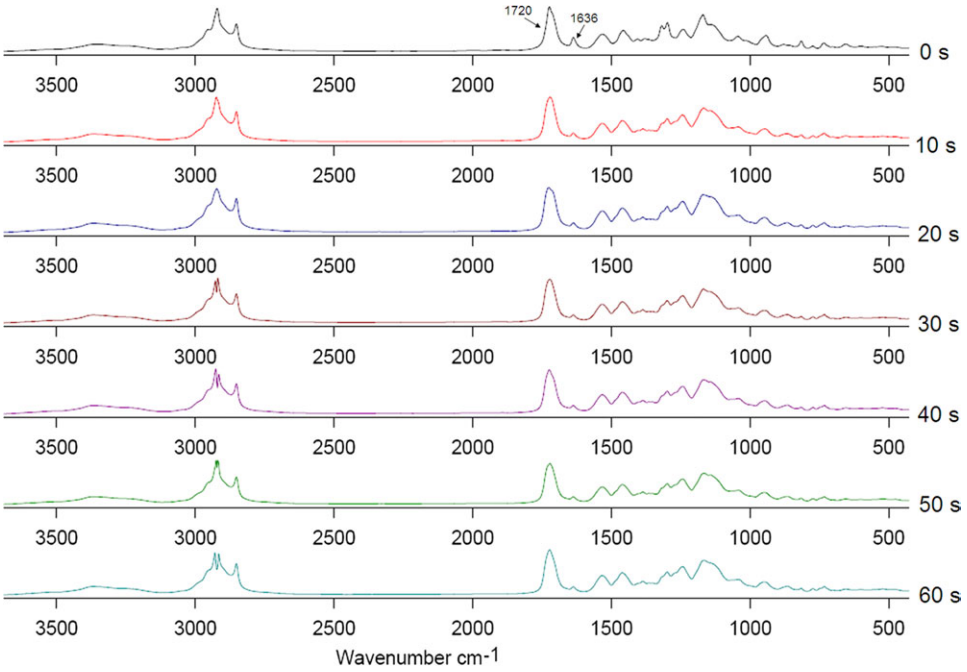


**Figure 2.** FTIR spectra of resin before and after being irradiated (UDMQA-12/TEGDMA resin formulation was taken as an example). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

### Preparation of Dental Resin Formulation

Photo-cured resin formulation was a mixture of UDMQA (or Bis-GMA), TEGDMA, CQ, and DMAEMA. Their mass ratio was 49.3:49.3:0.7:0.7 of UDMQA (or Bis-GMA)/TEGDMA/CQ/DMAEMA. All of resin formulations were stored in the dark before used.

### Measurement of Double Bond Conversion

The degree of double bond conversion (DC) during and after the photoinitiation of the polymerization was monitored by Fourier transform infrared spectroscopy (FTIR). One droplet of resin sample was coated on KBr Pellets to form a very thin film and the absorbance peak of the uncured sample was obtained. Then photopolymerization of the sample was carried out by irradiation of a dental light source (450mW/cm$^2$, QHL750, Dentsply International, USA) at room temperature. The spectra during the irradiation process were recorded every 10 s for 1 min (as shown in Figure 2). The DC was calculated from the aliphatic C=C peak at 1636 cm$^{-1}$ and normalized against the carbonyl C=O peak at 1720 cm$^{-1}$ according to the formula (1)

$$\mathrm{DC}(t) = \frac{(\mathrm{A_{C=C}}/\mathrm{A_{C=O}})_0 - (\mathrm{A_{C=C}}/\mathrm{A_{C=O}})_t}{(\mathrm{A_{C=C}}/\mathrm{A_{C=O}})_0} \quad (1)$$

where $\mathrm{A_{C=C}}$ and $\mathrm{A_{C=O}}$ are the absorbance peak area of methacrylate C=C at 1636 cm$^{-1}$ and carbonyl at 1720 cm$^{-1}$, respectively; $(\mathrm{A_{C=C}}/\mathrm{A_{C=O}})_0$ and $(\mathrm{A_{C=C}}/\mathrm{A_{C=O}})_t$ are the normalized absorbance of functional group at the radiation time of 0 and t, respectively; DC(t) is the conversion of methacrylate C=C as a function of radiation time.

### Measurement of Polymerization Shrinkage

Polymerization shrinkage was determined by density change of resin before and after curing. First, density of uncured resin was determined. A 10ml density bottle was weighed, filled with uncured resin and weighed again. The same bottle was then emptied, thoroughly washed and dried, filled with distilled water and weighed again. This procedure was repeated five times. The density of resin before curing ($D_r$) was then calculated as:

$$D_r = (M_r/M_w) \times D(T) \quad (2)$$

where $D(T)$ is the density of water at the room temperature, $M_r$ is the mass of uncured resin, $M_w$ is the mass of water.

Second, density of cured resin was determined. Resins were poured into a Teflon mold sized 25 mm × 2 mm × 2 mm, then light-cured using a dental light source at room temperature and about 5 mm of distance between the light tip and the radiometer face. Five specimens for every resin formulation were prepared. The cured resin specimen was removed and weighed to obtain the mass of cured resin ($M_s$). A 10 mL density bottle was filled with distilled water and weighed to obtain the mass of water and bottle ($M_{\mathrm{wb}}$). Cured resin was put into the bottle, spilled water was gently wiped with a soft absorbent paper, and then the bottle with water and cured resin was weighed to obtain $M_{\mathrm{sw}}$. The density of resin after curing ($D_s$) was calculated as:

$$D_s = \frac{M_s}{M_{\mathrm{wb}} + M_s - M_{\mathrm{sw}}} \times D(T) \quad (3)$$

Hence, the polymerization shrinkage ($S$) was calculated as:

$$S = \frac{D_s - D_r}{D_s} \times 100\% \quad (4)$$

### Three Point Bending Test

Eight specimens were prepared for every resin formulation (size 2 mm × 2 mm × 25 mm). Three point bending test (span 20 mm)

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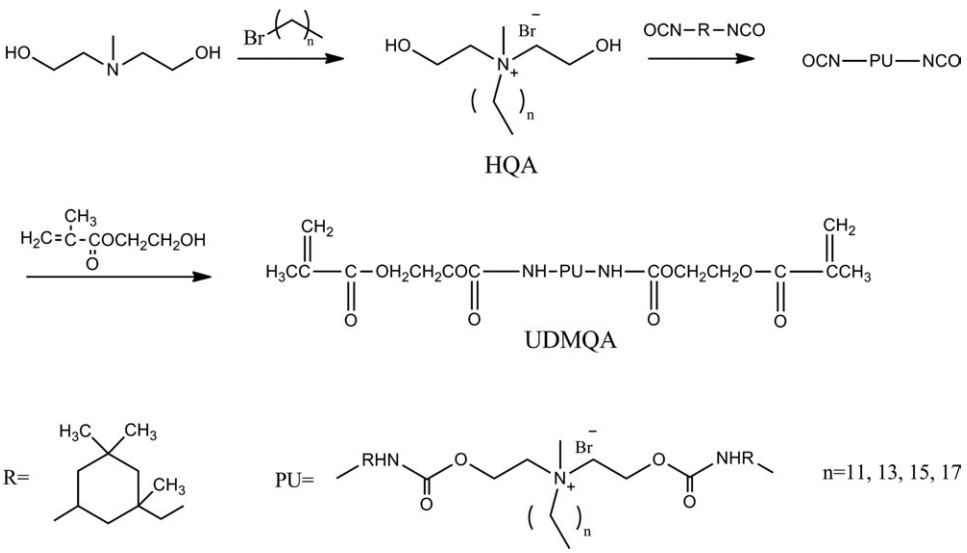


**Figure 3.** Synthesis route of UDMQAs.

was carried out to evaluate the flexural strength and modulus according ISO 10477:92 standard with a universal testing machine (Model Z010, Zwick GmbH & Co. KG, Germany) at a cross-head speed of 1.00 mm/min.

### Measurement of Water Sorption and Sol Fraction

Resins were added into a cylindrical Teflon mold with an internal diameter of 10 mm and a height of 1.0 mm, then light-cured for 60 s using a dental light source. Three specimens of each sample were prepared. The specimens were placed in a desiccator at room temperature under normal pressure and weighed every 24 h until a constant mass ($M_1$) was obtained (i.e., variation was less than 0.0001 g in any 24 h period). Afterwards, the specimens were immersed in distilled water. At fixed time intervals they were removed, blotted dry to remove excess water, weighed and returned to the water. Equilibrium mass ($M_2$) was obtained until there was no significant change in mass. The specimens were then dried at 60°C until their mass was constant, and the result was recorded as $M_3$. Water sorption (WS) and sol fraction (SF) were then calculated using the following formulae.

$$\mathrm{WS} = \frac{M_2 - M_3}{M_3} \times 100\% \quad (5)$$

$$\mathrm{SF} = \frac{M_1 - M_3}{M_1} \times 100\% \quad (6)$$

### Antibacterial Activity Test

Eight discs (1 mm thick and 15 mm in diameter) for every resin formulation were prepared for antibacterial activity test, five for direct contact test and three for agar diffusion test. All the cured specimens were immersed in distilled water for 24 h to remove unpolymerized monomer, and dried at 37°C. Before antibacterial test, all of specimens were sterilized by ultraviolet light for 20 min.

**Direct Contact Test (DCT).** After 24 h of anaerobic culture, suspension of *S. mutans* was adjusted to about $1 \times 10^7$ CFU/mL with brain heart infusion (BHI, Becton, Dickinson and Company, Sparks, MD) broth. Every cured resin was put in one well of a 24-well plate, and 50 $\mu$L of bacterial suspension was inoculated on the surface of the sample. After 12 h of anaerobic incubation at 37°C, 2 mL phosphate buffer solution (PBS) was added into each well, and the 24-well plate was vibrated under ultrasonic for 10 min. Totally, 100 $\mu$L of bacteria suspension was taken from every well and serially diluted with BHI broth. Finally, 20 $\mu$L of each diluted sample was inoculated on BHI agar plate, incubated anaerobically at 37°C for 48 h. The number of recovered bacteria was determined by counting the colonies.

**Agar Diffusion Test.** After 24 h of anaerobic culture, suspension of *S. mutans* was adjusted to about $1 \times 10^7$ CFU/mL with BHI broth. Totally, 300 $\mu$L of *S. mutans* suspension was spread on BHI agar plates, and cured disc specimens of every resin formulation were placed on the surface. The plates were incubated for 48 h at 37°C, and the inhibition zone around every specimen was measured.

### Statistical Analysis

The results were analyzed and compared using one-way ANOVA and Turkey's test at the significance level of 0.05.

## RESULTS

As shown in Figure 3, UDMQAs were synthesized via a three steps route. First, intermediate compounds HQAs were prepared by reacting the *N*-methyl diethanol amine with different commercial alkyl bromides through Menschutkin reaction, and then HQAs reacted with IPDI to form isocyanate terminated urethane precursors. Finally, UDMQAs were obtained by the reaction of isocyanate terminated urethane precursors with 2-hydroxyethyl methacrylate. All the structures of the UDMQAs and intermediate products HQAs were confirmed by FTIR (Figure 4) and $^1$H-NMR (Figures 5 and 6).

Figure 7 reflected the relationship between DC and irradiation time. As can be seen from Figure 7, all of dental resin had nearly the same photopolymerization behavior, DC increased significantly with increasing radiation time, and reached a maximum at nearly 20 s of radiation time; then, DC did not increase

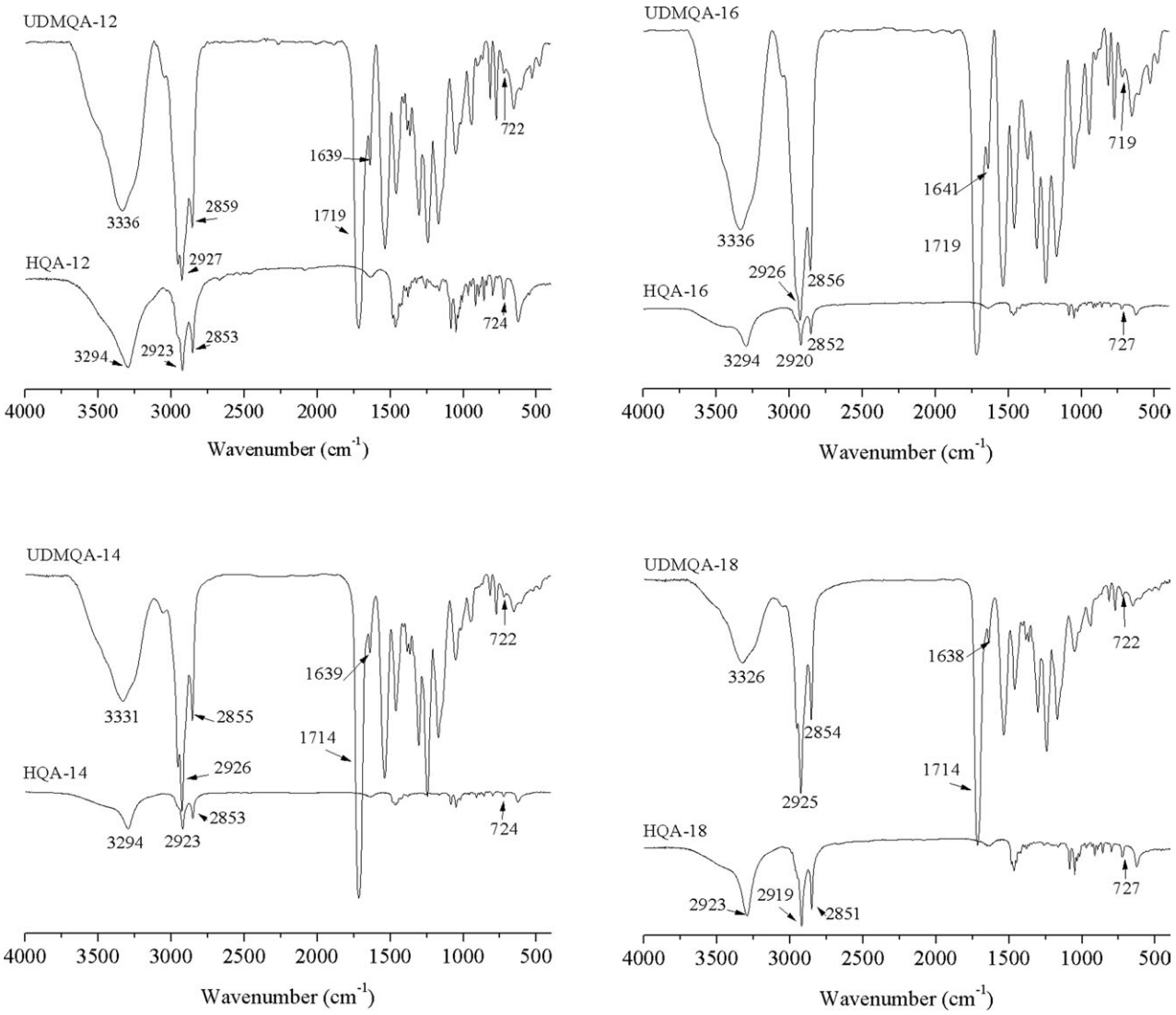


**Figure 4.** FTIR spectra of all HQAs and UDMQAs.

obviously with prolonged radiation time. The DC obtained for resins based on Bis-GMA and UDMQAs are listed in Table I. DC of UDMQA-12 and UDMQA-14-based resins were nearly the same as the DC of Bis-GMA-based resin ($P > 0.05$), while DC of UDMQA-16 and UDMQA-18-based resins were higher than that of Bis-GMA-based resin ($P < 0.05$).

Polymerization shrinkage, flexural strength (FS) and modulus (FM), water sorption and sol fraction, and results of DCT were summarized in Table I. All UDMQAs-based polymers had lower polymerization shrinkage, lower FS and FM, higher water sorption and sol fraction ($P < 0.05$) than Bis-GMA-based resin. The amounts of *S. mutans* recovered from the surface of UDMQAs-based polymer were less than that recovered from the surface of Bis-GMA-based polymer ($P < 0.05$), and the alkyl substituent chain length had no influence on the antibacterial activity of UDMQAs-based polymer ($P > 0.05$).

All of experimental dental polymers did not yield an inhibition zone on the agar plates inoculated with *S. mutans* (Figure 8).

## DISCUSSIONS

Since dental caries has been recognized as an infectious disease induced by cariogenic bacteria, attempts to create antibacterial restorative materials has become an attractive topic in dental materials science.[21] In this work, a series of large size molecules UDMQAs with quaternary ammonium structure were designed and synthesized to be used as antibacterial base monomer of dental resin.

When Bis-GMA in Bis-GMA/TEGDMA (50/50, wt/wt) resin system was totally replaced by UDMQAs, there was no negative effect on DC of resin, and even the DC of UDMQA-16 and UDMQA-18-based resins were higher than that of Bis-GMA-based resin ($P < 0.05$). The increase of DC might be mainly due to the long alkyl chain of quaternary ammonium salt present in the structure of UDMQAs, which could weaken the intermolecular interaction by increasing the distance and reducing the chain entanglement between polymer chains.[22] When the intermolecular interaction is decreased, the flexibility of

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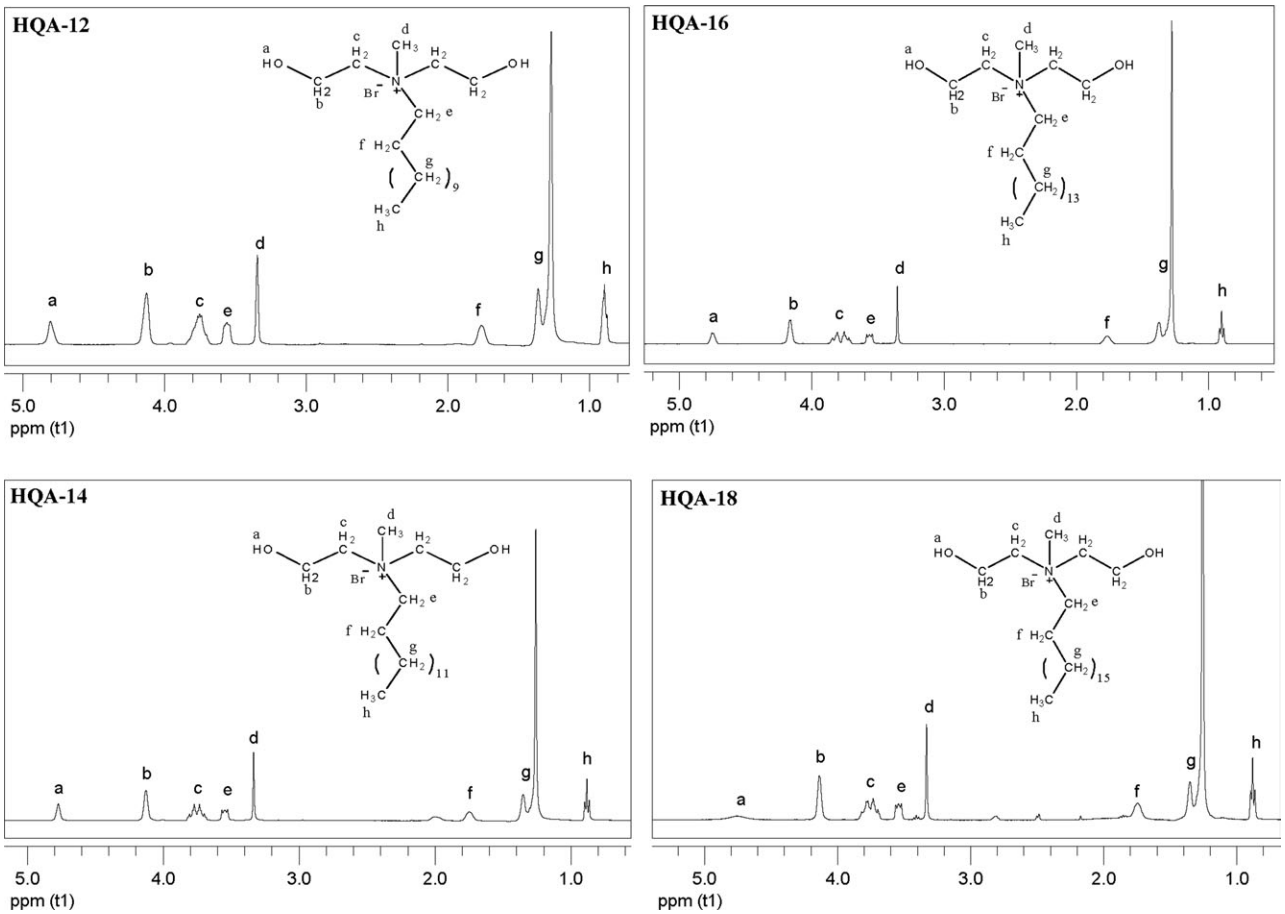


**Figure 5.** $^{1}$H-NMR spectra of HQAs.

polymeric network can be increased, and as a result of this, vitrification time will be delayed, leading to higher DC.[23] Compared with the FS and FM of Bis-GMA-based polymer, the lower FS and FM ($P < 0.05$) of UDMQAs-based polymers should also be attributed to the weaker intermolecular interaction of their polymer chain.

Water sorption and sol fraction are two important parameters for methacrylate-based dental materials. Water sorption represents the amount of water absorbed on the surface and into the material. The water intrusion in dental restorative materials can induce adverse effects to the materials, such as impairing mechanical properties,[24] elution of unreacted monomers,[25] hydrolysis,[26] and reducing thermal stability[27] in short an longer term. Sol fraction reveals the amount of unreacted monomers releasing out of the polymer network. The problem of sol fraction is that the released monomers may possibly lead to cytotoxicity and induce tissue inflammatory response of dental pulp and adjacent tissues.[28] Therefore, water sorption and sol fraction of methacrylate-based dental resin should not be too high. Unfortunately, all of UDMQAs-based polymers had higher water sorption and sol fraction than that of Bis-GMA-based polymer. In the structure of UDMQAs, there exist both positive and negative charges, which can absorb water,[29] so water sorption of UDMQAs containing polymers were higher than that of control polymer. Moreover, the weaker intermolecular interaction of UDMQAs containing polymers chain as mentioned above can also be a reason for their higher water sorption. Although UDMQAs-based polymers had higher DC than control polymer, which could lead to less unreacted monomers remaining in the polymer, their sol fractions were higher than control polymer's sol fraction. This might be attributed to the higher water sorption and weaker intermolecular interaction of UDMQAs-based polymers, which made unreacted monomers to be eluted more easily.

Polymerization shrinkage is the major drawback of methacrylate-based dental materials which may bring on marginal gaps between the tooth and the material, and the pathogenic bacteria can invade into the gaps, leading to recurrent caries.[30] Therefore, to some extent, possibility of secondary caries could be reduced if polymerization shrinkage of restorative materials was decreased. It was noticed that all of UDMQAs-based dental resins had lower polymerization shrinkage than Bis-GMA-based resin, and it would be the beneficial aspect when bring them into practical application. Compared with Bis-GMA (512), UDMQAs have higher molecular weight (1073 for UDMQA-12, 1101 for UDMQA-14, 1129 for UDMQA-16, and 1157 for UDMQA-18), which can decrease the double bond concentration in the resin system, and this should be the main reason for lower shrinkage of UDMQAs-based resins.[31,32]

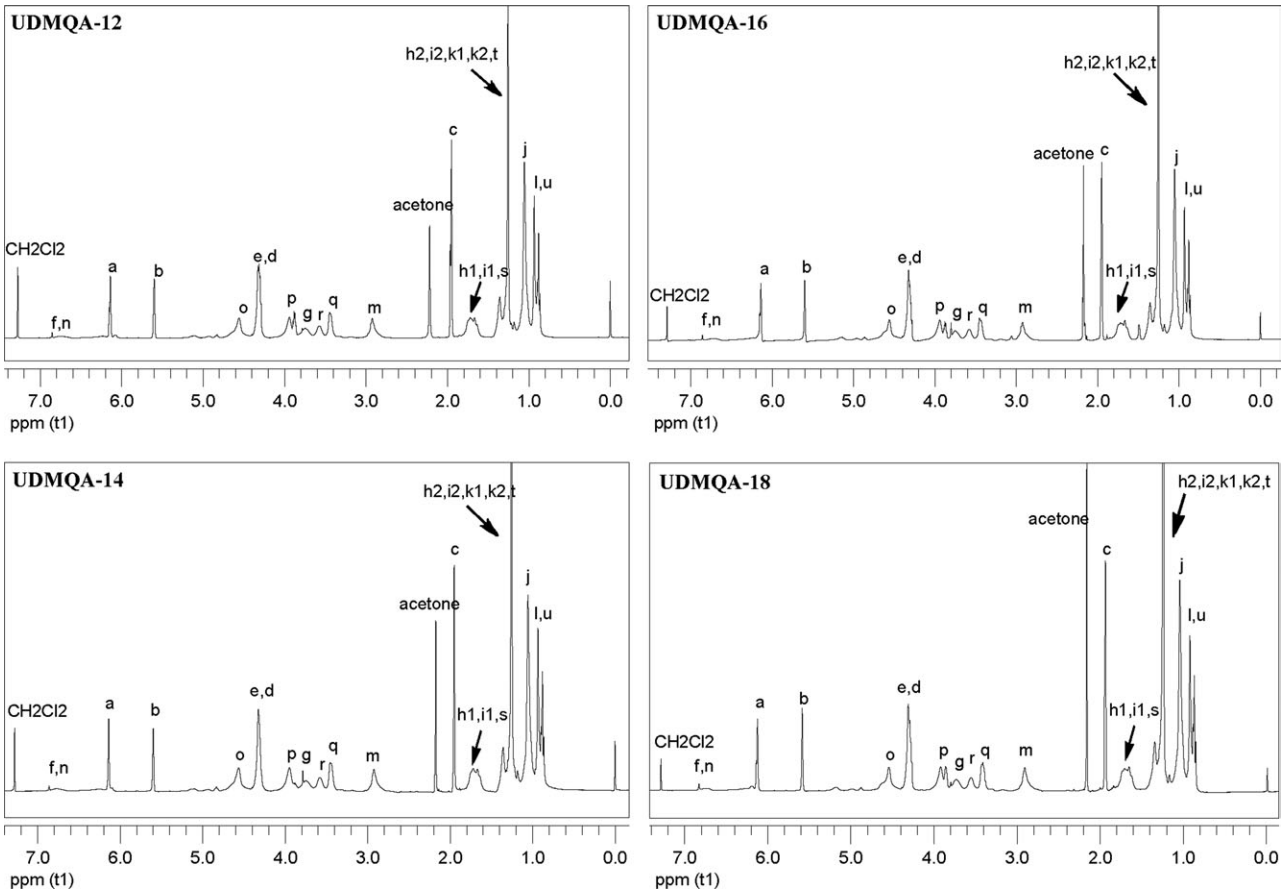


**Figure 6.** $^{1}$H-NMR spectra of UDMQAs.

From the results of DCT (Table I), it can be seen that the amounts of *S. mutans* recovered from the surface of UDMQAs-based resins were lower than that recovered from the surface of Bis-GMA-based resin, which means that UDMQAs-based resins had antibacterial activity against *S. mutans* owing to their quaternary ammonium structure.

Two antibacterial mechanisms could be used to explain the antibacterial activity of UDMQAs-based polymers: (i) the unreacted UDMQAs compounds released from the polymer into bacterial suspension can devitalize *S. mutans* in the suspension,[33,34] or (ii) the *S. mutans* attached to the surface of polymer is killed by UDMQAs which are immobilized in the polymer,[33,35] hence the lower amount of *S. mutans* recovered from the surface of UDMQAs-based polymers as compared to control. To know whether the antibacterial activity of UDMQAs-based polymer is due to the first or the second mechanism, ADT was carried out. As shown in Figure 8(f), an inhibition zone appears around the disc if antibacterial agent can be released from the disc into agar plate. According to ADT result, no inhibition zone can be observed from any agar plates with UDMQAs-based polymer [Figure 8(b–e)]. Therefore, the antibacterial activity of UDMQAs-based polymer was mainly attributed to the UDMQAs which were immobilized in the polymer network (i.e., second mechanism).

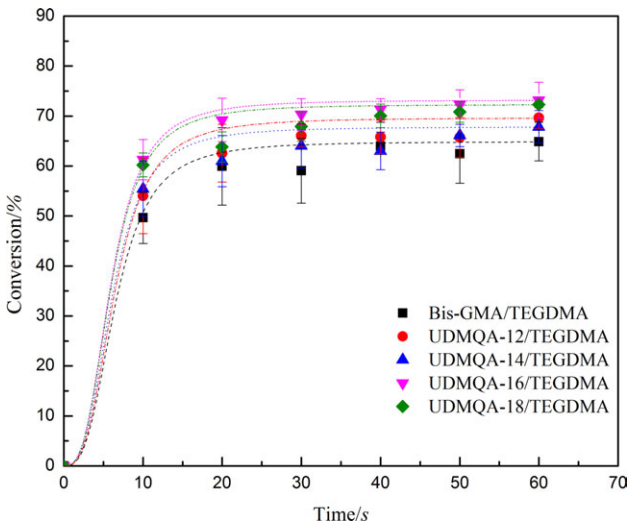


**Figure 7.** Double bond conversion versus irradiation time for all experimental resins. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

**Table I.** Double Bond Conversion, Polymerization Shrinkage, Flexural Strength and Modulus, Water Sorption, Sol Fraction and Results of Direct Contact Test

| | Properties (mean ± SD*) | | | | | | |
|---|---|---|---|---|---|---|---|
| Resin formulation | Double bond conversion (%) | Polymerization shrinkage (%) | Flexural strength (MPa) | Flexural modulus (GPa) | Water sorption (%) | Sol fraction (%) | Recovered S. mutans (Log(CFU/mL)) |
| Bis-GMA/TEGDMA | 64.9 ± 3.9$^{a}$ | 9.1 | 96.3 ± 9.3$^{a}$ | 2.31 ± 0.23$^{a}$ | 4.10 ± 0.10$^{a}$ | 2.31 ± 0.33$^{a}$ | 8.08 ± 0.02$^{a}$ |
| UDMQA-12/TEGDMA | 68.5 ± 0.8$^{a}$ | 7.3 | 78.4 ± 4.4$^{b}$ | 2.01 ± 0.17$^{b}$ | 8.62 ± 0.08$^{b}$ | 6.59 ± 0.24$^{b}$ | 7.89 ± 0.10$^{b}$ |
| UDMQA-14/TEGDMA | 66.2 ± 0.8$^{a}$ | 7.5 | 65.0 ± 6.9$^{c}$ | 1.76 ± 0.16$^{b,c}$ | 9.00 ± 0.07$^{c}$ | 5.81 ± 0.21$^{c}$ | 7.83 ± 0.15$^{b}$ |
| UDMQA-16/TEGDMA | 73.2 ± 3.6$^{b}$ | 7.3 | 74.5 ± 4.9$^{b,c}$ | 1.83 ± 0.12$^{b}$ | 8.17 ± 0.07$^{d}$ | 5.11 ± 0.23$^{d}$ | 7.91 ± 0.06$^{b}$ |
| UDMQA-18/TEGDMA | 72.3 ± 0.6$^{b}$ | 7.1 | 56.6 ± 2.5$^{d}$ | 1.53 ± 0.13$^{c}$ | 7.87 ± 0.09$^{e}$ | 7.09 ± 0.19$^{e}$ | 7.96 ± 0.02$^{b}$ |

*Lower case letters indicate statistical differences with a column (Tukey's test, $P = 0.05$).

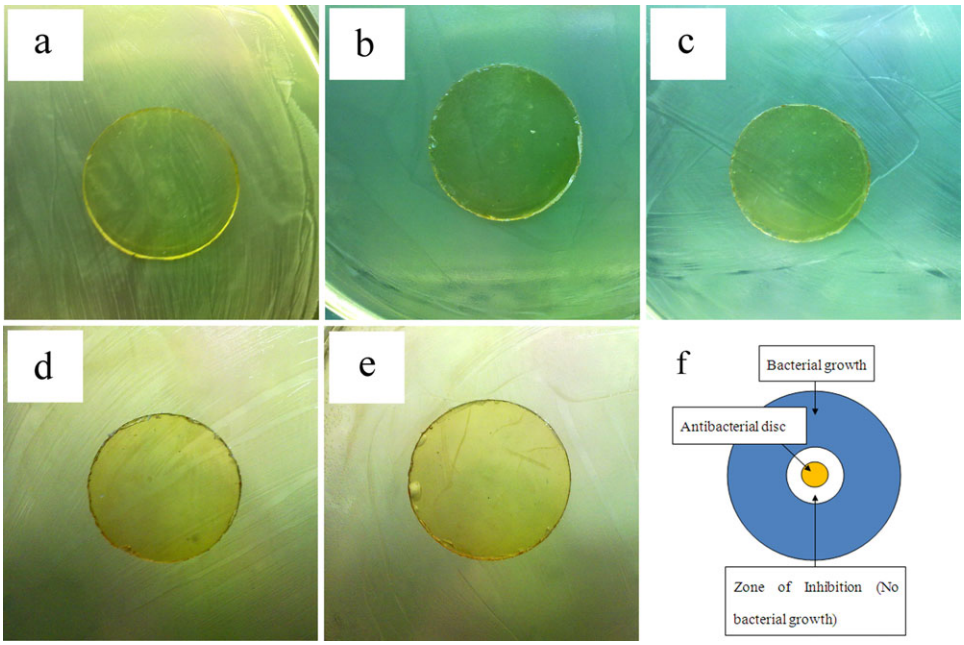


**Figure 8.** Pictures of Agar diffusion test: Bis-GMA-based polymer (a), UDMQA-12-based polymer (b), UDMQA-14-based polymer (c), UDMQA-16-based polymer (d), UDMQA-18-based polymer (e), and a typical diagram of ADT (f). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

## CONCLUSIONS

A series of novel dental resins were prepared by using synthesized dimethacrylate quaternary ammonium compounds UDMQAs as base monomers. Although the UDMQAs-based polymers had antibacterial activity, and lower polymerization shrinkage when compared with the Bis-GMA-based polymer, the lower flexural strength and modulus, higher water sorption and sol fraction of UDMQAs-based polymers are parameters which need to be improved before considering further preclinical research.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Tanner, J.; Robinson, C.; Söderling, E.; Vallittu, P. K. *Clin. Oral. Invest.* **2005**, *9*, 154.
2. Beyth, N.; Domb, A. J.; Weiss, E. *J. Dent.* **2007**, *35*, 201.
3. Tanner, J.; Carlén, A.; Söderling, E.; Vallittu, P. K. *J. Biomed. Mater. Res.* **2003**, *15*, 391.
4. Tanner, J.; Vallittu, P. K.; Söderling, E. *Biomaterials* **2001**, *22*, 1613.

5. Mjör, I. A.; Moorhead, J. E.; Dahl, J. E. *Int. Dent. J.* **2000**, *50*, 361.
6. Simoncic, B.; Tomsic, B. *Textil. Res. J.* **2010**, *80*, 1721.
7. Kenawy, E. R.; Worley, S. D.; Broughton, R. *Biomacromolecules.* **2007**, *8*, 1359.
8. Moran, J.; Addy, M.; Jackson, R.; Newcombe, R. G. *J. Clin. Periodontol.* **2000**, *27*, 37.
9. Imazato, S.; Torii, M.; Tsuchitani, Y.; McCabe, J. F.; Russell, R. R. B. *J. Dent. Res.* **1994**, *73*, 1437.
10. Imazato, S.; Russell, R. R. B.; McCabe, J. F. *J. Dent.* **1995**, *23*, 177.
11. Imazato, S. *Dent. Mater.* **2003**, *19*, 449.
12. Thome, T.; Mayer, M. P. A.; Imazato, S.; Geraldo-Martins, V. R.; Marques, M. M. *J. Dent.* **2009**, *37*, 705.
13. Xiao, Y. H.; Chen, J. H.; Fang, M.; Xing, X. D.; Wang, H.; Wang, Y. J.; Li, F. *J. Oral. Sci.* **2008**, *50*, 323.
14. Xiao, Y. H.; Ma, S.; Chen, J. H.; Chai, Z. G.; Li, F.; Wang, Y. J. *J. Biomed. Mater. Res. B Appl. Biomater.* **2009**, *90*, 813.
15. Chai, Z.; Li, F.; Fang, M.; Wang, Y.; Ma, S.; Xiao, Y.; Huang, L.; Chen, J. *J. Oral. Rehabil.* **2011**, *38*, 849.
16. Antonucci, J. M.; Zeiger, D. N.; Tang, K.; Lin-Gibson, S.; Fowler, B. O.; Lin, N. J. *Dent. Mater.* **2012**, *28*, 219.
17. Huang, L.; Xiao, Y. H.; Xing, X. D.; Li, F.; Ma, S.; Qi, L. L.; Chen, J. H. *Arch. Oral. Biol.* **2011**, *56*, 367.
18. He, J.; Söderling, E.; Österblad, M.; Vallittu, P. K.; Lassila, L. V. J. *Molecules.* **2011**, *16*, 9755.
19. He, J.; Söderling, E.; Vallittu, P. K.; Lassila, L. V. J. *Dent. Mater.* **2012**, *28*, e110.
20. Thorsteinsson, T.; Másson, M.; Kristinsson, K. G.; Hjálmarsdóttir, M. A.; Hilmarsson, H.; Loftsson, T. *J. Med. Chem.* **2003**, *46*, 4173.
21. Imazato, S.; Chen, J. H.; Ma, S.; Izutani, N.; Li, F. *Japan. Dent. Sci. Rev.* **2012**, *48*, 115.
22. Xu, X.; Wang, Y.; Liao, S.; Wen, Z. T.; Fan, Y. *J. Biomed. Mater. Res. Part B: Appl. Biomater. B* **2012**, *100*, 1151.
23. Sideridou, I. D.; Tserki, V.; Papanastasiou, G. *Biomaterials* **2002**, *23*, 1819.
24. Sideridou, I. D.; Karabela, M. M.; Vouvoudi, E. C. *Dent. Mater.* **2008**, *24*, 737.
25. Ferracane, J. L.; Condon, J. R. *Dent. Mater.* **1990**, *6*, 282.
26. Soderholm, K. J.; Zigan, M.; Ragan, M.; Fischlshweiger, W.; Bergman, M. *J. Dent. Res.* **1984**, *63*, 1248.
27. Costella, A. M.; Trochmann, J. L.; Oliveira, W. S. *J. Mater. Sci. Mater. Med.* **2010**, *21*, 67.
28. Chang, M. C.; Lin, L. D.; Chuang, F. H.; Chan, C. P.; Wang, T. M.; Lee, J. J.; et al. *Acta. Biomater.* **2012**, *8*, 1380.
29. Weng, J.; Guo, X.; Chong, V. J.; Howard, L.; Gregory, R. L.; Xie, D. *J. Biomed. Sci. Eng.* **2011**, *4*, 147.
30. He, J. W.; Liu, F.; Luo, Y. F.; Jia, D. M. *J. Appl. Polym. Sci.* **2012**, *125*, 114.
31. Patel, M. P.; Braden, M.; Davy, K. W. M. *Biomaterials.* **1987**, *8*, 53.
32. Dewael, M.; Truffier-Boutry, D.; Devaux, J.; Leloup, G. *Dent. Mater.* **2006**, *22*, 359.
33. Rupf, S.; Balkenhol, M.; Sahrhage, T. O.; Baum, A.; Chromik, J. N.; Ruppert, K.; et al. *Dent. Mater.* **2012**, *28*, 974.
34. Balamurugan, A.; Balossier, G.; Laurent-Maquin, D.; Pina, S.; Rebelo, A. H.; Faure, J.; et al. *Dent. Mater.* **2008**, *24*, 1343.
35. Imazato, S.; Imai, T.; Russell, R. R.; Torii, M.; Ebisu, S. J. *J. Biomed. Mater. Res.* **1998**, *39*, 511.