(54) Title: NOVEL PHOTOPOLYMERS AND USE IN DENTAL RESTORATIVE MATERIALS

(57) Abstract: Photopolymerizable polymer composites based on dimethacrylate systems have been increasingly utilized as dental restorative materials. One of the biggest drawbacks of current dental resin systems is the volume shrinkage and shrinkage induced stresses that arise during the polymerization. Other major problems include incomplete double bond conversion and insufficient wear resistance. This invention involves the development of an entirely novel approach to the photopolymerization process that utilizes thiol-ene systems as low shrinkage and ultra-low shrinkage stress dental restorative materials. Compared with the traditional dimethacrylate dental resins, these novel photopolymizations have demonstrated a dramatically decreased volume shrinkage, extremely rapid polymerization, abilities to photopolymerize ultrathick materials and achieve much higher conversion, lack of oxygen inhibition and ultra-low shrinkage stress due to low volume shrinkage and drastically delayed gel point conversion. These polymers have thus shown outstanding suitability as dental restorative materials.
NOVEL PHOTOPOLYMERS AND USE IN DENTAL RESTORATIVE
MATERIALS

Statement Regarding Federally Sponsored Research or Development

The invention was sponsored by NIH Grant No. DE 10959-05 and the
government has certain rights to this invention.

Field of the Invention

The present invention relates to a thiol-ene polymer system with high
conversion and more particularly to a thiol-ene polymer system for use as a dental
restorative resin.

Background

Currently, commercial photoactivated dental restorative resins are based on
dimethacrylates and the reaction mechanism is through chain-growth free radical
polymerization. Existing dimethacrylate systems are popular for fillings and other
dental prostheses because of their esthetic merit and "cure-on-command" feature.

Such dental restorative materials are often mixed with 45 to 85% by weight
(wt%) silanized filler compounds such as barium, strontium, zirconia silicate and/or
amorphous silica to match the color and opacity to a particular use or tooth. The
filler is typically in the form of particles with a size ranging from 0.01 to 5.0
micrometers.

The photoactivated restorative materials are often sold in separate syringes or
single-dose capsules of different shades. If provided in a syringe, the user dispenses
(by pressing a plunger or turning a screw adapted plunger on the syringe) the
necessary amount of restorative material from the syringe onto a suitable mixing
surface. Then the material is placed directly into the cavity, mold, or location of use.
If provided as a single-dose capsule, the capsule is placed into a dispensing device
that can dispense the material directly into the cavity, mold, etc. After the
restorative material is placed, it is photopolymerized or cured by exposing the
restorative material to the appropriate light source. The resulting cured polymer
may then be finished or polished as necessary with appropriate tools. Such dental
restoratives can be used for direct anterior and posterior restorations, core build-ups,
splinting and indirect restorations including inlays, onlays and veneers.
Although easy to use, these systems have several drawbacks, primarily associated with the polymerization volume shrinkage and shrinkage stress, and poor conversion of the dimethacrylate systems' monomers into polymer. The current systems can only reach a final double bond conversion of 55 to 75%, which not only contributes to the insufficient wear resistance and mechanical properties, but also jeopardizes the biocompatibility of the composites due to the leachable unreacted monomers. Dimethacrylate based resins exhibit significant volumetric shrinkage during polymerization and the induced shrinkage stress results in tooth-composite adhesive failure, initiating microleakage and recurrent caries, which significantly reduces the longevity and utility of current dental restorative composite.

Furthermore, as one tries to increase the final double bond conversion to reduce the unreacted monomers, the volumetric shrinkage and shrinkage stress unfortunately also increase, which has been a persisting problem since the development of this class of resins.

Yet another drawback associated with the current systems is odor. Because the polymers are polymerized in the mouth, odors are highly perceptible by the patient. Dimethacrylate based systems, due to the low conversion, after polymerization experience a high amount of leaching of unreacted monomers, which results in an unwanted and offensive taste and odor for some period of time after the procedure.

**Summary of the Invention**

The present invention can be thought of as a thiol-ene polymer system with a high conversion, low shrinkage and low shrinkage stress during curing. The thiol-ene system for use in making dental prosthetics having 10%-90% by weight of its functional groups as thiol functional groups (-SH) is disclosed. The thiol-ene system preferably has 10%-90% by weight of its functional groups as thiol functional groups, more preferably 15%-60% by weight thiol functional groups and even more preferably 45%-55% by weight thiol functional groups. In some embodiments, the balance of the functional groups in the system may consist of vinyl groups or may be a combination of vinyl groups and other functional groups.

Prior art dental restorative resins are based on dimethacrylates that use a chain-growth free radical polymerization mechanism. The thiol-ene polymerization proceeds through a totally different route: step growth polymerization facilitated by
rapid and facile chain transfer. Besides the impact of the polymerization mechanism on the gel point conversion and network formation, the thiol-ene systems have demonstrated decreased volume shrinkage and shrinkage stress during polymerization.

Thiol-ene polymerization has demonstrated dramatically reduced volume shrinkage, which hasn’t been reported previously in the literature.

Thiol-ene polymerizations have a significantly increased gel point conversion, which, together with the low shrinkage, results in ultra-low shrinkage stress. This feature is extremely beneficial to the dental restorative composite applications, which cannot be achieved by any current free radically polymerized dental resin systems.

The oligomerization of thiol-ene monomers will further reduce the polymerization shrinkage. In addition, elimination of low molecular weight reactants during oligomerization will result in dental resins with less odor than current methacrylate based systems.

Due to the mechanisms of the thiol-ene polymerization and the high conversion that has been achieved in the preliminary experiments, thiol-ene polymers contain much less unreacted monomer that can be leached out into the oral environment. This has been confirmed with the solvent extraction experiments conducted on commercial thiol-ene systems.

The thiol-ene polymerization has demonstrated much thicker curing depth than methacrylate based resin systems. This will greatly reduce the patient’s chair-time since one-step curing is feasible, especially for large cavity filling, where incremental filling has to be applied using current dental composite systems.

Reduced volume shrinkage during polymerization and the dramatically reduced shrinkage stress due to the reduced volume shrinkage and significantly delayed gel point conversion. These features will greatly alleviate the problems associated with shrinkage stress from current resin systems, such as interfacial bonding failure, microleakage and recurrent caries.

The extremely high functional group conversion of thiol-ene polymers significantly mitigates the problems associated with the current dimethacrylate resin systems which is associated with the incomplete double bond conversion.
The thick cure depth and lack of oxygen inhibition of thiol-ene systems leads to one-step filling and curing during restorations, compared with the incremental filling technique using current dental resin systems.

The thiol-ene systems can be initiated by camphorquinone itself under visible light irradiation, without the presence of the amine accelerator.

The present invention may be thought of as a method of preparing a shaped dental prosthetic device for use in a human mouth. In the method, a mixture of first monomers and second monomers is dispensed wherein each first monomer has at least one thiol functional group and each second monomer has at least one vinyl functional group, and wherein 10% to 90% of the functional groups in the mixture are thiol functional groups. The mixture is shaped into the form of the shaped dental prosthetic device and then photopolymerized.

The present invention may also be thought of as a dental prosthetic device that incorporates a polymer created from the polymerization of a mixture of first monomers having thiol functional groups and second monomers having vinyl functional groups; wherein at least about 10% the functional groups of the polymer are thiol functional groups.

The present invention may also be thought of as a photopolymerizable dental restorative material comprising particles of filler; first monomers having thiol functional groups; second monomers having vinyl functional groups; and an initiator. In the photopolymerizable dental restorative material, at least about 10% of the functional groups in the dental restorative material are thiol functional groups.

The present invention may also be thought of as a photopolymerizable mixture comprising first monomers having thiol functional groups; second monomers having functional groups; and an initiator; wherein at least about 10% of the functional groups in the photopolymerizable mixture are thiol functional groups.

**Brief description of the Drawings**

FIG. 1 illustrates a representation of a thiol-ene polymer created using PETMP/TATAO embodiment of the present invention.

FIG. 2 is a plot of experimental conversion data showing the conversion of allyl and thiol functional groups of a PETMP/TATAO embodiment of the present invention and the conversion of the vinyl groups of a PETMP/VE1312 embodiment.
of the present invention; in comparison with the conversion of a typical Bis-GMA/TEGDMA (70/30 by wt.) as a function of irradiation time.

FIG. 3 is a plot of the loss tangent as a function of temperature for PETMP/TATATO (Molar ratio: 3:4) and Bis-GMA/TEGDMA (Mass ratio: 7:3) polymer.

FIG. 4 is a photograph of a ball and a rod formed of embodiments of the present invention.

FIG. 5 is a photograph of an experimental device capable of simultaneous measurement of the shrinkage stress and conversion of a sample during polymerization.

FIG. 6 is a plot of shrinkage stress as a function of time for a typical Bis-GMA/TEGDMA polymer and a PETMP/TATATO embodiment of the present invention.

FIG. 7 is a plot of the shrinkage stress as a function of double bond conversion for the systems of FIG. 6.

FIG. 8 is a plot of the shrinkage stress as a function of double bond conversion for another PETMP/TATATO embodiment of the present invention.

**Written Description of the Invention**

Embodiments of the present invention are a thiol-ene polymer system. These systems have a high conversion, low shrinkage and low – shrinkage stress during curing. Embodiments of the thiol-ene system preferably has about 10%-90% of its functional groups as thiol functional groups, more preferably about 25%-60% thiol functional groups and even more preferably about 45%-55% thiol functional groups.

The balance of the functional groups in the system may be vinyl functional groups. The vinyl functional groups may be provided by allyls, allyl ethers, vinyl ethers, acrylates or other monomers containing vinyl groups. For all of the embodiments studied containing multithiols and multivinyls of either allyls, allyl ethers or vinyl ethers, the polymerizations all achieved much higher conversions (than typical methacrylate systems) and reacted much more quickly to that conversion. In addition to thiols and vinyl functional groups, in some embodiments additional functional groups may be provided to tailor and provide additional properties.

Because of the step growth mechanism of the polymerization, for highest conversion it is preferred to have approximately equal amounts of initial functional
groups (i.e., 50% thiol functional groups and 50% vinyl functional groups). For example, one preferred composition is pentaerythritol tetramercaptopropionate/Triallyl-1,3,5-triazine-2,4,6-trione (PETMP/TATATO) with a molar ratio of 3:4, or equal amount of SH and C=C groups.

Thiol bearing monomers suitable for embodiments the present invention include any monomer having thiol (mercaptan or “SH”) functional groups. Thiols are any of various organic compounds having the general formula RSH which are analogous to alcohols but in which sulfur replaces the oxygen of the hydroxyl group. Suitable monomers may have one or more functional thiol groups and be of any molecular weight. Examples of suitable thiol bearing monomers include:
pentaerythritol tetramercaptopropionate (PETMP); 1-Octanethiol; trimethylolpropane tris(3-mercaptopropionate); Butyl 3-mercaptopropionate; 2,4,6-trioxo-1,3,5-triazina-triy (triethyl-tris (3-mercaptopropionate); and 1,6-Hexanedithiol.

Monomers having “-ene” or vinyl functional suitable for embodiments the present invention include any monomer having one or more functional vinyl groups, i.e., reacting “C=C” groups. Examples of suitable vinyl group bearing monomers include: Triallyl-1,3,5-triazine-2,4,6-trione (TATATO); Triethylene glycol divinyl ether (TEGDVE); Vinyl Acrylate; triethylene glycol dimethacrylate; trimethylolpropane diallyl ether; and Dodecyl Vinyl ether (DDVE).

Thiol-ene systems may also include and/or utilize various initiators, fillers, and accelerators depending on the application. For example, if photopolymerization using visible light is desired, camphorquinone may be used as an initiator. Alternatively, if ultraviolet photopolymerization is desired, then 2,2-dimethoxy-2-phenylacetophenone (DMPA) may be used as an initiator. Amine accelerators may also be used, as well as other accelerators. However, embodiments of the thiol-ene system can be readily initiated by just camphorquinone, without the presence of the amine accelerator. This is largely beneficial to the biocompatibility of photo-cured dental composites since studies have shown that certain tertiary amine accelerators, such as N,N-dimethyl-p-toluidine, are carcinogenic and mutagenic.

The thiol-ene systems of the present invention have some significant and unique advantages compared with (meth)acrylate polymerizations, which are extremely beneficial for dental resin applications. These advantages include: high gel-point conversion which significantly decreases shrinkage stress; rapid
polymerization rate and lack of oxygen inhibition; nearly complete consumption of low molecular weight reacting species due to the nature of the step-growth mechanism, which limits the amount of leachable species and exhibiting less perceptible odor; versatile kinetics and structure-property design based on tailoring the thiol-ene monomer chemistry.

Experimentation shows, for a tri-allyl/tetra-thiol system, gel point conversions of up to about 40% were observed.

Another advantage of thiol-ene systems is that they can replace existing methacrylate systems. Thiol-ene polymers can be mixed and applied in the same manner currently used by dentists using methacrylate systems. The thiol-ene systems can be mixed with fillers as is typical in methacrylate systems. Depending on the initiator used, existing light sources used to photopolymerize the methacrylate systems may also be used. Likewise, dental restorative materials using thiol-ene polymer systems may be supplied in single-dose capsules or syringes.

**Examples**

Experimental work on the thiol-ene polymer embodiments as dental restorative materials was performed to demonstrate the feasibility and advantages of these polymers over currently used dental restorative materials. More specifically, the following monomers were studied:

![Pentaerythritol tetramercaptopropionate (PETMP)](image)

![Triallyl-1,3,5-triazine-2,4,6-trione (TATATO)](image)

![1-Octanethiol](image)
1,6-Hexanedithiol

Triethylene glycol divinyl ether (TEGDVE)

Dodecyl Vinyl ether (DDVE)

In addition, the following methacrylate system was used as a comparison:

2,2-Bis[4-(2-hydroxy-3-methacryloyloxypropyloxy) phenyl] propane (Bis-GMA)

Triethylene glycol dimethacrylate (TEGDMA)

The various systems above were polymerized under various conditions and the resulting polymers were tested. These included PETMP/TATATO (Molar ratio: 3:4); PETMP/VE1312 (Molar ratio: 3.4:4); PETMP/ Bisphenol A Divinylether (DVEBPA) (Molar ratio 1:2); and 2,4,6-trioxo-1,3,5-triazina-triy (triethyl-tris (3-mercaptopo propionate) (T-BMPA)/VE1312 (Mol ratio: 3.4:3).

FIG. 1 illustrates a representation of an embodiment of a thiol-ene polymer created by polymerizing a mixture of PETMP/TATAO.
Polymerization kinetics investigation of thiol-ene systems

FTIR (Magna 750, Nicolet Instrument Corp., Madison, WI) was used to study the polymerization kinetics of the thiol-ene materials used in this study because of its inherent advantage of being able to measure the thiol and vinyl conversions simultaneously and rapidly. The infrared peak at 1643 per centimeter (cm$^{-1}$) was used for determining the allyl group conversion (of TATATO) and the peak at 2572 cm$^{-1}$ was used for the thiol group conversion.

FIG. 2 is a plot of experimental conversion data showing the conversion of allyl and thiol functional groups of a PETMP/TATATO embodiment of the present invention; the conversion of the vinyl groups of a PETMP/VE1312 embodiment of the present invention; and the conversion of a non-thiol system Bis-GMA/TEGDMA (70/30 by wt.) as a function of irradiation time. In these experiments 0.1 wt% DMPA was used as an initiator. The polymer systems were cured using an ultraviolet irradiation intensity equal to 5.0 mW/cm$^2$ at a cure temperature ($T_{cure}$) = 37°C. All thiol-ene monomer mixtures were prepared to have an equivalent concentration of the two functional groups.

As shown in FIG. 2, the polymerization of PETMP/TATATO occurs at a much higher rate than the typical dental restorative resin system Bis-GMA/TEGDMA (70/30 by wt.) cured under the same conditions. For each of the embodiments investigated, the conversion rate was such that at least about 90% of ultimate functional group conversion was achieved within 10 seconds. In the case of double bond conversion of the PETMP/TATATO embodiment, 90% of the ultimate double-bond functional group conversion was achieved within 8 seconds and 90% of the ultimate thiol functional group conversion was achieved within 10 seconds. For the PETMP/VE1312 embodiment of the present invention, 90% of the ultimate double-bond functional group conversion was achieved within approximately 3 seconds.

Also shown in FIG. 2, the final conversion of the allyl group was found to be approximately 90% and the thiol group final conversion was approximately 86%, while for Bis-GMA/TEGDMA the final conversion is only about 65%. The slight difference in the final conversion of the allyl and the thiol is caused by a small amount of homopolymerization that occurs with the allyl functional group.
The following is a list of polymerization kinetic results for various other thiol-ene systems studied. The polymerization conditions are the same as used in the experiments of FIG. 2 (0.1 % DMPA; initial curing temperature at 37 °C; 5.0 mW/cm²).

<table>
<thead>
<tr>
<th>System</th>
<th>Molar Ratio</th>
<th>Ultimate C=C Conversion</th>
<th>Ultimate SH Conversion</th>
<th>Time to Maximum Polymerization Rate (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETMP/TATATO</td>
<td>3:4</td>
<td>90%</td>
<td>85%</td>
<td>1.2</td>
</tr>
<tr>
<td>PETMP/VE1312</td>
<td>3.4:4</td>
<td>91%</td>
<td>93%</td>
<td>0.7</td>
</tr>
<tr>
<td>PETMP/DVEBPA</td>
<td>1:2</td>
<td>78%</td>
<td>80%</td>
<td>2.1</td>
</tr>
<tr>
<td>T-BMPA/VE1312</td>
<td>3.4:3</td>
<td>84%</td>
<td>81%</td>
<td>1.1</td>
</tr>
</tbody>
</table>

DVEBPA is Bisphenol A divinylether (a di-vinylether); T-BMPA is 2,4,6-trioxo-1,3,5-triazina-triy (triethyl-tris (3-mercapto propionate)) (a tri-thiol).

In addition to the PETMP/TATATO system, a vinyl ether oligomer was copolymerized with the PETMP to evaluate the relative performance of vinyl ether. VEctomer® VE1312 (Morflex Inc., Greensboro, NC), a multifunctional vinyl ether containing a multifunctional polyester backbone, was used for this experiment. VE1312 has a number average molecular weight of 1250 g/mol, with average functionality of 3.4. Clearly, the combination of oligomerizing the vinyl group and changing to the vinyl ether increased the polymerization rate significantly. For all of the commercial systems studied containing multithiols and multivinyls of either allyls, allyl ethers or vinyl ethers, the polymerizations all achieved much higher conversions and reacted much more quickly to that conversion.

The experimentation shows that, in addition to higher conversion, dramatically reduced oxygen inhibition has been observed for all the thiol-ene polymerizations, as shown in FIG. 2. Although the experiment discussed above used ultraviolet light to simplify the initiating system, other experiments have also demonstrated that camphorquinone by itself readily initiates these polymerizations without the presence of an amine accelerator.

**Material properties investigation of commercial thiol-ene systems**

In addition to the kinetics, various material property measurements were performed. Specimens for dynamic mechanical analysis (DMA) testing were photocured for 10 min with 10.0 mW/cm² of UV light at ambient conditions. A
DMA7e (Perkin-Elmer, Norwalk, CT) was used to measure the glass transition
temperature, T_g, of a PETMP/TATATO embodiment of the present invention.
DMA was conducted over a temperature range of -50 ~ 120 °C with a ramping rate
of 5 °C using extension mode (sinusoidal stress of 1 Hz frequency) and the loss
tangent peak was monitored as a function of temperature as shown in FIG. 3. The
loss tangent is defined as the polymer’s loss modulus divided by storage modulus.
During a DMA test, loss tangent peak corresponds to the viscoelastic relaxation of
polymer chain or segments. Normally, the largest loss tangent peak can be
associated with the polymer’s glass transition peak and the temperature of the loss
tangent peak maximum was used to define T_g (glass transition temperature). For
this sample, the glass transition temperature was found to be approximately 64°C.
Each sample for the property measurement was prepared with an equal molar ratio
of thiol functional groups to vinyl functional groups and was monitored with near
infrared spectroscopy. Under these conditions, the vinyl group conversion was
found to be approximately 90% in all cases.

For the flexural strength studies, monomer samples were photopolymerized
in a Teflon® mold (specimen dimensions: 25±2 mm × 2±0.1 mm × 2±0.1 mm) with
580 mW/cm² visible light for 30 s on each side. Five specimens were prepared for
each sample. A 3-point flexural test was carried out with a MTS® 858 Mini Bionix
system (MTS Systems Corporation, Eden Prairie, MN, USA) using a span width of
20 mm (10 mm for PETMP/TATATO embodiments) and a crosshead speed of 1
mm/min. The flexural strength (σ) and flexural modulus (E_f) in MegaPascals (MPa)
were calculated using the following equations:

\[ \sigma = \frac{3Fl}{2bh^2} \]  
\[ E_f = \frac{Fl^3}{4bh^3d} \]  

where F is the peak load (in N), l is the span length (in mm), b is the specimen width
(in mm), h is the specimen thickness (in mm); and d is the deflection (in mm) at load
F_l (in N) during the straight line portion of the trace (ISO/DIS 4049, 1987).
ISO/DIS 4049 is the international standard for “Dentistry—Polymer-based filling,
restorative and luting materials”. Flexural strength test is one of the tests specified in this standard for the polymer-based filling, restorative and luting materials.

As shown in Table 1, the flexural strength and flexural modulus of PETMP/TATATO are found to be 71.4 ± 2.7 MPa and 1.6 ± 0.3 GPa, respectively. Compared with the flexural strength of 93.2 ± 8.3 MPa and flexural modulus of 2.6 ± 0.1 GPa for Bis-GMA/TEGDMA system, this result indicates that the mechanical properties of PETMP/TATATO are not as high as current Bis-GMA/TEGDMA control system. However, it still exceeds the requirements for flexural strength test specified in ISO/DIS 4049. Furthermore, the quartz glass filled PETMP/TATATO system exhibits greater improvement in flexural strength and flexural modulus compared with Bis-GMA/TEGDMA system filled with the same amount of filler (Table 1).

Table 1. Flexural strength test results for filled and unfilled PETMP/TATATO and Bis-GMA/TEGDMA. Both resin systems contain 0.3 wt% CQ and 0.8 wt% EDAB as visible light initiator. For filled systems, 60 wt% silanized quartz filler (mean particle size of 5 μm) was used. All samples were cured with 580 mW/cm² visible light for 30 s on each side (n=5).

<table>
<thead>
<tr>
<th>System</th>
<th>Flexural Strength (MPa)</th>
<th>Flexural Modulus (GPa)</th>
<th>Strain at Break (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETMP/TATATO (Mol 3:4)</td>
<td>71.4 ± 2.7</td>
<td>1.6 ± 0.3</td>
<td>11.7 ± 0.9</td>
</tr>
<tr>
<td>PETMP/TATATO/Filler</td>
<td>112.0 ± 8.0</td>
<td>5.4 ± 0.7</td>
<td>3.9 ± 0.8</td>
</tr>
<tr>
<td>BisGMA/TEGDMA (Mass 7:3)</td>
<td>93.2 ± 8.3</td>
<td>2.6 ± 0.1</td>
<td>7.1 ± 2.4</td>
</tr>
<tr>
<td>BisGMA/TEGDMA/Filler</td>
<td>125.8 ± 7.3</td>
<td>7.5 ± 0.5</td>
<td>2.1 ± 0.3</td>
</tr>
</tbody>
</table>

In addition to measuring the flexural strength and glass transition temperature of the model thiol-ene system, extraction studies were performed. As per Stansbury et al. each specimen was weighed immediately following polymerization. Soxhlet extraction of each specimen was conducted for 10 hours at 60°C, with dichloromethane used as the solvent. The mid-IR spectrum of the solvent after extraction was obtained and compared with that of the pure dichloromethane. No change in the infrared spectrum of the extracting dichloromethane was observed when compared with the pure dichloromethane. Also, no detectable substance was found following rotary evaporation of the extracting dichloromethane. After
extraction, each specimen was dried to constant mass under 20 inch Hg vacuum at 60°C. For the thiol-ene samples this process took approximately 60 hours, and the average weight loss of the dried specimens was found to be from 0.4% to 0.6% relative to the original mass before extraction. This number compares extremely well with 11% extraction loss in a typical Bis-GMA/TEGDMA control sample polymerized under similar conditions to 68% methacrylate conversion. The number also compares reasonably well with the prediction for the amount of unreacted monomer remaining in the system, i.e., the amount of unreacted thiol or ene functional groups. Using the observed 86% thiol conversion and 90% vinyl conversion, the fraction of thiol monomer unreacted is calculated as (for the tetrathiol monomer) \((1-0.86)^4 = 0.04\)% and the fraction of unreacted vinyl monomer is calculated as (for the trivinyl monomer) \((1-0.9)^3 = 0.1\)%.

Thus, it was not expected that there would be a significant amount of extractable material at these conversions, which was verified by the experiments.

Finally, to demonstrate physically some of the advantages of thiol-ene polymers, large, stress-free samples were prepared by photopolymerization of embodiments of the present invention. These polymers include a 20 inch long rod that was polymerized from the top and a solid ball that was also polymerized from the top. The ball is approximately two inches in diameter. Each of these materials had minimal shrinkage, and more importantly, remained uncracked throughout the polymerization due to the minimal polymerization shrinkage stress. These samples are presented in FIG. 4.

**Polymerization volume shrinkage of thiol-ene polymers**

For samples such as many of the thiol-ene polymerizations that are lower viscosity and have relatively high gel point conversions, it is necessary to develop a different methodology for volume shrinkage measurements. For these systems, a straightforward method to measure the volume shrinkage was applied: measure the initial volume before polymerization by measuring the long dimension in a narrow, constant diameter tube, photo-cure the monomer, and then measure the final volume after polymerization by measuring the long dimension again. This technique is especially useful in studying the shrinkage of the stepwise-polymerized linear or crosslinking system, the latter has a much delayed gel-point and is therefore
inappropriate to study using linometer or strain gauge. By using this approach, the volume shrinkage of thiol-vinyl ether and thiol-(trialllyl-triazine-trione) embodiments of the present invention was investigated. Interestingly, the molar volume change for C=C bonds during polymerization are much lower than the acrylate or methacrylate systems, which produce 22.5–23 ml of shrinkage for every mole of double bond polymerized. Table 2 showed the results of this volume shrinkage study. Thus, it is not only the dramatic increase in gel point conversion that reduces the shrinkage stress in this system, but also the fact that each double bond that reacts leads to approximately half of the shrinkage that occurs in a traditional free radical polymerization.

**Table 2. Volume shrinkage measurement using static volume change method**

<table>
<thead>
<tr>
<th>System</th>
<th>Volume Shrinkage (%)</th>
<th>Molar Volume Change for C=C (ml/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMA (Patel et al. 1983)</td>
<td>20.6</td>
<td>22.5</td>
</tr>
<tr>
<td>HDT/TEGDVE (Molar Ratio: 1:1)</td>
<td>7.1</td>
<td>12.7</td>
</tr>
<tr>
<td>OT/DDVE (Molar Ratio: 1:1)</td>
<td>2.9</td>
<td>12.6</td>
</tr>
<tr>
<td>OT/TATATO (Molar Ratio: 3:1)</td>
<td>6.1</td>
<td>15.1</td>
</tr>
</tbody>
</table>

MMA: Methyl methacrylate; HDT:1,6-Hexanediithiol; TEGDVE: Triethylene glycol di(vinyl ether); OT:1-Octanethiol; DDVE: Dodecyl vinyl ether; TATATO: Triallyl-1,3,5-triazine-2,4,6-trione.

**Simultaneous measurement of thiol-ene shrinkage stress and conversion**

This experimental set-up is capable of simultaneous measurement of the shrinkage stress and conversion, both on exactly the same sample at the same time. The *in situ*, real-time monitoring of the polymerization was achieved by guiding the near-IR beam through the sample, which was mounted on the tensometer, then refocusing the transmitted signal to the near-IR detector. The tensometer, designed by American Dental Association (ADA), is based on the cantilever beam deflection theory: shrinkage force generated by the composite during curing causes the beam to bend, and the deflection is measured with a linear variable differential transformer.
(LVDT). The shrinkage force is then calculated using the beam constant of the
cantilever beam. Therefore, the shrinkage stress value is obtained by dividing the
shrinkage force by the composite sample cross-sectional area. With the combination
of different beam lengths and materials, it is possible to measure the shrinkage stress
accurately over a wide range of values. FIG. 5 presents a photograph of this novel
experiment set-up.

Using the combined tensometer and remote near-IR technique, the
simultaneous shrinkage stress and conversion of Bis-GMA/TEGDMA and
PETMP/TATATO were measured from the same sample at the same time. As
shown in FIG. 6, the final shrinkage stress achieved by a PETMP/TATATO
embodiment of the present invention is less than 12% of the Bis-
GMA/TEGDMA system, both cured under identical conditions of visible light
irradiation intensity of 330 mW/cm² for 5 min at room temperature.

The extremely low shrinkage stress of thiol-ene polymers resulted from
not only the relatively high gel point conversion but reduced volume shrinkage
that each double bond generates during polymerization. A plot of the shrinkage
stress as a function of double bond conversion is shown in FIG. 7. It further
illustrated the advantages of thiol-ene polymers for dental restorative materials:
dramatically reduced shrinkage stress and improved functional group
conversion.

The simultaneous shrinkage stress as a function of double bond conversion
for another embodiment (PETMP/TATATO system with 0.5 wt% CQ cured using
375 mW/cm² visible light) is shown in FIG. 8. It can be seen that shrinkage stress
did not start to build up until approaching the gel point conversion (theoretical gel
point f_g = 40.8% for this system). This agrees very well with the prediction that any
volume shrinkage that occurred before the gel point will not result in shrinkage
stress, as the shrinkage can be readily accommodated by the flow of the liquid
mixture of oligomers. The maximum shrinkage stress developed was about 0.21
MPa, which was less than 10% of the maximum shrinkage stress of the Bis-
GMA/TEGDMA system cured under the same conditions.

**Synthesis of reactive oligomeric thiol and ene materials**

The purposes of synthesizing oligomeric thiol and ene materials are to
optimize both polymer properties and polymerization performance and eliminate
odor concerns. Because of the step growth nature of the thiol-ene photopolymerization, it is possible to oligomerize (both synthetic and commercially available) monomers to a significantly higher extent of polymerization prior to formulating the materials and completing the polymerization in the restoration. This technique is expected to have enormous advantages over the low molecular weight embodiments of the present invention studied herein. First, since the overall functional group concentration will be decreased dramatically, the shrinkage will correspondingly be decreased while still maintaining the identical ultimate network structure and material properties. Secondly, with higher molecular weight thiols, it will be more facile to purify the oligomers and remove the trace, low molecular weight compounds responsible for the odor in these systems and to limit further the amount of extractables.

The various embodiments described above are provided by way of illustration only and should not be construed to limit the invention. Those skilled in the art will readily recognize various modifications and changes that may be made to the present invention without following the example embodiments and applications illustrated and described herein, and without departing from the true spirit and scope of the present invention, which is set forth in the following claims.
Claims

We Claim:

1. A method of preparing a shaped dental prosthetic device for use in a human mouth comprising:
   dispensing a mixture of first monomers and second monomers, each first monomer having at least one thiol functional group and each second monomer having at least one vinyl functional group, wherein 10% to 90% of the functional groups in the mixture are thiol functional groups;
   shaping the mixture into the form of the shaped dental prosthetic device; and
   photopolymerizing the shaped mixture.

2. The method of claim 1, wherein the mixture includes an initiator that initiates polymerization of the mixture upon exposure to light from an associated light source and photopolymerizing comprises:
   exposing the shaped mixture to an effective amount of light from the associated source to initiate polymerization.

3. The method of claim 2, wherein the initiator is camphorquinone.

4. The method of claim 3, wherein the associated light source is a visible light source.

5. The method of claim 2, wherein the initiator is 2,2-dimethoxy-2-phenylacetophenone and the associated light source is an ultraviolet light source.

6. The method of claim 1, wherein each first monomer has at least two thiol functional groups.

7. The method of claim 1, wherein 25% to 60% of the functional groups in the mixture are thiol functional groups.

8. The method of claim 7, wherein 45% to 55% of the functional groups in the mixture are thiol functional groups.
9. The method of claim 8, wherein about 50% of the functional groups in the mixture are thiol functional groups.

10. The method of claim 2, wherein the exposing is performed only once in a single exposing step.

11. The method of claim 6, wherein each first monomer is an oligomer of monomers having thiol functional groups.

12. The method of claim 1, wherein each second monomer is an oligomer of monomers having vinyl functional groups.

13. A dental prosthetic device comprising:
   a polymer created from the polymerization of a mixture of first monomers having thiol functional groups and second monomers having vinyl functional groups; wherein at least about 10% the functional groups of the polymer are thiol functional groups.

14. The dental prosthetic device of claim 13, wherein the mixture further comprises an initiator.

15. The dental prosthetic device of claim 13, wherein at least about 25% of the functional groups of the mixture are thiol functional groups.

16. The dental prosthetic device of claim 13, wherein at least about 45% of the functional groups of the mixture are thiol functional groups.

17. The dental prosthetic device of claim 13, wherein at least about 50% of the functional groups of the mixture are thiol functional groups.

18. The dental prosthetic device of claim 13 further comprising:
   particles of filler within the polymer.
19. The dental prosthetic device of claim 13, wherein the mixture was shaped into the dental prosthetic device and then photopolymerized until at least about an 85% conversion of the thiol functional groups of the mixture is achieved.

20. The dental prosthetic device of claim 13 having a volume shrinkage of less than 10% after polymerization.

21. The dental prosthetic device of claim 13 having a shrinkage stress of less than 0.5 MPa.

22. The dental prosthetic device of claim 13 having a shrinkage stress of less than 1.5 MPa.

23. A photopolymerizable dental restorative material comprising:
   particles of filler;
   first monomers having thiol functional groups;
   second monomers having vinyl functional groups; and
   an initiator;
   wherein at least about 10% of the functional groups in the dental restorative material are thiol functional groups.

24. The photopolymerizable dental restorative material of claim 23, wherein at least about 25% of the functional groups in the dental restorative material are thiol functional groups.

25. The photopolymerizable dental restorative material of claim 23, wherein at least about 45% of the functional groups in the dental restorative material are thiol functional groups.

26. The photopolymerizable dental restorative material of claim 23, wherein at least about 50% of the functional groups in the dental restorative material are thiol functional groups.
27. The photopolymerizable dental restorative material of claim 23, wherein at least about 60% of the functional groups in the dental restorative material are thiol functional groups.

28. The photopolymerizable dental restorative material of claim 23 that when polymerized obtains a thiol functional group conversion of greater that 85%.

29. The photopolymerizable dental restorative material of claim 23 that when polymerized exhibits a volume shrinkage of less than 10%.

30. The photopolymerizable dental restorative material of claim 23 that when polymerized creates a polymer having an average weight loss, when dried, of 0.4 to 0.6% relative to an original mass before extraction.

31. A dispensing device comprising an unpolymerized quantity of the photopolymerizable dental restorative material of claim 23.

32. The photopolymerizable dental restorative material of claim 23 that when polymerized creates a polymer having a shrinkage stress of less that 3.0 MPa.

33. The photopolymerizable dental restorative material of claim 23 that when polymerized creates a polymer having a shrinkage stress of less that 1.5 MPa.

34. The photopolymerizable dental restorative material of claim 23 that when polymerized creates a polymer having a shrinkage stress of less that 0.5 MPa.

35. A photopolymerizable mixture comprising:
   first monomers having thiol functional groups;
   second monomers having functional groups; and
   an initiator;
   wherein at least about 10% of the functional groups in the photopolymerizable mixture are thiol functional groups.
36. The photopolymerizable mixture of claim 35, wherein the functional groups of
the second monomer consist of vinyl functional groups.

37. The photopolymerizable mixture of claim 35 having a thiol functional group
conversion of greater than 85% upon polymerization.

38. The photopolymerizable mixture of claim C2 having a vinyl functional group
conversion of greater than 85% upon polymerization.

39. The photopolymerizable mixture of claim 35 having a glass transition
temperature of greater than 60 degrees Celsius.

40. The photopolymerizable mixture of claim 35 having a volume shrinkage of less
than 10% after polymerization.

41. The photopolymerizable mixture of claim 35 having a volume shrinkage of less
than 5% after polymerization.

42. The photopolymerizable mixture of claim 35 having a volume shrinkage of less
than 3% after polymerization.

43. The photopolymerizable mixture of claim 35 having a volume shrinkage of less
that 10%, a glass transition temperature greater than 60 degrees Celsius and a
flexural strength of greater than 65 Mega Pascals after polymerization.
FIG. 1
FIG. 3
FIG. 6

Shrinkage Stress (MPa)

Time (min)

PETMP/TATATO
Bis-GMA/TEGDMA
FIG. 7
FIG. 8
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : A61C 13/00, 13/08; B29C 35/08; C08F 2/50; C08G 75/04.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
USPATENTS, DERWENT, EPO, IPO

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category *</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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<tbody>
<tr>
<td>Y</td>
<td>US 5,100,929 A (JOCHUM et al) 31 March 1992 (31.03.1992), Abstract, column 2, line 33, to column 3, line 20, column 3, lines 40-55, column 4, lines 26-54, column 5, lines 9-60, column 6, lines 19-37, and Examples 1-3.</td>
<td>1-12</td>
</tr>
<tr>
<td>A</td>
<td>US 6,384,107 B2 (LIU) 7 May 2002 (07.05.2002), Abstract, column 5, line 56, to column 6, line 56, column 13, lines 18-27, column 14, lines 20-30, column 14, line 62, to column 15, line 16, and Example 5.</td>
<td>1-12</td>
</tr>
<tr>
<td>Y</td>
<td>US 6,479,622 B1 (GROSS et al) 12 November 2002 (12.11.2002), Abstract, column 4, lines 15-65, Glossary in columns 5-6, column 7, line 56, to column 8, line 20.</td>
<td>1,2,5</td>
</tr>
</tbody>
</table>

Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents:
**T** later document published after the international filing date or priority date, and of potential significance with regard to the inventions as claimed,
**F** later document published after the international filing date or priority date, and not in conflict with the application but cited to understand the principle or theory underlying the invention
**X** document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
**Y** document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is considered in combination with one or more other such documents, such combination being obvious to a person skilled in the art
**A** document member of the same patent family

Date of the actual completion of the international search
10 March 2005 (10.03.2005)

Date of mailing of the international search report
31 MAR 2005

Form PCT/ISA/210 (second sheet) (January 2004)
C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
</table>

Form PCT/ISA/210 (continuation of second sheet) (January 2004)
INTERNATIONAL SEARCH REPORT

Box No. I Nucleotide and/or amino acid sequence(s) (Continuation of item 1.b of the first sheet)

1. With regard to any nucleotide and/or amino acid sequence disclosed in the international application and necessary to the claimed invention, the international search was carried out on the basis of:
   a. type of material
      - [ ] a sequence listing
      - [ ] table(s) related to the sequence listing
   b. format of material
      - [ ] in written format
      - [ ] in computer readable form
   c. time of filing/furnishing
      - [ ] contained in the international application as filed
      - [ ] filed together with the international application in computer readable form
      - [ ] furnished subsequently to this Authority for the purposes of search

2. In addition, in the case that more than one version or copy of a sequence listing and/or table relating thereto has been filed or furnished, the required statements that the information in the subsequent or additional copies is identical to that in the application as filed or does not go beyond the application as filed, as appropriate, were furnished.

3. Additional comments:

Form PCT/ISA/210 (continuation of first sheet(1)) (January 2004)
## INTERNATIONAL SEARCH REPORT

### Box No. II  Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. **☐** Claims Nos.:
   because they relate to subject matter not required to be searched by this Authority, namely:

2. **☐** Claims Nos.:
   because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. **☐** Claims Nos.:
   because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

### Box No. III  Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
Please See Continuation Sheet

1. **☐** As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. **☐** As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. **☐** As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. **☒** No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.: 1-12

**Remark on Protest**

- **☐** The additional search fees were accompanied by the applicant’s protest.
- **☐** No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet(2)) (January 2004)
BOX III. OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING
This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claim(s) 1-12, drawn to a method of preparing a dental device, comprising shaping a polymerizable thiol-ene mixture and photopolymerizing the shaped mixture.

Group II, claim(s) 13-22, drawn to a dental prosthetic device comprising a polymer obtained from a thiol-ene composition.

Group III, claim(s) 23-30 and 32-34, drawn to a photopolymerizable dental material comprising a filler, thiol monomers, vinyl monomers and an initiator.

Group IV, claim(s) 31, drawn to a dispensing device comprising a photopolymerizable material.

Group V, claim(s) 35-43, drawn to a photopolymerizable mixture comprising a thiol monomer, a vinyl monomer and an initiator.

The inventions listed as Groups I-V do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the feature that links the groups of claims is "wherein at least about 10% of the functional groups in the polymerizable mixture are thiol functional groups". This feature does not provide a special technical feature since compositions comprising compounds having thiol functional groups that provide at least 10% thiol functional groups to the compositions are well known in the dental art. See US Patent 5,100,929 or US Patent 5,889,132.