Biomimetic Adhesive Thiol-Ene Films For Improved Adhesion

Laken L. Kendrick

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BIOMIMETIC ADHESIVE THIOL-ENE FILMS
FOR IMPROVED ADHESION

by

Laken L. Kendrick

A Thesis
Submitted to the Honors College of
The University of Southern Mississippi
in Partial Fulfillment
of the Requirements for the Degree of
Bachelor of Science
in the Department of Polymer Science and High Performance Materials

May 2015
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Abstract

Current dental restoration materials fall short in adhesion and often pull away from the surface of the tooth upon curing. This project seeks to design polymers that can adhere to wet, heterogeneous surfaces as potential materials for dental restoration applications. The goal of this project is to mimic the structure and adhesive properties of natural adhesives containing 3,4-dihydroxyphenyl-L-alanine (DOPA). We will synthesize mono- and di-functional DOPA derivatives with catechol functionality and investigate their adhesion compared to their non-catechol-containing alternative through incorporation into a model thiol-ene photopolymerization. Functional group conversion, real time kinetics, and adhesion data will be used to analyze these materials. Successful completion of this study may provide improved understanding of the design parameters necessary to achieve wet adhesion to dental surfaces, and may provide a new route for the development of dental restoration composites that result in reduced delamination at the composite-tooth interface and ultimately lower failure rates.

Key Terms: 3,4-dihydroxyphenylalanine (DOPA), adhesion, catechol, thiol-ene
Acknowledgements

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I would like to thank my parents and extended family for the immeasurable support and love they have provided while always encouraging me to pursue my dreams. I am so grateful to them for everything they have accomplished and the life they provided for me. Finally, a special thank you to my grandfather, Travis Camp, who has always been my loudest cheerleader and toughest critic. His guidance has always pushed me to become a better version of myself.

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APE</td>
<td>Penaerythritol Triallyl Ether</td>
</tr>
<tr>
<td>DADHBA</td>
<td>N,N-diallyl-3,4-dihydroxybenzamide</td>
</tr>
<tr>
<td>DADMBBA</td>
<td>N,N-diallyl-3,4-dimethoxybenzamide</td>
</tr>
<tr>
<td>DMB-Cl</td>
<td>3,4-dimethoxybenzoyl chloride</td>
</tr>
<tr>
<td>DMBA</td>
<td>3,4-dimethoxybenzoic acid</td>
</tr>
<tr>
<td>Eug</td>
<td>Eugenol</td>
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<tr>
<td>EugOH</td>
<td>Deprotected Eugenol</td>
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<tr>
<td>MeEug</td>
<td>Methyl Eugenol</td>
</tr>
<tr>
<td>PETMP</td>
<td>Pentaerythritol tris(3-mercaptopropionate)</td>
</tr>
<tr>
<td>RT-FTIR</td>
<td>Real-Time Fourier Transform Infrared Spectroscopy</td>
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</table>
Chapter I: Introduction

Novel materials and processes for adhesion have led to significant advances in the field of adhesive dentistry, a field that relies on adhesion or bonding of dental composites (i.e. filling materials for repair of cavities) to the natural substance of teeth for operative and preventive dentistry applications. Currently, the state-of-the-art dental resin is composed of a mixture of organic monomers, photoinitiator, and inorganic fillers. The monomers in these systems polymerize and crosslink upon exposure to light (photopolymerization) and adhere the resin to the tooth surface. As a consequence of the dental restoration environment, adhesion must occur under wet or damp conditions. However, wet adhesion continues to be a major challenge for the development of improved dental restoration materials.

Nature provides an inexhaustible source of inspiration for the design of adhesives, including adhesives produced by intertidal marine mussels – a species that relies on attachment to foreign objects as a fundamental part of survival. The marine mussel exhibits a unique ability to adhere to wet, rough surfaces through adhesive proteins. Marine mussel adhesive proteins contain the catecholic amino acid 3,4- dihydroxyphenyl-L-alanine (DOPA), a modified amino acid believed to be responsible for the mussel’s adhesion behaviors. The ability of the DOPA moiety to participate in hydrogen bonding, metal-ligand complexation, and π-π aromatic interactions enables strong adhesion to a variety of surface functionalities. Because of its biocompatibility, DOPA-containing materials may be excellent candidates for dental restoration applications. However, extraction of these adhesives from natural sources is unrealistic due to many factors such as high cost and low
production. An alternative route to obtain DOPA analogues is via accessible synthetic pathways and the incorporation of these synthetic mimics as active adhesive constituents has proliferated in recent years offering the ability to explore these compounds for biocompatible materials. 6,7,8

Chapter II: Literature Review

Light-induced polymerization is a commercially viable process that offers numerous economic and technical advantages over conventional thermal polymerization, particularly toward the fabrication of crosslinked thermosets for dental applications. These advantages include rapid through-cure, low energy requirements, ambient temperature processing, solvent-free resin compositions, and spatial and temporal control over the polymerization process. Despite such advantages, relatively few examples have been reported that employ photopolymerization for fabrication of polymer networks containing catechol functionality derived from DOPA-mimics. 9,10,11 Light-induced radical-mediated thiol-ene reactions provide many advantages over traditional photocurable resins that arise from the mechanism of thiol-ene network formation.

![Thiol-ene free radical chain transfer reaction](image)

**Figure 1.** Thiol-ene free radical chain transfer reaction

Thiol-ene network formation, as shown in Figure 1, occurs via a free-radical step-
growth process facilitated by a rapid, highly efficient chain transfer reaction between multifunctional alkenes and thiols, providing insensitivity to oxygen inhibition and homogeneous polymer network structures. Recent work by Sparks et al. showed that incorporation of a dopamine acrylamide monomer into a thiol-ene system increased macroscopic adhesion to a variety of surfaces, but suffered from reduced mechanical properties and significant amounts of inhibition at higher DOPA monomer concentration. The dopamine acrylamide thiol-ene system also required dimethylformamide (DMF) as a solvent, which is incompatible with dental applications. This prospectus seeks to address these aforementioned issues with our initial work in adhesive thiol-ene materials, and to further elucidate the role played by the DOPA analogues with an increased binding affinity in order to achieve enhanced adhesion and network properties at lower concentrations. It is the aim of this prospectus to understand and elucidate the fundamental design parameters necessary to enhance the catechol binding interactions of DOPA derivatives and to then impart adhesive functionality to, while enhancing network properties of, photocurable thiol-ene resins via incorporation of DOPA-derived monomers. We hypothesize that decreasing the pKa of DOPA derivatives will lower the oxidation potential of these small molecules, which will in turn reduce their propensity to self-polymerize and increase their affinity for coordination to heterogeneous surfaces.

As previously mentioned, the intertidal marine mussels exhibit a unique ability to adhere to a variety of wet, heterogeneous substrates. The mussel byssus contains both plaques and threads (Figure 2), but the plaques are the sites of interfacial adhesion. While the byssus contains a complex system of proteins, the proteins located in the byssal
plaques contains the amino acid 3,4-dihydroxyphenylalanine which is believed to play a major role in interfacial adhesion.

**Figure 2.** Anatomy of *M. edulis* mussel and byssus structures

It has been well documented that the catecholic moiety present in DOPA is responsible to the adhesive abilities of the molecule. Gomez et al. 16 combined Attenuated Total Reflection Infared (ATR-IR) and Resonance Raman spectroscopy to show that a catechol molecule will bind to an anatase TiO₂ nanoparticle via a stable bidentate chelation mode or via hydrogen bonding to TiO₂ surface groups. Similarly, Israelachvili et al. 17 investigated DOPA’s oxidative response to pH to explore three binding modes: dual hydrogen bonding, one hydrogen bonding and one metal-molecule binding, or chelation, and dual chelation. The authors showed that while the amount of DOPA bound to a TiO₂ surface decreases with increasing pH due to oxidation of the catechol in the presence of oxygen, the binding mechanism moves towards the more stable dual chelation mode and therefore the strongest adhesion forces were observed at pH 7.5.

Messersmith et al. 18 functionalized an AFM tip with a single DOPA molecule and studied adhesion to both organic and inorganic surfaces. Their findings showed that DOPA in its unoxidized (catechol) form adhered strongly to inorganic surfaces via reversible
coordination bond, but provided a bimodal adhesion response with DOPA in the oxidized quinone form. The bimodal adhesion resulted from the lower adhesion force attributed to the quinone-surface interaction. However, on organic surfaces (i.e. amine-terminated self-assembled monolayers) the oxidized form of the catechol, or the quinone form, showed the highest adhesion likely through the formation of covalent bonds resulting from a Michael-addition between the primary amine on the surface and quinone on the AFM probe.

Thus, the oxidation of DOPA is not always beneficial to adhesion. In 1999, Deming et al.\textsuperscript{19} showed that the catecholic moiety of DOPA will readily undergo oxidation in basic conditions in the presence of an oxidant such as oxygen. This quinone formation in DOPA led to self-polymerization through ill-defined pathways involving radical coupling of quinones and formation of Michael adducts. Figure 3 shows a possible pathway to polydopamine, although the mechanism and structure are still ill-defined. The formation of polydopamine resulted in greater bulk, cohesive interactions and less adhesive interactions at inorganic surfaces.

![Figure 3. Formation of polydopamine](image-url)
Yu et al. \(^{20}\) published similar results by studying the adhesive binding of DOPA-modified proteins at various pH levels. The results showed a decrease in adhesion with increasing pH, suggesting that the quinone formation does not contribute strongly to adhesion. However, as reported by Wilker et al., \(^{21}\) some oxidation can lead to cross-linking of the bulk which will increase cohesive forces and improve adhesion. In order to improve biomimetic DOPA adhesives in polymeric systems, it is important to understand how oxidation affects the surface adhesion and achieve a balance between auto-oxidation and adhesion.

Inspired by the salient features of natural bioadhesives and the previous mentioned single molecule experiments, interest in designing synthetic polymeric systems that incorporate DOPA and analogous catecholic moieties as active adhesive constituents has proliferated in recent years. The earliest examples focused on the synthesis of DOPA-containing polypeptides \(^{22,23,24}\) while more recent efforts have focused on the synthesis of linear and branched polymeric systems that incorporate dopamine or other catechol derivatives as pendant side chains or end groups. \(^{8}\) Dopamine functionalized polymeric systems based on polyethylene glycol, \(^{10,25-35}\) polyamides, \(^{25}\) polystyrenes, \(^{21,37-43}\) polyurethanes, \(^{26}\) and polyacrylates \(^{45-50}\) have been reported, and have enabled the development of self-healing polymer networks \(^{27}\) hydrogels, \(^{10,26,28,51,52}\) coacervates, \(^{6,48,53}\) nanoparticle stabilizers, \(^{29,54}\) and imaging agents. \(^{54,55}\)

Obviously, the surface adhesion of DOPA-mimics has also provided exciting opportunities for the development of sealants, \(^{56}\) adhesives, \(^{6,8,21,57,58}\) and functional films for a variety of applications. \(^{8,30,35,42,50,59}\) For such applications, the catechol may serve as an anchor for immobilizing a polymer coating onto a surface \(^{60,61}\) or may impart both adhesive
and cohesive properties to the applied polymeric system.\textsuperscript{28} In this direction, free radical copolymerization of dopamine methacrylamide or 3,4-dihydroxystyrene with other acrylate or styrene derivatives has provided the prevalent strategy for incorporating catechol moieties into polymeric structures. For example, Stepuk et al.\textsuperscript{29} recently reported the development of metal-polymer adhesives derived from thermal free radical copolymerization of dopamine methacrylamide or 3,4-dihydroxystyrene with methyl methacrylate. The resulting copolymers yielded improvements in macroscopic adhesion to aluminum and titanium substrates when presented in the non-oxidized catechol form, while samples pre-oxidized to the quinone form showed little effect on adhesive properties.

Similarly, Matos-Pérez et al.\textsuperscript{21} reported a systematic study elucidating the relationship between polymer composition and degree of crosslinking on adhesion to various substrates for a series of poly(3,4-dihydroxystyrene-co-styrene) copolymers obtained by thermal polymerization. In this case, crosslinking was achieved through oxidation of the pendent catechols with a strong oxidizing agent such as tetrabutylammonium periodate, while degree of crosslinking was controlled by the amount of 3,4-dihydroxystyrene in the copolymer. Improvements in adhesion were observed upon crosslinking for samples containing up to 33 mol\% 3,4-dihydroxystyrene, while further increases in 3,4-dihydroxystyrene concentration were detrimental to adhesive properties illustrating an important balance between adhesive interactions of the polymer with the substrate and cohesive interactions within the polymer itself.

Aside from thermal polymerization, an interesting route to bioinspired catechol-functionalized polymer coatings and adhesives is photopolymerization. As mentioned in the introduction, photopolymerization is an industrially viable process that offers numerous
economic and technical advantages over conventional thermal polymerization, particularly toward the fabrication of crosslinked thermosets. However, relatively few examples have been reported that employ photopolymerization for fabrication of polymer networks containing catechol functionality.9,49,58 Chung and coworkers 30 used photopolymerization to prepare lightly crosslinked dopamine methacrylamide/2-methoxyethyl acrylate copolymers in the presence of ethylene glycol dimethacrylate to investigate the effect of viscoelastic properties of the network on adhesion measured by indentation. The presence of crosslinker provided improved work of adhesion under wet conditions, while the non-crosslinked copolymer showed the highest work of adhesion under dry conditions in comparison to non-catechol control samples.

Most recently, Xue et al. 31 published the preparation of a photocurable bioadhesive based on copolymerization of dopamine methacrylamide with an acrylate-functionalized poly(vinyl alcohol). The authors reported networks containing 40 wt% dopamine methacrylamide and 1 wt% acrylate-functionalized poly(vinyl alcohol) provided the highest adhesion to glass substrates as determined by lap-shear tensile tests. However, the synthesis of such bioadhesives required greater than 48 wt% N-methylpyrrolidone during preparation, which diminishes the bio- or environmentally friendly aspects of solvent-free photopolymerization. In general, photocurable resins based solely on acrylates, methacrylates, or styrenics, such as those previously described, yield highly heterogeneous networks, and also suffer from oxygen inhibition necessitating longer cure times to reach high conversions. 32

Alternatively, cross-linked polymer networks derived from light-induced radical-mediated thiol-ene reactions provide many advantages over traditional acrylate or
methacrylate resins.\textsuperscript{12-14} Thiol-ene polymer networks form via a free-radical step-growth process facilitated by a rapid, highly efficient chain-transfer reaction between multifunctional enes and thiols which provides insensitivity to oxygen inhibition and homogeneous network structures with well-defined physical and mechanical properties. Thus, thiol-ene photopolymerizations proceed very rapidly, but reach the gel-point only at relatively high functional group conversions yielding uniform networks with reduced shrinkage and stress. The homogeneity of the network is typically reflected by a narrow-ranged glass transition (T\textsubscript{g}) occurring over 15 – 20 °C (compared with up to 100 °C range for heterogeneous methacrylate networks).

Properties and functionality of the network system can also be diversely varied based on the wide range of commercially available or easily attainable monomers with alkene functionality providing opportunities to design binary and ternary networks via copolymerization.\textsuperscript{64-69} While thiol-ene photopolymerization has indeed been utilized to develop a broad range of functional materials,\textsuperscript{12-14} the incorporation of DOPA-mimics into photocurable thiol-ene networks has only been explored preliminarily by the Patton Group as a route to alter network properties and improve adhesive interactions with substrate surfaces.

\textbf{Chapter III: Experimental Methods}

All reagents and solvents used in the following procedures were obtained from Fisher Scientific and Sigma Aldrich Chemical Company and used without further purification unless specified in the procedure. Pentaerythritol tetra-3-mercaptopropinoate (PETMP) was obtained from Bruno Bock, Inc. The photoninitiator, Darocur 1173, also
known as 2-hydroxy-2-methyl-1-phenyl-1-propanone, was obtained from Sigma Aldrich Chemical Company.

**Figure 4.** Chemical structures of monomers and photoinitiator

*Deprotected eugenol formation via methyl eugenol acid deprotection*

In a typical reaction, 8.00 g (45 mmol) of methyl eugenol was dissolved into 50 mL of dry toluene and a catalytic amount (0.25 wt%) of tris(pentafluorophenyl)borane (TPFPB), under an N\textsubscript{2} atmosphere, followed by the slow addition of 16 mL (100 mmol, 2.2 mol equiv.) triethylsilane. Methane gas was rapidly evolved as the reaction proceeded. After reaction completion was determined by \textsuperscript{1}H NMR, the catalyst was removed by passing the reaction mixture through a neutral alumina plug with CH\textsubscript{2}Cl\textsubscript{2} as the eluent, followed by removal of solvent under vacuum to recover the pure product as a colorless oil (Yield: 93\%); \(\delta\textsubscript{H} (300\text{MHz, CDCl}_{3}; \text{Me}_4\text{Si}) 0.70-0.78 (12\text{H, m, CH}_2), 0.96-1.01 (18\text{H,}}
11

8.00 g EugTES (21 mmol) was dissolved in 10 mL of THF and purged with N₂ for 45 minutes. The solution was then transferred, under N₂, to a reaction vessel containing HCl solution, and mixed rapidly. The reaction proceeded quickly and completion was confirmed via thin layer chromatography. The organic layer was extracted into CH₂Cl₂ and then washed with H₂O, followed by drying and filtration. The solvent was removed via vacuum to recover the pure product as a white solid (Yield, 54%); δH (300MHz, CDCl₃; Me₄Si) 3.25 (2H, d, CH₂), 5.03-5.08 (2H, m, CH=CH₂), 5.24 (1H, s, OH), 5.32 (1H, s, OH), 5.86-5.99 (1H, m, CH=CH₂), 6.62-6.81 (3H, m, Ar-H); δC (300MHz, CDCl₃, Me₄Si) 39.5, 115.4, 115.6, 121.1, 133.4, 137.6, 141.5, 143.3.

Scheme 2. Methyl eugenol TES protection and acid deprotection to yield EugOH.

Synthesis of 3,4-dimethoxybenzoyl chloride (DMB-Cl)

3,4-dimethoxybenzoyl chloride (DMB-Cl) was synthesized by dissolving 5g of 3,4-dimethoxybenzoic acid (DMBA) in thionyl chloride and refluxing for 2 hours. Excess thionyl chloride was removed by rotary evaporation and vacuum overnight to recover the pure product as white solid. (Yield: 99%) δH (300MHz, CDCl₃; Me₄Si) 3.93-3.97 (6H, d, CH₃), 6.92-6.95 (1H, d, Ar-H), 7.53 (1H, d, Ar-H), 7.82-7.85 (1H, m, Ar-H).
Scheme 2. Synthesis of 3,4-dimethoxybenzoyl chloride

Synthesis of N,N-diallyl-3,4-dimethoxybenzamide (DADMBA)

DMB-Cl (4g) was dissolved in dichloromethane in a 100 mL round bottom flask and purged under nitrogen gas while cooled to 0°C. Triethylamine (TEA) (2 mol excess) was added dropwise to the solution. Diallylamine (DAA) (1.5 mol excess) was then added to the solution and reacted for 2 h. Reaction mixture was then washed with 1M HCl (5x), dried, filtered, and solvent removed to produce off-white product, N,N-diallyl-3,4-dimethoxybenzamide (DADMBA). (Yield: 85%)

$\delta^H (300MHz, CDCl_3; Me_4Si) 3.87-3.89 (6H, d, CH_3), 4.01 (4H, s, CH_2), 5.18-5.26 (4H, t, CH=CH_2), 5.83 (2H, s, CH=CH_2), 6.82-7.07 (3H, m, Ar-H).

Scheme 3. Synthesis of N,N-diallyl-3,4-dimethoxybenzamide

Synthesis of N,N-diallyl-3,4-dihydroxybenzamide (DADHBA)

DADMBA (2g) was dissolved in dichloromethane in a 100 mL round bottom flask and purged under nitrogen gas while cooled to 0°C. Boron tribromide (BBr$_3$) (4 mol excess) was added dropwise to the solution. The solution was stirred overnight, then quenched with water. The reaction mixture was then washed with water thoroughly. All aqueous phases were collected, combined, and extracted with dichloromethane. The
organic phases were combined and concentrated via evaporation to recover a white powder, N,N-diallyl-3,4-dihydroxybenzamide (DADHBA). (Yield: 60%) δ_H (300MHz, CDCl₃; Me₄Si) 3.91-4.11 (4H, d, CH₂), 5.16-5.30 (4H, m, CH=CH₂), 5.74-5.84 (2H, d, CH=CH₂), 6.67-6.69 (3H, m, Ar-H).

Scheme 4. Synthesis of N,N-diallyl-3,4-dihydroxybenzamide

Incorporation of DOPA-derivatives into thiol-ene films

Eug, MeEug, EugOH, and DADHBA compounds was added at various mole percentages (10 mol%, 20 mol%, 30 mol%, and 50 mol%) to an APE-PETMP thiol-ene photocurable resin maintaining a 1:1 thiol:alkene functional group stoichiometry. The thiol and alkene components were added to a scintillation vial along with the catechol species in the specified mole concentrations. Photoinitiator (3 wt%) was then added. For mixtures containing DADHBA, the minimal amount of DMF was added to ensure monomer homogeneity (approximately .17 mL for every 10 mol% of monomer). The resin was drawn down to a film thickness of 2 mils on various substrates and cured under ambient atmosphere under a mercury UV lamp. DADHBA-containing films were placed in a vacuum oven for 72 hours to remove any remaining solvent before testing.

Characterization

A Varian Mercury Plus 300MHz NMR spectrometer operating at a frequency of 300.13 MHz with VNMR 6.1C software was used to evaluate structure and purity of monomers: eugenol (Eug), methyl eugnol (MeEug), deprotected eugenol (EugOH), 3,4-
dimethoxybenzoic acid (DMBA), 3,4-dimethoxybenzoyl chloride (DMBCl), N,N-diallyl-3,4-dimethoxybenzamide (DADMBBA), N,N-diallyl-3,4-dihydroxybenzamide (DADHBBA).

Kinetic data was collected using real-time FTIR (RT-FTIR) spectroscopy to determine conversion of the thiol and alkene functional groups. The RT-FTIR studies were conducted using a Nicolet 8700 spectrometer with a KBr beam splitter and a MCT/A detector with a 320-500 nm filtered ultraviolet light source. Each sample was sandwiched between two NaCl plates (25 mm x 4 mm) and exposed to UV light with an intensity of approximately 20 mW/cm². A series of scans were recorded, where spectra were taken approximately 3 scans/s with a resolution of 4 cm⁻¹.

To determine the macroscopic adhesion of the catechol-containing thiol-ene films, films were characterized using cross-hatch adhesion and pull-off adhesion testing. Cross-hatch adhesion is a qualitative method where cross-hatch cuts are made into the film, tape is applied then removed at 180 degrees according to ASTM D-3359. The amount of material left is rated on a scale of 0B to 5B – with 0B being complete failure and 5B complete adhesion. Pull-Test adhesion data will be obtained using a PosiTest AT-M Adhesion Tester (DeFelsko Corp.) according to ASTM D-4541, where LOCTITE® 2h marine epoxy adhesive will be used to adhere aluminum test dollies (diameter of 20 mm) to the surface of the film. The pull-off adhesion test is a quantitative measurement, where the normal force required to pull an aluminum dolly from the substrate is determined using the thiol-ene resins as the adhesive materials.
Chapter IV: Results

FTIR was employed to characterize the thiol-ene photopolymerization kinetics. FTIR data is shown in Figure 5 for EugOH-APE-PETMP samples at varying mol% EugOH before and after photopolymerization. The area shaded in blue highlights the alkene peak at 3078 cm\(^{-1}\) and the green area highlights the thiol peak at 2569 cm\(^{-1}\). On the left, the pre-polymerization spectra show peaks for the presence of alkene and thiol. After photopolymerization (right), the peaks attributed to the alkene and thiol functional groups disappear indicating high conversion of these functional groups to produce the thiol-ene network. In Figures 6-8, MeEug, EugOH, and DADHBA systems are shown.

![Figure 5. Pre- (left) and post-polymerization (right) RT-FTIR spectra of MeEug-APE-PETMP samples at varying mol% MeEug](image-url)
Figure 6. Pre- (left) and post-polymerization (right) RT-FTIR spectra of Eug-APE-PETMP samples at varying mol% Eug

Figure 7. Pre- (left) and post-polymerization (right) RT-FTIR spectra of EugOH-APE-PETMP samples at varying mol% EugOH
For each sample, functional group conversion was determined by calculating the change in peak area over time. In Figures 7-10, the conversion plots versus time for each sample film are shown. For neat systems, containing only APE and PETMP, near quantitative (complete) conversion was observed. In Figures 6 and 7, films containing 10 mol% Eug or MeEug also reach near quantitative conversion (>99%).
As shown in Figure 8, samples containing 10 mol% of EugOH begins to exhibit a decrease in the conversion. This observation is believed to be due to the radical inhibiting behavior of phenolic compounds. This radical inhibition decreases conversion to 80% in the EugOH_{50}-APE_{50}-PETMP system.
For the systems containing DADHBA, a lower conversion is observed compared to systems containing eugenol or eugenol derivatives. Due to the nature of a diallyl amine derivative and its ability to homopolymerize or form a stable five-membered ring compound, a decrease in conversion (to 40%) is shown in the DADHBA solo plot in Figure 9. This homopolymerization or ring formation can interfere with DADHBA incorporation into the thiol-ene network which decreases conversion. Also, due to the catechol moiety, radical inhibition is still a problem.

Table 1 contains the calculated conversion values of all systems. Thiol functional group conversion decreases to 68% for the DADHBA$_{50}$-APE$_{50}$-PETMP system. However, the alkene functional group conversion is 80%. The decreased thiol conversion with a unequivalent alkene conversion is attributed to the homopolymerization of DADHBA where our polymerization is not reaching 1:1 thiol-ene conversion. While some decrease

![Figure 12](image-url)  
**Figure 12.** Kinetic plot vs. time for DADHBA-APE-PETMP samples with varying mol% DADHBA and DADHBA neat
in conversion is expected, we are exploring further to minimize this side reaction to increase conversion.

**Table 2.** Conversion values for all systems

<table>
<thead>
<tr>
<th>Thiol-ene System</th>
<th>Conv. (%)</th>
<th>Thiol-ene System</th>
<th>Conv. (%)</th>
</tr>
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<tbody>
<tr>
<td>MeEug-APE-PETMP</td>
<td>&gt;99</td>
<td>EugOH-APE-PETMP</td>
<td>&gt;99</td>
</tr>
<tr>
<td>0:100</td>
<td>&gt;99</td>
<td>0:100</td>
<td>&gt;99</td>
</tr>
<tr>
<td>10:90</td>
<td>&gt;99</td>
<td>10:90</td>
<td>&gt;97</td>
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<td>&gt;99</td>
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<td>DADHBA-APE-PETMP</td>
<td>EugOH-APE-PETMP</td>
<td>DADHBA-APE-PETMP</td>
</tr>
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<td>&gt;99</td>
<td>0:100</td>
<td>&gt;99</td>
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<td>&gt;99</td>
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</tr>
<tr>
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<td>96</td>
<td>25:75</td>
<td>81/93</td>
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<td>35:65</td>
<td>76/89</td>
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Cross-hatch adhesion data for all systems was collected, and the results are shown in Table 2. The catechol-containing compounds (EugOH and DADHBA) both showed improved adhesion across multiple substrates (aluminum, glass, steel, and marble) compared to the non-catechol containing DOPA derivatives (Eug and MeEug). EugOH\textsubscript{35}-APE\textsubscript{65}-PETMP and DADHBA\textsubscript{50}-APE\textsubscript{50}-PETMP showed good adhesion for multiple substrates. EugOH\textsubscript{50}-APE\textsubscript{50}-PETMP and DADHBA\textsubscript{50}-APE\textsubscript{50}-PETMP both exhibited excellent adhesion to aluminum, glass, steel, and marble. MeEug-APE-PETMP and Eug-APE-PETMP systems showed poor adhesion on all substrates for mol\% 35 or under due. For the MeEug, it is not expected to exhibit adhesion due to no catechol in the monomer. However, the Eug system should exhibit some adhesion due to the phenol, but at low mol\%, the amount of phenol in the system is not enough to show significant adhesion. Eug\textsubscript{50}-APE\textsubscript{50}-PETMP showed good adhesion for steel and marble, which is most likely due to mechanical adhesion induced by surface roughness of the substrates.
Table 3. Cross-hatch adhesion data for all samples

<table>
<thead>
<tr>
<th>Cross-Hatch Adhesion Testing</th>
<th>Aluminum</th>
<th>Glass</th>
<th>Steel</th>
<th>Marble</th>
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</table>

Chapter V: Conclusions

In this research project, our objective was to investigate how incorporation of catechol-containing DOPA derivatives would affect adhesive properties of thiol-ene films. Compared to non-catechol containing DOPA derivatives, such as methyl eugenol and eugenol, the synthetic catechol-containing derivatives, deprotected eugenol and N,N-diallyl-3,4-dihydroxybenzamide, showed improved adhesion in the films on a variety of substrates. However, radical inhibition due to the phenolic compounds and homopolymerization of the DADHBA monomer complicate the photopolymerization process and affect the adhesion behavior. Variation of the mole percentage of each catechol compound in the system affected the amount of inhibition or homopolymerization, and further studies to determine the optimal mole percent to balance the conversion and unwanted side reactions would be necessary. Overall, this study successfully determined
that catechol-containing compounds could be incorporated into thiol-ene networks for improved adhesion.
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