SYNTHESIS AND FORMULATION OF NOVEL POLYMERS FOR THE DESIGN OF
EXTENDED WEAR CONTACT LENS MATERIALS AND SURFACES

A Thesis

Presented to

The Graduate Faculty of The University of Akron

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Crystal Cyrus

May, 2009
SYNTHESIS AND FORMULATION OF NOVEL POLYMERS FOR THE DESIGN OF EXTENDED WEAR CONTACT LENS MATERIALS AND SURFACES

Crystal Cyrus

Thesis

Approved:

Advisor
Dr. Coleen Pugh

Co-Advisor
Dr. Scott Collins

Department Chair
Dr. Ali Dhinojwala

Accepted:

Dean of the College
Dr. Stephen Cheng

Dean of the Graduate School
Dr. George Newkome

Date
ABSTRACT

Controlled free radical polymerization techniques have been employed for the synthesis of polymers for contact lens application. Diblock polyampholyte copolymer brushes of Si/SiO₂//poly(acrylic acid-block-2(4)-vinyl pyridine) were synthesized by atom transfer radical polymerization (ATRP) using a “grafting from” strategy. These polyampholytes showed stimuli responsive behavior with pH. Polymer brushes can be attached to a lens surface.

The advantages to using a controlled radical polymerization technique for polymer brush synthesis are control over the brush thickness, via control of molecular weight, synthesis of polymers possessing narrow molecular weight distributions, and the ability to prepare block copolymers by re-initiation of dormant chain ends and subsequent extension of the polymer chains.

Polyelectrolytes and hydrophilic polymers were synthesized using reversible-addition fragmentation chain transfer (RAFT) polymerization. Copolymerization with monomers containing an epoxy group allows polymers to be attached to the lens surface.
ACKNOWLEDGEMENTS

I would like to thank my research advisor Dr. William Brittain and post-doctoral mentor Dr. Neil Ayres for providing me the opportunity and guidance for carrying out this research at the University of Akron. I am grateful to my thesis advisor Dr. Scott Collins for his counsel and correction during performing and writing this thesis research. I would like to show my appreciation towards my formal seminar committee and thesis advisors: Dr. Coleen Pugh and Dr. Judit Puskas in the Department of Polymer Science and Dr. Jay Künzler and Dr. Alok Awasthi at Bausch and Lomb. Last but not least, encouragement from my fellow graduate students in the Department of Polymer Science and colleagues in the Polymer and Surface Science group at Bausch and Lomb is also highly appreciated. Gratitude is also due to my family and friends from church.
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CHAPTER I

INTRODUCTION

1.1 Preface

This thesis is concerned with the use of controlled free radical polymerization techniques, including atom transfer radical polymerization (ATRP) and reversible-addition fragmentation chain transfer (RAFT) polymerization for the synthesis of new polymers for contact lens materials.

The first chapter in this thesis describes research performed initially at the University of Akron’s Department of Polymer Science. Polyampholyte diblock copolymer polymer brushes were synthesized utilizing atom transfer radical polymerization. Polymer brushes could be attached to the surface on a contact lens to modify the surface properties such as wettability. These polyampholytes were responsive to stimuli such as pH and added electrolyte concentration. The polymer brushes were immersed in aqueous HCl, NaOH or buffer solutions and the thickness response was measured using ellipsometry. Water contact angle measurements and ATR-FTIR (attenuated total reflectance fourier transform infrared) spectroscopy characterization was performed. Polymer brushes attached to the surface of lens cases could be explored later.

The second part describes the work done at Bausch and Lomb on polyelectrolytes and hydrophilic polymers for contact lens materials using RAFT polymerization
techniques. Common polymers that are used in contact lens formulations were studied, including poly(vinyl pyrrolidinone) (PVP) and poly(dimethyl acrylamide) (PDMA). Cationic polyelectrolytes such as quaternary methacrylates were studied. Polyacrylic acid (PAA) was also researched, which is capable of being converted to an anionic polyelectrolyte at high pH. These hydrophilic monomers were copolymerized with monomers containing epoxy functional groups such as glycidyl methacrylate. The epoxy functionality allows the polymer to be attached to the surface of a contact lens since the epoxy group can react with the aminated or hydroxylated lens surface. Thus, both of these sections utilize controlled free radical polymerization (CRP). This introductory chapter reviews CRP approaches directed toward the synthesis of polyelectrolyte and polyampholyte materials as routes to formulations of use in contact lens research.

1.2 Silicone-Based Hydrogels for Contact Lens Application

The design of the ultimate extended wear contact lens has been a challenging task. Extended wear is defined as continuous contact lens wear with minimal adverse physiological response. The polymers used in contact lenses must achieve both bulk and surface properties that are required for extended wear application. Surface structure and composition of polymers determine many of the physical properties such as wetting, friction, electrostatic charging and adhesion. Recent efforts to design new silicone-based hydrogels for extended wear application look promising. This development involves the design of the bulk polymer and a biocompatible surface. Typically, extended wear soft contacts are silicone hydrogels with poly(dimethylsiloxane) and hydrophilic segments.
1.2.1 *Introduction to Hydrogels*

Hydrogels are hydrophilic polymers that reversibly absorb water but are insoluble in water due to the presence of a three-dimensional network. The hydrophilicity is due to the presence of hydrophilic groups, such as hydroxyl, carboxyl, amide and sulfonic acid groups. The swollen equilibrated state results from a balance between the osmotic driving forces that cause the water to enter the hydrophilic polymer and the forces exerted by the polymer chains in resisting expansion.

The extended wear contact lens must possess strict material requirements, including optical transparency, chemical and thermal stability, biocompatibility with the ocular environment and good wettability to eye tears. The lens must resist deposition of tear components, hydrate well, be permeable to ions and be non-irritating to the eye. Hydrogels must also possess suitable mechanical properties. The modulus of elasticity must be low for patient comfort. The rupture or tear strength must be high for lens handling durability. Lens materials must resist evaporative dehydration, possess high levels of fluid transport and exhibit an optimum range of viscoelastic characteristics. These properties provide patient comfort, lens movement and ocular health. In addition, it is important that the material can be polymerized and processed by present contact lens manufacturing techniques. This typically involves a free radical initiated, compression casting of methacrylate functionalized hydrophilic monomers.

The material must also be permeable to oxygen. Most of the cornea obtains oxygen from the atmosphere due to a lack of blood vessels within the central cornea. Covering the cornea with a lens that does not permeate oxygen at acceptable levels limits the supply of oxygen to the cornea. An inadequate supply of oxygen may lead to adverse
physiological responses, including corneal edema, inflammation, infections and corneal ulcers. The key intrinsic material properties that are a measure of oxygen diffusion are oxygen permeability ($Dk$, where $D$ is the diffusion coefficient and $k$ is a proportionality coefficient called the Henry's law coefficient) and oxygen transmissibility ($Dk/L$) where the actual amount of oxygen reaching the cornea is inversely proportional to the lens thickness $L$. The units for oxygen permeability are barrers; one barrer $= 10^{-11} \text{ cm}^3 \text{O}_2(\text{STP})/\text{(cm}^2 \text{s mm Hg})$. In terms of barrers: $\text{cm}^3$ of $\text{O}_2$ is a molar quantity of oxygen rather than a true volume. It represents the quantity of oxygen that would take up one cubic centimeter at standard temperature and pressure (STP). The cm represents the thickness of the material whose permeability is being evaluated, and $1/\text{cm}^2$ is the reciprocal of the surface area of the material. Most practitioners say an oxygen permeability of 87 barrers is suitable for extended wear.3

There has been an extensive amount of research in the design of new materials with improved oxygen permeability for extended wear lens applications. There are three classes of contact lens material: 1) the hard, high modulus contact lens materials; 2) the soft, low modulus contact lens materials that possess little or no water; and 3) hydrogels, such as silicone. In the latter case, oxygen transmission requirements have been addressed through the use of siloxane and fluorosiloxane containing hydrogels.

1.2.2 High Water Content Hydrogels

The first potential materials developed toward the ultimate contact lens were high water content hydrogels.2 The oxygen permeability of the lens increases with water content. The design of high water hydrogels consists of the polymerization of
hydrophilic monomers such as N-vinyl pyrrolidinone (NVP), dimethylacrylamide (DMA), and methacrylic acid (MA). The ionic functionality in a basic buffered saline environment dramatically increases the water content of the resultant hydrogel. For example, a formulation consisting of 94 w/w % poly(2-hydroxyethyl methacrylate (PHEMA) copolymerized with 6 w/w % MA results in an ionic cross-linked hydrogel, following immersion in a buffered saline hydration, that contains 70% water (compared to PHEMA that contains 38% water). PHEMA is comfortable to wear and possesses excellent wettability and deposit resistance. The limitation of PHEMA is that is has a low permeability to oxygen (10 barrers) and is not suited for long-term wear applications.

There are limitations to high water content hydrogels, such as poor tear strength, that give poor handling durability. They often exhibit a high affinity for protein, particularly the hydrogels possessing an ionic functionality.\(^4\) These protein deposits can affect material wetting, patient comfort, visual acuity and may even cause inflammatory responses. In addition, in dry environments, high water content hydrogels can induce a clinical response known as epithelial dehydration (a dehydration of the corneal epithelial cells). This results in damage to the corneal epithelial cells. This phenomenon is a result of the high rate of water evaporation that occurs with the high water content hydrogels.

1.2.3 Soft Silicone-Based (Anhydrous) Elastomers

Another approach in the design of an extended wear contact lens is to develop materials based on polydimethylsiloxane (PDMS) elastomers.\(^2\) PDMS appeared to be an ideal polymer for use in an extended wear lens because it possesses a low modulus of elasticity, excellent transparency, and high oxygen permeability. The oxygen
permeability of pure PDMS is approximately 600 barrers, which is 60 times the oxygen permeability of poly(HEMA).\textsuperscript{5} The PDMS lenses were typically based on methacrylate functionalized siloxanes (M\textsubscript{2}D\textsubscript{x}) and were cured utilizing typical radical polymerization techniques.

\[ \text{M}_2\text{D}_x \]

Clinical results showed that there was no change in corneal physiology with long term wear (probably due to the extremely high oxygen permeability of PDMS). Unfortunately, PDMS also suffers from several serious drawbacks. The major drawback is that PDMS is completely non-wettable to tears, thus requiring surface treatment to impart wettability. These surface treatments were typically ineffective, resulting in surfaces that possessed marginal wetting characteristics and a high affinity for lipids. Another significant drawback was that silicone lenses under normal wear conditions adhered to the cornea.\textsuperscript{2} Adhesion of the silicone-based elastomers could possibly result from the low water transport and high recovery characteristics of silicone.

1.2.4 \textit{Silicone Hydrogels}

Silicone based hydrogels have been studied for contact lens application in an attempt to combine the high oxygen permeability of PDMS and the excellent comfort, wetting and deposit resistance of conventional low water, non-ionic hydrogels. This approach also involved an attempt to design materials that did not adhere to the cornea
and would minimize the epithelial dehydration observed with high water content hydrogels. It would provide a lens possessing levels of oxygen permeability high enough for extended wear application with minimal physiological impact.

The basic building blocks of a silicone hydrogel are a methacrylate- or vinyl-functionalized polydimethylsiloxane, a hydrophilic monomer and a cross-linker. These monomers are mixed, and under the appropriate conditions, undergo a polymerization reaction that results in a water insoluble gel. One challenge in the design of silicone hydrogels is that silicone-based monomers are hydrophobic and insoluble in hydrophilic monomers. Generally, copolymerization of silicones with hydrophilic monomers, such as N-vinyl pyrrolidinone (NVP) results in opaque, phase-separated materials.

In many cases, a co-solvent such as hexanol or isopropanol can be used to solubilize the siloxane and hydrophilic monomer. In addition, the copolymerization of methacrylate-functionalized silicones with hydrophilic monomers results in materials with reduced water content, loss of surface wettability and increased lipophilic character. Lipid uptake can also lead to a loss in material wettability. Methacrylate end-capped siloxanes containing hydrophilic side chains, copolymerized with high concentrations of hydrophilic monomers, such as DMA and NVP, resulted in transparent hydrogels possessing high levels of oxygen permeability without the use of a solubilizing co-solvent; if the methacrylate end-capped polydimethylsiloxanes do not have hydrophilic side-chains the materials are phase-separated.

The design of a silicone hydrogel involves several research stages. 1) The first is the synthesis phase, which consists of first designing and preparing novel siloxane and hydrophilic monomers that when polymerized will result in transparent materials.
Once the siloxane monomers are synthesized and purified and the solubility in hydrophilic monomers is established, the next phase of research consists of formulating a silicone hydrogel that possesses all the material requirements of an extended wear lens. Statistical experimental design is used to minimize the number of formulations required for testing. Formulations are typically prepared by bulk polymerization using conventional radical polymerization techniques with either thermal or ultraviolet initiation. Extraction of the final polymer is performed with an organic solvent, such as isopropanol to eliminate unreacted monomers. The design of a chemistry and formulation that achieves the desired material characteristics, consistently in a commercial operation, may take several years of research.

Surface modification, if necessary, is the third phase of contact lens development. A variety of surface treatment options exist. For example, the lens can be plasma treated to generate amine functionality on the surface of the lens. The lens can then be coated with another polymer that has some functional group such as an epoxy group. This allows the polymer dissolved in borate buffered saline to attach to the lens and change their surface properties, such as wettability.

Bausch and Lomb has already designed a transparent silicone hydrogel which was introduced commercially as Balafilcon™, based on a tris(trimethylsiloxy)silylpropyl (TRIS) substituted vinyl carbamate (TPVC). The TPVC molecule contains the hydrophobic silicone portion. Attached directly to the silicone, through a strong chemical linkage, is a hydrophilic, water-soluble vinyl carbamate group. The TPVC molecule is soluble in all proportions with hydrophilic monomers such as HEMA and NVP. In addition, the vinyl carbamate group provides a polymerization link for the attachment of
hydrophilic monomers. Polymerization of TPVC with NVP and a cross-linker using UV initiation resulted in transparent, high Dk, low modulus gels that are insoluble in water.

The key to the design of a successful silicone hydrogel is to balance the concentration of silicone and hydrogel (hydrophilic monomer) to achieve optimum levels of oxygen permeability and water transport, while still minimizing lens dehydration.

Decreasing the concentration of NVP resulted in hydrogels with lower water content and higher oxygen permeability. The reduction in water content reduced the fluid transport of the material, which may result in lens adhesion and affect the overall clinical performance of the material. Conversely, polymerization of TPVC with increasing levels of NVP resulted in hydrogels with higher water content and, as a result of the lower concentration of TPVC, lower levels of oxygen permeability. A higher water content will affect the dehydration characteristics of the material. Balance of the concentration of these monomers is essential to optimize the overall lens performance of the material.

There is an important advantageous relationship between oxygen permeability (Dk) and percent water for the TPVC-based silicone hydrogels. In contrast to conventional non-silicone-based hydrogels, the Dk decreases with increasing water
content, due to the lower concentration of TPVC with higher water content copolymers. Other approaches include hydrogels based on urethane functionalized silicones and methacrylate end-capped polydimethylsiloxanes containing fluorinated side chains.

1.3 Controlled Free Radical Polymerization

Controlled free radical polymerization is a chain polymerization from which irreversible chain transfer and irreversible chain termination (deactivation) rates are very slow compared to propagation.\textsuperscript{8,9} Living radical polymerizations, including atom transfer radical polymerization (ATRP) and reversible-addition fragmentation chain transfer (RAFT) polymerization, are used to achieve control of molecular weight and provide narrow molecular weight distribution of chains (polydispersity index = 1.05-1.2). These synthetic methods offer polymers of controlled composition, end-functional polymers, high purity block copolymers, and complex architectures such as stars. Block copolymers are prepared by sequential addition of monomers. End-functional polymers may be obtained in quantitative yield; the end groups can be characterized by NMR spectroscopy and MALDI-mass spectrometry.

A set of criteria is used to determine if a polymerization is considered living. Ideally, the mechanism of a living radical polymerization involves only initiation and propagation, followed at the end by an intentional chain termination or transfer. Chain initiation must be similar to propagation. All of the chains are initiated at the start of the reaction and grow at the same rate. Propagation continues until all of the monomer is consumed and may continue if more monomer is added to the reaction system. The concentration of active species remains constant, and a plot of $\ln([M]_0/[M]_t)$ vs. time is
linear. A plot of number average molecular weight $\bar{M}_n$ vs. conversion is linear. The polymers produced have a low polydispersity index (PDI).  

1.3.1 Atom Transfer Radical Polymerization (ATRP)

ATRP is also called transition-metal mediated radical polymerization. The mechanism of ATRP is shown in Scheme 1.

\[
\text{P-X} + \text{Cu(I)/Ligand} \xrightleftharpoons[k_{\text{deact}}]{k_{\text{act}}} \text{P} + \text{X-Cu(II)/Ligand} + \text{M} \xrightarrow[k_p]{k_t} \text{P-P} \quad \text{dead polymer}
\]

Scheme 1. ATRP mechanism.

Radicals are generated through a reversible redox process mediated by a transition metal, such as a copper complex (Cu-X/Ligand). In the deactivation process, propagating radicals are trapped by an atom transferred from a metal (copper) complex in its higher oxidation state. This atom is commonly a halogen such as Cl or Br. Activation involves a redox reaction between the polymer end group and the metal complex in its reduced state. The halogen transfers from the initiator or the dormant polymer chain end to the transition metal complex. The initiator or polymer chain becomes active and is able to propagate. The polymer chains grow by addition of monomer to the active intermediate radicals (P•).

In order for ATRP to be controlled, the dynamic equilibrium must lie to the left toward the deactivated or dormant species. This decreases the rate of polymerization. Termination by coupling of the radicals on two different chains is also minimized as the rate of termination is second order with respect to the active species while propagation is
first order. If the equilibrium constant is too large, the chains will terminate due to the
high radical concentration. The equilibrium constant must be high enough for the
monomer to polymerize at a reasonable rate. The halogen atom must rapidly and
selectively migrate between the growing chain and the transition-metal complex.\textsuperscript{9}

1.3.1.1 \textit{Reaction Conditions for ATRP}

There are a variety of reaction conditions available for ATRP. The metal complex
determines in which direction the equilibrium lies. The metal center must have at least
two readily accessible oxidation states separated by one electron and have reasonable
affinity toward a halogen. The ligand should complex fairly strong with the metal.
Metals used include Cu, Fe, Ru, Ni and Pd. CuBr\textsubscript{2} can be added to monomers that show
a chelating effect (the monomer competes with the ligand to bind to the metal).\textsuperscript{9}

Vinyl acetate, simple olefins and monomers that coordinate strongly with metal
centers do not polymerize well by ATRP. However, ATRP can be used to polymerize
several types of monomers, including styrenes, acrylates, methacrylates, acrylonitrile,
acrylamides and vinyl pyridine. Typical initiators include benzylic halides, \(\alpha\)-haloesters
and sulfonyl halides. Initiation must be fast and quantitative. The initiator selected is
typically a low molecular weight species that is structurally analogous to the propagating
radical. For acrylates, \(\alpha\)-bromo-propionates are used, and \(\alpha\)-bromoisobutyrate are better
for methacrylates. Benzyl bromide or phenylethyl bromide are used for styrene.\textsuperscript{9}

Multidentate nitrogen-based ligands provide better solubility for the transition
metal catalyst in organic media. Known ligands include \(\text{N,N,N',N'}\)-tetramethylethylene
diamine (TMEDA), \(1,1,4,7,10,10\)-hexamethytriethylene triamine (HMTETA),
N,N,N′,N″,N‴-pentamethyldiethylene triamine (PMDETA) and bipyridine derivatives. The redox properties of the metal are affected by complexation of the ligand to the metal, and the ease of reduction/oxidation is also related to the coordination geometry in both the reduced and oxidized states. Bipyridine-based ligands rapidly exchange in solution when complexed to a copper (I) center, increasing the possibility for ligand substitution reactions (with solvent or monomer). The activity of the catalyst is generally lower when TMEDA is the ligand. PMDETA acts as a tridentate ligand and shows a high potential for the controlled polymerization of a variety of monomers. HMTETA is a tetradentate amine ligand used to polymerize styrene, methyl acrylate and methyl methacrylate; however, it is extremely sensitive to air and hygroscopic.10

ATRP can be performed in bulk, but a wide variety of solvents have been used. Common solvents include ketones and alcohols. The solvent should not assist in side reactions (chain transfer to solvent) or be acidic. Polar media helps to dissolve the Cu complex. Anisole and diphenyl ether have been used with less polar monomers such as styrene to provide greater catalyst solubility. Reverse ATRP involves addition of the transition metal complex in its higher oxidation state, which shifts the equilibrium of the reaction toward the left side and slows down the polymerization.9

ATRP is a living radical synthetic technique widely used to produce polymer brushes. However, ATRP cannot be used for some functional monomers, for example acrylic acid. The acid functionality inherent in the monomer will poison the ATRP catalyst.11 In the presence of acid the nitrogen atoms in the ligand are protonated and cannot bind to the metal. There is also a chelating effect of the deprotonated monomer.
1.3.2 *Reversible Addition-Fragmentation Chain Transfer (RAFT) Polymerization*

There are other living/controlled free radical polymerization techniques that offer a variety of other synthetic possibilities. In RAFT polymerization, the product of chain transfer is a chain transfer agent with similar activity to the precursor transfer agent. This process is also referred to as degenerative chain transfer. The polymeric starting materials and the products have equivalent properties and differ only in molecular weight. RAFT polymerization can be used for a wide variety of vinyl monomers, including acidic and polar monomers. RAFT polymerization can be performed in heterogeneous media. It is used to synthesize end functional polymers and stimuli-responsive block copolymers. The mechanism of RAFT polymerization with thiocarbonylthio esters (ZC(=S)SR) is the sequence of addition–fragmentation equilibria shown in Scheme 2.

**Scheme 2. Mechanism of RAFT polymerization.**
Initiation and radical–radical termination occur as in conventional radical polymerization. Early in the polymerization, a propagating radical ($P_n^\cdot$) adds to the thiocarbonylthio ester ($RSC(Z)=S$, 1). Fragmentation of the intermediate radical generates a polymeric dithioester (3) and a new radical ($R^\cdot$). Reaction of the radical ($R^\cdot$) with monomer forms a new propagating radical ($P_m^\cdot$). Rapid equilibrium between the active propagating radicals ($P_n^\cdot$ and $P_m^\cdot$) and the dormant polymeric dithioester 3 provides equal probability for all chains to grow. RAFT yields narrow polydispersity polymers. When the polymerization is complete, the chains retain the dithioester end group. Radical–radical termination is not directly suppressed. Radicals are not formed or destroyed during chain equilibration. The rate of RAFT polymerization is thus similar to conventional radical polymerization. The molecular weight of the polymer is much lower than polymer formed in the absence of a RAFT agent. The number of living polymer molecules with RAFT ends greatly exceeds the number formed by termination. The intermediates (2 and/or 4) may react reversibly with propagating radicals and may be mediators of radical polymerization by reversible termination. RAFT agents (1) with a poor leaving group R may provide control of polymerization by a similar mechanism.\textsuperscript{9,12}

Primary dialkyl trithiocarbonates ($Z=SR$) are inert in radical polymerization of styrene and butyl acrylate. When radicals add to these trithiocarbonates, the intermediate rapidly reverts to starting materials. There is no effect on the polydispersity.\textsuperscript{9}

Polydispersities in RAFT polymerization depend on the chain transfer constants associated with the initial and polymeric RAFT agents. The initial RAFT agent should be rapidly consumed. The effectiveness of the RAFT agent depends on the monomer and the properties of the free radical leaving group R. The $Z$ group activates or deactivates
the thiocarbonyl double bond of the RAFT agent 1 and modifies the stability of the intermediate radicals 2 and 4. The transfer constants depend on the R and Z substituents. The chain transfer agent 1 and polymeric RAFT agent 3 should have a reactive C=S double bond (high $k_{\text{add}}$ or $k_{\text{addP}}$). The intermediate radicals 2 and 4 should fragment rapidly (high $k_\beta$ or $k_{\text{-addP}}$, weak S–R bond in intermediate) with no side reactions. The intermediate 2 should partition in favor of products ($k_\beta \geq k_{\text{-add}}$). The expelled radicals must efficiently re-initiate polymerization ($k_i > k_p$).9,12

The guidelines for selecting a RAFT chain transfer agent depend on the monomer (Chart I). For the Z group (activates C=S towards free radical addition), addition rates decrease and fragmentation rates increase from left to right. For the R group, fragmentation rates decrease from left to right. A dashed line indicates control of molecular weight but poor polydispersity or substantial retardation.9,12

Chart 1. Choosing an effective RAFT agent.
1.3.2.1 Reaction Conditions for RAFT Polymerization

RAFT agents include dithioesters, trithiocarbonates and xanthates (the polymerization employing xanthates is termed MADIX). Trithiocarbonates work well for styrene and (meth)acrylic monomers. Substituents that help addition give slower fragmentation. The R group should be a good free radical leaving group with respect to the propagating radical. Electrophilic substituents, groups that stabilize the incipient radical (through resonance) and bulky substituents make R a better leaving group. Penultimate effects should be considered. Primary and secondary amines and thiols are incompatible with RAFT agents.\textsuperscript{9,12}

RAFT is initiated by a source of free radicals from an initiator such as azobisisobutyronitrile (AIBN). A variety of solvents used include organic solvents, alcohols, water, ionic liquids and supercritical carbon dioxide. Some RAFT agents are hydrolytically sensitive to alkaline media. A wide range of temperatures up to 140°C have been reported. Under high pressures (1-9 kbar), radical-radical termination is slow and higher molecular weights and high rates of polymerization are reached. In the presence of Lewis acids, the tacticity of homopolymers can also be controlled.\textsuperscript{9,12}

Alkyl xanthates and dialkyl dithiocarbamates are not effective for (meth)acrylates and styrene. For xanthates, substituents that make the lone pair on the O less available for delocalization with the C=S group activates the RAFT agent towards addition of monomer. Effective dithiocarbamates have the N lone pair as part of an aromatic ring or possess an adjacent electron withdrawing or conjugating substituent. Xanthates are used with vinyl acetate, but dithioesters and trithiocarbonates are not (slow fragmentation of the radical adduct).\textsuperscript{9,12}
In general, RAFT agents are efficient for either styrene and methacrylates or for electron rich monomers like vinyl acetate and NVP. Monosubstituted monomers such as acrylates require high temperatures to avoid graft copolymerization.  

1.4 Polymer Brushes

Polymer brushes are assemblies of macromolecules that are tethered by one end to a surface or interface. When the chains are in close proximity to each other, they elongate to avoid overlapping due to the excluded volume effect. Controlled radical polymerization can be used to synthesize polymer brush systems including polymer micelles, block copolymers at fluid–fluid interfaces (e.g. microemulsions and vesicles), grafted polymers on a solid surface, adsorbed diblock copolymers and graft copolymers at fluid–fluid interfaces. Polymer chains are chemically bonded to or adsorbed onto a substrate. They can be used as adhesives, protein-resistant surfaces for biomedical applications, chromatographic devices, lubricants, polymer surfactants, polymer compatibilizers, colloid stabilizers and to prevent flocculation. Photo-, pH- or oxidoreduction-sensitive polymer brushes covalently tethered on porous membranes are used to regulate flow rate. Patterned thin organic films can be used for microelectronics, biomimetic materials and drug delivery.

The chemical compositions of polymer brushes tethered on a solid substrate surface can be homopolymer, mixed homopolymer, random copolymer or block copolymer brushes. Homopolymer brushes refer to an assembly of tethered polymer chains consisting of one type of repeat unit. Block copolymer brushes refer to an assembly of tethered polymer chains consisting of two or more homopolymer chains.
covalently connected to each other at one end. Polymer brushes can be divided into neutral and charged polymer brushes.\(^8\)

Polymer brushes are prepared by either physisorption or covalent attachment. Covalent attachment offers greater thermal and solvent stability. Covalent attachment using the “grafting to” technique involves tethering preformed polymer chains to a surface. It often suffers from low grafting density and thus lower film thickness. The polymer molecules must diffuse through the attached polymer layer to reach the reactive sites on the surface. Steric hindrance for surface attachment increases as the thickness of the polymer film increases. Covalently tethered polymer brushes with a high grafting density are prepared using the “grafting from” technique.\(^8\) This approach requires immobilizing initiators onto the substrate followed by \textit{in situ} surface-initiated polymerization to generate the tethered polymer brush with a high grafting density (Equation 1).

\[
\text{grafting density } (\sigma) = \frac{h}{v^{1/3}N} = \frac{h\rho L}{M_n}  
\]

The grafting density is the number of chains per unit area. In Equation 1, \(h = \) height of the brush, \(v = \) a dimensionless excluded volume parameter, \(N = \) number of monomers in the chain, \(\rho = \) density, \(L = \) length of chain, and \(M_n = \) number average molecular weight. When the grafting density is high, this forces chain overlap, and the average separation between chains at the tethering surface, \(d\), is much smaller than the radius of gyration.\(^{13,14}\)
1.4.1 *Polyelectrolytes*

Polyelectrolytes can be used for a variety of important applications, including surface property tailoring, chemical gating, nanolithographic patterning, and stabilizing aqueous solutions, gels and colloidal suspensions.\(^{15,16}\) They can be used to induce flocculation (precipitation), and impart surface charge to neutral particles that enable their dispersion in aqueous media. Since they are water-soluble, they can be used in medical applications such as implant coatings and controlled drug release systems.

Although the synthesis and properties of polymer brushes have been extensively researched, little research has been reported on charged, tethered polymer assemblies. Due to their important applications, increasing interest is building in polyelectrolyte brushes. The systems show diverse aggregation behavior and are stimuli-responsive in nature (i.e. change thickness or conformation in solutions of different ionic strength).

Strong (or quenched) polyelectrolytes are able to dissociate completely in solution. Weak (or annealed) polyelectrolytes partially dissociate at intermediate pH (pK\(_a\) or pK\(_b\) = 2-10); therefore the fractional charge is modified by changing pH.\(^{16,17}\) Dissociation releases counterions in solution, which affects the ionic strength and charge separation.

The polymer conformation is affected by solvent affinity and charge. Coulombic repulsion leads to an expanded, rigid-rod-like chain conformation. When salt is added, the charges along the polymer chain will be screened by counter-ions from the added salt. The chain will collapse to the more conventional random coil conformation. This is known as the polyelectrolyte effect. The structure and conformation of the chains is determined by the counterion density. Repulsions between the charges are screened by
increasing salt concentration, and the chains will contract. The Coulomb energy is decreased by the chain bending and bringing opposite charges closer together. In a polyelectrolyte polymer brush, the brush height typically depends on the Coulombic repulsions and chain elasticity. In the presence of salt, the brush thickness is defined by the counterion density, grafting density and system energy. The polyelectrolyte effect can be observed by measuring a film thickness by ellipsometry.16, 17

Polyelectrolyte polymer brushes attached to the surface of a contact lens can be used to modify the surface properties. These polymer brushes can be grown from functional groups on the lens. The use of controlled free radical polymerization in the synthesis of polymer brushes for lens surfaces offers a number of advantages. These include control over the brush height or film thickness and the ability to prepare block copolymers by the sequential activation of the dormant chain ends in the presence of different monomers.8,9

1.4.1.1 Synthesis of Polyelectrolyte Polymer Brushes Using ATRP

There are limited synthetic methods for preparing a “grafting from” polyelectrolyte polymer brush in the literature. Brittain et al. synthesized annealed polyelectrolyte polymer brushes that become charged in solutions of different ionic strength.18 This work showed that poly(tert-butyl acrylate) (5) polymer brushes made by ATRP can be converted to poly(acrylic acid) (6) brushes through pyrolysis (heating the substrate to 190-200°C in a vacuum oven), which did not cleave the anchoring ester in the initiator layer. Expansion of the polyelectrolyte brush upon addition of base demonstrated the polyelectrolyte effect. As the acid groups along the polymer backbone
became deprotonated, the like charges experienced Coulombic repulsions forcing the polymer to adopt an extended conformation, reflected by an increase in brush thickness. In the presence of added monovalent (NaCl) and divalent (CaCl$_2$) salt, the brush height decreased with increasing salt concentration. The divalent salt resulted in a faster collapse of the brush height.$^{18}$

Kong et al. studied 6 and poly(sodium 4-styrenesulfonate) (7) synthesized by surface-initiated ATRP.$^{19}$ These polyelectrolyte-coated, convex surfaces of multi-walled carbon nanotubes resembled core-shell structures. The water solubility of the carbon nanotubes was improved by the addition of 7. Layer-by-layer electrostatic self-assembly was conducted using the functionalized carbon nanotubes in which poly[(2-(N,N-dimethylaminoethyl) methacrylate] (8) and 7 were the polycations and polyanions. At low pH values, 8 became protonated and cationic.

Armes and co-workers synthesized poly(2-hydroxypropyl methacrylate) (9) or poly(2-hydroxyethyl methacrylate) and poly[2-(diethylamino)ethyl methacrylate] (PDEAEMA) (10) by ATRP using sequential monomer addition.$^{20}$ Polymer 9 was
formed using a poly(ethylene oxide)-based macro-initiator, followed by the polymerization, which formed polymer 10. Excess 2-sulfobenzoic acid (SBA) cyclic anhydride was used to esterify the hydroxy groups to provide copolymer 11. This zwitterionic diblock copolymer 11 self-assembled into micelles on adjusting the pH of the solution to neutral pH. The polymers formed colloidal polyelectrolyte complexes in aqueous solution.

Armes and co-workers reported polyelectrolyte-grafted silica particles prepared by grafting initiators onto silica particles, followed by surface-initiated ATRP. The polymers studied included 7, poly(sodium 4-vinylbenzoate) (12), 8 and 10 in protic media. The polyelectrolyte-grafted silica particles had pH-dependent colloidal stabilities. Cationic polyelectrolyte-grafted silica particles were stable at low or neutral pH and
aggregated at high pH. Anionic polyelectrolyte-coated silica particles became unstable at
down pH. The hydrodynamic diameter was measured to show the pH-responsive behavior.

Liu and co-workers reported poly(1-ethyl-3-(2′-methacryloyloxy ethyl)
imidazolium chloride) (13) brushes grafted onto a gold surface via surface-initiated
ATRP and studied the swelling/collapsed behavior of the brushes in different electrolyte
solutions. The interfacial resistance was characterized using electrochemical
impedance spectroscopy and cyclic voltammetry. The effects of the concentration and
type of electrolytes and temperature were investigated. The NaClO₄ concentration had a
dramatic influence on the electrochemical properties of the brushes. There was a
significant drop in charge transfer with 0.1 M NaClO₄. This brush collapsed due to salt
screening, which led to the formation of a permeable layer.
Müller and co-workers presented cylindrical brushes of polymer 8 prepared by ATRP using the grafting-from strategy on a mica surface. The PDMAEMA brushes showed worm-like structures and pH responsiveness. The quaternized strong cationic polyelectrolyte analog, poly{[2-(methacryloxy)ethyl]trimethylammonium iodide} (14) brushes, had similar worm-like morphologies. The cationic brushes collapsed in solution with high concentrations of monovalent NaBr salt. The hydrodynamic radius decreased with increasing pH.

Tan and co-workers reported diblock copolymers of \( t \)-butyl methacrylate and 10 synthesized by ATRP. Zwitterionic block copolymers of poly(methacrylic acid-\( b \) -2-(diethylamino)ethyl methacrylate) (15) were obtained by hydrolysis and showed pH-
dependent reverse micellization behavior. Micellar aggregates formed and had low polydispersity indices at a low pH of 2 and high pH of 12. Micelles formed at pH 2 were larger with a looser core due to hydration of the acid segments. In the presence of aq. NaCl, the size of the micelles decreased due to draining of the hydrated micellar core due to osmotic pressure. The DEAEMA-core micelles formed at pH 12 were compact and small. Addition of NaCl had only a small effect. The micellar size reduced only slightly due to electrostatic screening.

1.4.1.2 Synthesis of Polyelectrolytes Using RAFT Polymerization

Liu and co-workers reported the controlled synthesis of weakly charged zwitterionic diblock copolymers of 2-(dimethylamino)ethyl methacrylate (8) and sodium acrylate (16) using RAFT polymerization with cumyl dithiobenzoate as the RAFT agent. The micelles and reverse micelles that formed were affected by the net charge density of the copolymer. The hydrodynamic radius of the micelle was the smallest at extreme (high or low) pH where either of the blocks was charged. The micelles swelled with increasing pH near the isoelectric point.
McCormick and co-workers reported pH-dependent formation of cationic block copolymer micelles using poly[\(\text{ar-vinylmethylbenzyl}\)trimethylammonium chloride-\(b\)-\(N,N\)-dimethylvinylmethylbenzylamine] (17) prepared via RAFT polymerization. At pH <5.5, the dimethylvinylmethylbenzylamine block became fully protonated, and the block copolymer acted as a polyelectrolyte, dissolving molecularly in acidic water. At pH >7, the dimethylvinylmethylbenzylamine block becomes deprotonated, and the block copolymers aggregated into micelles composed of hydrophobic microdomains formed from the deprotonated blocks.

Storsberg and co-workers utilized RAFT polymerization to prepare a variety of stimuli-responsive amphiphilic ionic, non-ionic and zwitterionic block copolymers in organic and aqueous media. The hydrophilic character of the blocks was switched by changing the pH, temperature or salt content. The types of stimuli-sensitive macro-
surfactants included: (a) both blocks were fixed hydrophilic and hydrophobic blocks, (b) hydrophilic segment-\(b\)-stimuli-sensitive block, (c) hydrophobic segment-\(b\)-stimuli-sensitive block and (d) both blocks were stimuli-sensitive. Poly(N,N-dimethylaminoethyl methacrylate) 8 was a permanently hydrophobic unit. Poly[(ethylene glycol) acrylate] and poly(N,N-dimethylacrylamide) served as non-ionic, permanently hydrophilic blocks. Poly(styrene sulfonate) 7 was an ionic, permanently hydrophilic block. Poly(N-acryloylpyrrolidine) (18), poly(N-isopropylacrylamide) (19), poly(vinyl benzoic acid) (20) and the poly(sulfobetaine) (21) were used for the stimuli-sensitive blocks. A few of the block copolymers studied included poly(n-butyl acrylate-\(b\)-18), poly(19-\(b\)-18) and poly(18-\(b\)-N,N-dimethylacrylamide). Poly(vinyl benzoic acid) (20) is a pH-sensitive polymer that is only water-soluble at high pH where it is deprotonated. The new zwitterionic polymer 21 showed switching behavior and solubility in aqueous solvents that was sensitive to the type and concentration of inorganic salts added. The polymer did not dissolve in pure water or in 0.01 M HCl, but it was soluble in 0.5 M aq. NaBr, NaCl or NaClO₄.
Polymerization of polar monomers required water-soluble RAFT agents such as the ionic dithiobenzoate shown below. Non-ionic monomers were polymerized in organic solvent with conventional hydrophobic dithiobenzoates.

Magnin and co-workers reported the synthesis of comb and diblock copolymers of sodium 2-acrylamido-2-methylpropanesulfonate and methoxypolyethyleneglycol methacrylate (22) using RAFT polymerization. Adsorption behavior and stability properties of the alumina suspensions of these copolymers were studied. Changes in the electrokinetic properties of the alumina suspension after addition of the copolymers were monitored. The particle $\zeta$-potential decreased with increasing pH. A shift in the isoelectric point to a more acidic value was observed. Particle charges reversed when the amount of added copolymer reached a critical level.
1.4.1.3 Polyampholytes

Polyampholytes are macromolecules that contain both positively and negatively charged groups on a polymer chain.\(^{16}\) Diblock polyampholytes are charged macromolecules that bear both cationic and anionic charged groups on different blocks of the polymer chain. When we have a diblock copolymer with opposite charges along the chain, we see the opposite effect of adding salt – the so-called anti-polyelectrolyte effect. The chain will expand due to screening of the attractions rather than the repulsions in the polyelectrolyte.

Commonly, weak acids and bases are employed so that varying the pH changes the net charge of the polyampholyte in an aqueous solution. The thickness of the brush changes, demonstrating the stimuli-responsive behavior of these polymers as salt screens interactions between the oppositely charged segments. The isoelectric point of the polymer is the pH value at which the number of positive and negative charges is equal.\(^{16}\) At this pH, the brush thickness decreases, and around this pH the copolymer will show the characteristics of a polyampholyte. However, at either high or low pH, the polymer exhibits polyelectrolyte behavior due to charge asymmetry. An increase in the thickness is expected due to Coulombic repulsions. Localization of like charges increases electrostatic interactions between oppositely charged blocks such that block copolymers differ from random copolymers.

1.4.1.4 Polyampholyte Polymer Brushes

Brittain et al. synthesized several types of new polymer brushes by ATRP, including poly[dimethylaminoethyl methacrylate-b-methacrylic acid] poly(DMAEMA-b-
MAA) diblock polyampholyte polymer brushes. First, poly(dimethylaminoethyl methacrylate-\textit{b}- tert-butyl methacrylate) diblock copolymer polymer brushes were prepared. The synthesis of this neutral polymer was followed by pyrolysis of the tert-butyl methacrylate (\textit{tert}-BMA) segments.\textsuperscript{29} In the presence of added 0.5 M NaBr, the polymer brushes exhibited the anti-polyelectrolyte effect (chain expansion upon addition of electrolyte or salt). The attractions between the opposite charges along the chain experienced screening due to the added salt, and the chain elongated.

Other work reporting the synthesis of polyampholyte polymer brushes is limited. Several papers describe mixed polymer brushes (assemblies of oppositely charged polyelectrolyte homopolymers) that could be similar to diblock polyampholytes. A variety of pH responsive behavior has been seen. Mahltig and co-workers synthesized diblock copolymers of poly(DMAEMA-\textit{b}-MAA) by anionic polymerization and observed the adsorption of polymer micelles onto oxidized silicon (SiO\textsubscript{2}) surfaces as a function of pH, salt type and salt concentration.\textsuperscript{30, 31} At high and low pH, adsorption of either block occurred when one block was charged even though the surface had the same charge as the polymer.\textsuperscript{32, 33} No adsorption occurred at the isoelectric point (IEP).\textsuperscript{34, 35} Adsorption increased in the presence of bivalent salts or at high salt concentration.\textsuperscript{36}

Weakly charged polyelectrolyte and polyampholyte polymer brushes with a variety of compositions and conformations were reported by Genzer and co-workers.\textsuperscript{37} Huck and co-workers reported the use of stimuli-responsive polybetaine polyelectrolyte brushes for the reversible actuation of cantilevers.\textsuperscript{38}

Rühe and co-workers reported the free radical polymerization of a methacrylic acid polymer brush using a grafting from approach.\textsuperscript{39} This brush showed the
polyelectrolyte effect (an increase in thickness of the brush with an increase of pH). This was due to dissociation of the carboxylic acid groups, a higher charge density and higher osmotic pressure of the counterions. Electrostatic interactions and osmotic pressure of the counterions controlled the swelling of the brush. At low salt concentration of NaNO₃, they described an “osmotic brush” where the cations exchange with protons, the degree of dissociation increased and the swelling increased. At high salt concentrations they had a “salted brush” and the polyelectrolyte effect was seen. The salt screened the negative charges, and the brush collapsed. This qualitatively agreed with theory, which predicts brush height $L \propto \text{(salt concentration)}^{-1/3}$.

Huck and co-workers reported the synthesis of triblock copolymer polyampholyte brushes by ATRP using a thiol initiator on a gold substrate. The first block was [2-(methacryloyloxy)ethyl]trimethylammonium chloride (23) as a cationic block closest to the substrate. The second middle block was a methyl methacrylate (24) neutral block. The third block was a sodium methacrylate (25) anionic block. The thickness of the cationic block in 0.1 and 1.0 M potassium iodide salt solutions showed the polyelectrolyte effect (the thickness decreased as more salt was added and the positive charges were screened by the salt counter-ions).
In conclusion, the background literature on the synthesis of several contact lens materials or applicable compounds (and their properties) made using ATRP and RAFT has been discussed. The research described in this thesis used each of these techniques to synthesize materials for bulk, solution or surface of ophthalmic materials to study the properties of these polymers and evaluate their potential use in designing new contact lens chemistries.
CHAPTER II

EXPERIMENTAL

2.1 Materials

Tert-butyl acrylate (Aldrich, 98 %) was passed through a column of activated, basic alumina before use. 2-Vinyl pyridine (Aldrich, 97 %) and 4-vinyl pyridine (Aldrich, 95 %) were distilled prior to use. Cuprous bromide (Aldrich, 98%) was purified as described in the literature. Silicon wafers were purchased from Polishing Corporation of America and cleaned prior to use in accordance with a published procedure. The synthesis and deposition of the surface bound initiator, (11-(2-bromo-2-methyl)propionyloxy)undecyl trichlorosilane, has been reported previously. N,N,N',N''-Pentamethyldiethylenetriamine (PMDETA, Aldrich, 99%), ethyl 2-bromoisobutyrate (Br-iB, Aldrich, 98%), 1,1,4,7,10,10-hexamethyltriethylenetetramine (HMTETA, Aldrich, 97%), 2-(dimethylamino)ethyl methacrylate (DMAEMA, Aldrich, 98%), copper(II) bromide (Aldrich, 99%), 1-bromohexane (Aldrich, 98%), 1-bromododecane (Aldrich, 97%), anhydrous acrylic acid (Aldrich, 99%), 2,2'-azobis(2-methylpropionitrile) (AIBN, Aldrich, 98%), anhydrous acetone (Aldrich, HPLC grade), anhydrous methanol (Aldrich, 99.8%), anhydrous 2-propanol (Aldrich, 99.5%), anhydrous acetonitrile (99.8%), anhydrous chloroform (Aldrich, 99%) and anhydrous 1,4-dioxane (Aldrich, 99.8%) were used as received. Dimethyl acrylamide (DMA,
Aldrich, 98%) and 2-N-vinyl pyrrolidinone (NVP, Aldrich, 99%) were distilled under nitrogen gas prior to use. The synthesis of the RAFT agents has been reported by Moad and coworkers.44

2.2 Instrumentation

FTIR-GATR spectra were recorded using a Bruker Tensor 27 spectrometer using a GATR accessory with Ge ATR crystal (Harrick Scientific). Spectra were recorded at 2 cm⁻¹ resolution and 256 scans were collected. Contact angles were determined using a Rame Hart NRL-100 contact angle goniometer equipped with a tilting stage. Drop volumes were 10 μL. Ellipsometric measurements were performed ten times for each thickness measurement on a Gaertner model L116C ellipsometer with He-Ne laser (λ = 632.8 nm) and a fixed angle of incidence of 70°. Molecular weight analyses of poly(vinyl pyridine) were performed by gel permeation chromatography (GPC) with a Waters 501 pump, two PLgel (Polymer Laboratories) mixed D columns (5 μm) and a Waters 410 differential refractometer. The eluent was dimethyl formamide (DMF) and the flow rate was 0.7 mL/min at 35 °C). The columns were calibrated using narrow molecular weight distribution (MWD) PMMA standards (200 to 1.0 x 10⁶ g/mol) (Polymer Laboratories). Data analysis was performed with the E-Z Chrom software package. Molecular weight analyses of poly(tert-butyl acrylate) were performed using three Waters HR µStyrage columns and a Wyatt DAWN EOS multi-angle laser light scattering (MALLS) detector with a Waters 410 differential refractometer. The eluent was THF at 35 °C and a 1 mL/min flow rate. Data analysis was performed with the Wyatt ASTRA v4.73.04 software package. The polymers were characterized by ¹H
NMR spectroscopy using a Varian Unity Inova (400 MHz). The relative molecular weights were determined by GPC with a Waters 820 LC using polystyrene standards (THF/2ml/min. for NVP and DMA and MeOH:water 50:50 for polyelectrolytes).

2.3 Substrate Preparation

ATR crystals and silicon wafers were cleaned by treatment with freshly prepared "piranha" solution (70/30 v/v concentrated H₂SO₄/30% aqueous H₂O₂) at 100°C for two hours and were then rinsed with distilled water and dried with a stream of clean air. Note that the "piranha" solution is extremely reactive and should be handled with appropriate care. The "piranha" solution was prepared by slowly adding the concentrated H₂SO₄ solution to the H₂O₂ solution.

2.4 General Procedure for Deposition of Surface Bound Initiator

Into a dried round-bottom flask, a freshly cleaned silicon wafer was placed. The flask was purged with nitrogen gas. Dry toluene (10 mL) and a 25 vol. % solution of the trichlorosilane initiator in toluene (0.2 mL) were added to the flask via a syringe, and the flask was heated at 60 °C for four hours under a nitrogen gas atmosphere. The silicon wafer was then removed, sequentially washed with toluene and tetrahydrofuran, and then dried in a stream of air. The thickness was 5 nm, and the water contact angles were measured as \( \theta_{\text{advancing}} = 70 ^\circ \) and \( \theta_{\text{receding}} = 88 ^\circ \).

2.5 Typical ATRP Synthesis of a Si/SiO₂//poly(2-vinyl pyridine) Brush

A Schlenk flask was charged with 2-vinyl pyridine (15 mL, 0.14 mol) and 1,1,4,7,10,10-hexamethyltriethylenetetramine (0.14 mL, \( 5.1 \times 10^{-4} \) mol) and degassed.
three times using the freeze-pump-thaw method. Cu(I)Br (0.067 g, 4.6×10^{-4} mol) and Cu(II)Br_{2} (0.010 g, 4.6×10^{-5} mol) were added to a second Schlenk flask, which was degassed by three vacuum/nitrogen fill cycles. The solution from the first flask was then added to the inorganic salts via a cannula, which had been flushed with N_{2}, and the mixture heated to the reaction temperature of 80 °C until a homogenous solution had formed. A silicon wafer which was modified with the ATRP initiator ((11-(2-bromo-2-methyl)propionyloxy)undecyltrichlorosilane) was placed into a third Schlenk flask, which was degassed by three vacuum/nitrogen fill cycles. Free initiator, ethyl 2-bromoisobutyrate, (0.68 mL, 4.63×10^{-4} mol) was added to the flask containing the wafer, followed by the reaction solution from the second flask via a cannula. The reaction was allowed to proceed for 12 h before quenching by exposure to oxygen (air) and cooling. The wafer was isolated, rinsed with dichloromethane, ethanol and THF, before being placed in a Soxhlet extractor with dichloromethane for 24 h, sonicated in dichloromethane for 30 min. to remove any physisorbed polymer and dried under a stream of air. The thickness was 34 nm, and the water contact angles were measured as θ_{advancing} = 66 ° and θ_{receding} = 80 °. The M_w = 65,200 g/mol, M_n = 23,000 g/mol and PDI = 2.83.

2.6 Synthesis of a Si/SiO_2/poly(4-vinyl pyridine) Brush by ATRP

A Schlenk flask was charged with 2-vinyl pyridine (15 mL, 0.14 mol) and 1,1,4,7,10,10-hexamethyltriethylenetetramine (HMTETA) (0.14 mL, 5.1×10^{-4} mol) from Sigma-Aldrich and anhydrous 2-propanol (15 mL). The flask was degassed 3 times using the freeze-pump-thaw method. Cu(I)Br (0.067 g, 4.6×10^{-4} mol) and Cu(II)Br_{2} (0.010 g,
4.6×10^{-5} \text{ mol}) were added to a second Schlenk flask, which was degassed by three vacuum purge/nitrogen fill cycles. The solution from the first flask was then added to the inorganic salts via a cannula, and the mixture was heated to the reaction temperature of 60 °C until a homogenous solution had formed. A silicon wafer modified with the ATRP initiator (11-(2-bromo-2-methyl)propionyloxy)undecyltrichlorosilane) was placed into a third Schlenk flask, which was degassed by three vacuum purge/nitrogen fill cycles. Free initiator, ethyl 2-bromoisobutyrate, (0.68 mL, 4.6×10^{-4} \text{ mol}) was added to the flask containing the wafer, followed by the reaction solution from the second flask via cannula. The reaction was allowed to proceed for 12 h before being quenched by exposure to oxygen (air) and cooling. The wafer was isolated, rinsed with dichloromethane, ethanol and THF, before being placed in a Soxhlet extractor with dichloromethane for 24 h, sonicated in dichloromethane for 30 min to remove any physisorbed polymer, and dried under a stream of air. The thickness was 16 nm, and the water contact angles were measured as \( \theta_{\text{advancing}} = 54 ^\circ \) and \( \theta_{\text{receding}} = 68 ^\circ \).

2.7 Typical ATRP Synthesis of a Si/SiO\(_2\)//poly(tert-butyl acrylate) Brush

A Schlenk flask was charged with tert-butyl acrylate (14 mL, 9.7×10^{-2} \text{ mol}), \( N,N,N',N'',N'''-\text{pentamethyldiethylenetriamine} \) (0.20 mL, 9.6×10^{-4} \text{ mol}) and anhydrous acetone (7.0 mL) and degassed using the freeze-pump-thaw method (3 cycles). Cu(I)Br (0.069 g, 4.8×10^{-4} \text{ mol}) was added to a second Schlenk flask and three vacuum purge/nitrogen fill cycles were performed. The solution from the first flask was added to the Cu(I)Br via cannula, and the mixture heated to the reaction temperature of 60 °C until a homogenous solution had formed. A silicon wafer modified with an ATRP initiator
((11-(2-bromo-2-methyl)propionyloxy)undecyltrichlorosilane) was placed into a third Schlenk flask and three vacuum/nitrogen fill cycles were performed. Free initiator, ethyl 2-bromisobutyrate, (0.050 mL, 3.4×10⁻⁴ mol) was added to the flask with the wafer, followed by the reaction solution from the second flask via a cannula. The reaction was allowed to proceed for 18 h before being quenched by exposure to oxygen (air) and cooling. The wafer was isolated, rinsed with dichloromethane, ethanol and THF, before being placed in a Soxhlet extractor with THF for 24 h, sonicated in THF for 30 min to remove physisorbed polymer and dried by air. The thickness was 13 nm, and the water contact angles were measured as θ\text{advancing} = 78 ^\circ \text{ and } θ\text{receding} = 89 ^\circ.\text{ The } M_n = 10,100 \text{ g/mol and PDI } = 1.20.

2.8 Synthesis of a Si/SiO\textsubscript{2}/poly(tert-butyl acrylate-\textit{b}-vinyl pyridine) by ATRP

A Si/SiO\textsubscript{2}/poly(tert-butyl acrylate) polymer brush was prepared as described above, and chain extended with 2- or 4-vinyl pyridine using the same procedure as for the homopolymer vinyl pyridine brush. A Schlenk flask was charged with 2-vinyl pyridine (15 mL, 0.14 mol) and 1,1,4,7,10,10-hexamethyldiethylenetriamine (0.14 mL, 5.1×10⁻⁴ mol) and degassed three times using the freeze-pump-thaw method. Cu(I)Br (0.067 g, 4.6×10⁻⁴ mol) and Cu(II)Br\textsubscript{2} (0.010 g, 4.6×10⁻⁵ mol) were added to a second Schlenk flask and three vacuum/nitrogen fill cycles performed. The solution from the first flask was then added to the inorganic salts via a cannula, and the mixture was heated to the reaction temperature of 80 °C until a homogenous solution formed. The silicon wafer modified with the poly(t-BA) was placed into a third Schlenk flask and three vacuum/nitrogen fill cycles performed. Free initiator, ethyl 2-bromisobutyrate, (0.68 mL,
4.6×10^{-4} \text{ mol}) was added to the flask containing the wafer, followed by the reaction solution from the second flask via a cannula. The reaction was allowed to proceed for 12 h before being quenched by exposure to oxygen (air) and cooling. The wafer was isolated, rinsed with dichloromethane, ethanol and THF, before being placed in a Soxhlet extractor with dichloromethane for 24 h, then sonicated in dichloromethane for 30 min to remove any physisorbed polymer, and dried under a stream of air. The thickness was 20 nm, and the water contact angles were measured as $\theta_{\text{advancing}} = 61^\circ$ and $\theta_{\text{receding}} = 82^\circ$.

2.9 Typical Synthesis of Si/SiO$_2$/poly(acrylic acid-$b$-vinyl pyridine) by Pyrolysis

A silicon wafer containing a neutral tethered poly($t$-BA-$b$-2-VP) copolymer brush was placed on a watch glass and heated to 190 $^\circ$C for one hour. The wafer was removed, immersed in water at 50 $^\circ$C for 16 h, and then dried in a stream of air. ATR-FTIR spectroscopy of the wafer after removal from the deionized water and drying under a stream of air revealed no peaks in the IR spectrum that could be attributed to possible acid anhydride formation. The thickness was 9 nm, and the water contact angles were measured as $\theta_{\text{advancing}} = 56^\circ$ and $\theta_{\text{receding}} = 76^\circ$.

2.10 Quaternization of Si/SiO$_2$/poly(acrylic acid-$b$-4-vinyl pyridine) Brush

A silicon wafer bearing a Si/SiO$_2$/poly(acrylic acid-$b$-vinyl pyridine) polymer brush was synthesized and subsequently immersed in a 2 M solution of methyl iodide in nitromethane and heated at 40 $^\circ$C for five hours. The wafer was then removed from solution, rinsed with methanol, and sonicated in methanol for 45 minutes. The thickness was 9 nm, and the water contact angles were measured $\theta_{\text{advancing}} = 64^\circ$ and $\theta_{\text{receding}} = 70^\circ$. 
2.11 Treatment of Polyelectrolyte Brushes with pH (Buffer and Salt) Solutions

The salt solutions were made using 0.1 N hydrochloric acid or 0.1 N sodium hydroxide standards. Buffer solutions were made using Metrepak pHydrion capsules. The pH 3 buffer contained 70-80 % potassium biphthalate and 20-30 % sulphamic acid. The pH 4 buffer was 100 % potassium biphthalate. The pH 5 buffer was 75-85 % potassium biphthalate and 15-25 % dibasic sodium phosphate. The pH 6 buffer was 75-85 % monobasic potassium phosphate and 15-25 % dibasic sodium phosphate. The pH 7 buffer was 60-70 % dibasic sodium phosphate and 30-40 % monobasic potassium phosphate. The pH 8 buffer was 80-90 % dibasic sodium phosphate and 10-20 % monobasic potassium phosphate. The pH 9 buffer contained 70-80 % sodium bicarbonate and 20-30 % sodium carbonate. The diblock copolymer sample was immersed in an aqueous HCl solution (100 mL) (adjusted to pH=3 using a pH meter by diluting the HCl with deionized water) in a glass vial for 30 min. The sample was then removed from the solution and dried with a stream of clean air followed by characterization using tensiometry. This procedure was conducted on all polyelectrolyte diblock copolymer samples.

2.12 Synthesis of $[N-(2-(methacryloyloxy)ethyl)-N,N\text{-dimethyl-1-hexylammonium}\text{bromide}]$ (26)

The synthesis of this compound was reported by Russell and coworkers. In a 2 L 3-neck round bottom flask, equipped with a digital thermometer and a reflux condenser, dimethylaminoethyl methacrylate (19.7 g), bromohexane (24.75 g), anhydrous CH$_3$CN (100 mL) and anhydrous CHCl$_3$ (50 mL) were combined and heated to 40 °C for
24 h. A 4 L beaker containing approximately 2.5 L of diethyl ether was placed underneath a dropping funnel filled with the reaction mixture and a mechanical stirrer. The product was added drop-wise to the stirring ether to form a precipitate, which was then filtered using a Buchner funnel and a 1 L filter flask. The product was dried in a vacuum oven for 16 h. Yield = 29 g. Compound 26; $^1$H NMR (DMSO-$d_6$) $\delta$ 0.87 (t, 3 H, $J = 6.6$ Hz, N+(CH$_3$)$_2$(CH$_2$)$_5$CH$_3$), 1.29 (broad m, 6 H, N+(CH$_3$)$_2$CH$_2$CH$_2$(CH$_2$)$_3$CH$_3$), 1.69 (m, 2 H, N+(CH$_3$)$_2$CH$_2$CH$_2$(CH$_2$)$_3$CH$_3$), 1.91 (s, 3 H, CH$_2$=C(CH$_3$)), 3.15 (s, 6 H, N+(CH$_3$)$_2$(CH$_2$)$_5$CH$_3$), 3.43 (m, 2 H, N+(CH$_3$)$_2$CH$_2$(CH$_2$)$_3$CH$_3$), 3.78 (m, 2 H, OCH$_2$CH$_2$N+(CH$_3$)$_2$(CH$_2$)$_5$CH$_3$), 4.64 (m, 2 H, OCH$_2$CH$_2$N+(CH$_3$)$_2$(CH$_2$)$_5$CH$_3$), 5.76 and 6.08 (s, 2 H, CH$_2$=C(CH$_3$)) ppm.

2.13 Synthesis of [N-(2-(methacryloyloxy)ethyl)-N,N-dimethyl-1-dodecyl ammonium bromide] (27)

The synthesis of this compound was also reported by Russell and coworkers.$^{45}$ In a 2 L 3-neck round bottom flask, equipped with a digital thermometer and a reflux condenser, dimethylaminoethyl methacrylate (DMAEMA) (38 g), bromododecane (75 g), anhydrous CH$_3$CN (200 mL) and anhydrous CHCl$_3$ (100 mL) were combined and heated to 40 °C for 24 h. A 4 L beaker containing approximately 2.5 L of diethyl ether was placed underneath a dropping funnel filled with the reaction mixture and a mechanical stirrer. The product was added drop-wise to the stirring ether to form a precipitate, which was then filtered using a Buchner funnel and a filter flask. The product was dried in a vacuum oven overnight (~16h). Yield = 58.2g. Compound 27; mp 80~83 °C, $^1$H NMR (CDCl$_3$) $\delta$ 0.86 (t, 3 H, $J = 6.6$ Hz, N+(CH$_3$)$_2$(CH$_2$)$_{11}$CH$_3$), 1.30 (broad m, 18 H,
2.14 Typical RAFT Copolymerization of 26

To a 500 mL, three-neck round bottom flask was charged 26 (8.7 g, 0.020 mol), 2,2’-thiocarbonyl bis(sulfane diyl)dodecyl(2-methyl propanoic acid) (0.54 g, 0.0015 mol), AIBN (0.025 g, 0.00015 mol) and 50 mL of methanol (anhydrous). A magnetic stirring bar was introduced, the flask was fitted with a reflux condenser and digital thermometer, and the contents were allowed to mix at room temperature until a homogeneous solution was obtained. For the copolymerizations, dimethyl acrylamide (0.30 g, 0.003 mol) was added to the flask. The solution was purged with nitrogen gas for 30 min using a syringe needle and needle tubing adapter at room temperature. The flask was placed in a pre-heated oil bath stabilized at 50 °C and the reaction was allowed to proceed for 23 h. The mixture was precipitated slowly into 2.5 L of anhydrous ethyl ether. The resulting solid was then filtered and vacuum dried at room temperature. The polymer was characterized by $^1$H NMR spectroscopy and GPC. The $M_w = 6,280 \text{ g/mol}$ and PDI = 1.85. $^1$H NMR spectroscopy indicated no incorporation of 26 and showed residual 4° methacrylate comonomer (0.9 ppm for alkyl Me and 1.9 for Me).

2.15 Synthesis of Poly(acrylic acid) by RAFT

A 500 mL three-neck round bottom flask was fitted with a reflux condenser and a digital thermometer. Acrylic acid (10.0 g, 0.139 mol), S, S- bis[1-carboxy-1-methyl
ethyl] trithiocarbonate (0.392 g, 1.39×10⁻³ mol), AIBN (0.023 g, 1.39×10⁻⁴ mol) and 15 mL of methanol (anhydrous) were added to the flask. A magnetic stirring bar was introduced, and the contents were allowed to mix at room temperature until a homogeneous solution was obtained. The system was then purged with nitrogen (or argon) for 30 min via syringe at room temperature. The flask was placed in a pre-heated oil bath stabilized at 50 °C and the reaction was allowed to proceed for 96 h. The mixture was cooled to room temperature and approximately 5 mL of THF was added to the flask. The product was precipitated slowly into 2.5 L of anhydrous ethyl ether. The resulting solid was then filtered and vacuum dried at room temperature. GPC was used to characterize the polymer. The M_w = 2,220 g/mol and PDI = 1.02.

2.16 Typical RAFT Polymerization of Dimethyl Acrylamide

A 500 mL three-neck round-bottom flask was fitted with a reflux condenser and digital thermometer. Dimethyl acrylamide (20 mL, 4.81 g, 48.5 mmol), 2,2’-thiocarbonyl bis(sulfane diyl)bis(2-methyl propanoic acid) (0.780 g, 0.485 mmol), AIBN (0.066 g, 0.20 mmol) and 64 mL of 1,4-dioxane (anhydrous) were added to the flask. A magnetic stirring bar was introduced, and the contents were allowed to mix at room temperature until a homogeneous solution was obtained. The system was then purged with nitrogen (or argon) for 30 min via syringe at room temperature. The flask was placed in a pre-heated oil bath equilibrated at 50 °C and the reaction was allowed to proceed for 7 h. An aliquot was withdrawn from the mixture, before the second monomer was added, and quenched by cooling to room temperature, precipitating in ether and drying in a vacuum oven. Glycidyl methacrylate (GMA) (2.5 mL, 2.67 g, 18.8 mmol) or monomer 26 (6.06
g, 18.8 mmol) was then added to the flask and the reaction heated for another 24 hours for the block copolymerizations. The mixture was cooled to room temperature and approximately 5 mL of THF was added to the flask. The product was precipitated slowly into 2.5 L of anhydrous ethyl ether. The resulting solid was then filtered and vacuum dried at room temperature. The polymers were characterized by GPC. For poly(DMA), the $M_w = 0$ g/mol and PDI = . When the GMA was incorporated, the $M_w$ increased to 8,640 g/mol, and the PDI = 1.86. $^1$H NMR spectroscopy confirmed that GMA was incorporated (Figure 17 (b), resonances at 3.8 and 4.3 ppm). When the 26 was added, the $M_w = 6,280$ g/mol, and the PDI = 1.85. The polymers were also characterized by $^1$H NMR spectroscopy. $^1$H NMR spectroscopy indicated no incorporation of 26 and showed residual 4° methacrylate comonomer (0.9 ppm for alkyl Me and 1.9 for Me).

### 2.17 Typical RAFT Polymerization of $N$-vinyl pyrrolidinone

A 500 mL three-neck round-bottom flask was fitted with a reflux condenser and a digital thermometer. $N$-vinyl pyrrolidinone (40 mL, 41.6 g, 0.3743 mol), ethyl 2-(ethyloxycarbonothioylthio) propionate (EEXP) (0.175 g, $8.4 \times 10^{-4}$ mol), AIBN (0.050 g, $3 \times 10^{-4}$ mol) and 100 mL of 1,4-dioxane (anhydrous) were added to the flask. A magnetic stirring bar was introduced, and the contents were allowed to mix at room temperature until a homogeneous solution was obtained. The system was then purged with nitrogen (or argon gas) for 30 min via syringe at room temperature. The flask was placed in a pre-heated oil bath set at 60 °C and the reaction was allowed to proceed for 96 h. Anhydrous methanol (50 mL) was added to lower the viscosity of the mixture. The mixture was cooled to room temperature, and the product was precipitated slowly into 2.5 L of anhydrous diethyl ether, filtered, and dried in a vacuum oven at room temperature.
overnight. The molecular weight of the resulting polymer typically ranged between 50-60 kg/mol ($M_n$, GPC). Yields ranged from 75-95%, depending on the efficiency of the filtration step. For the block copolymerizations, glycidyl vinyl carbamate (13.4 g, 9.3 x $10^{-2}$ mol) was added to the flask and the reaction was stirred for 23 h before it was precipitated into diethyl ether, filtered and dried in a vacuum oven at room temperature. The polymers were characterized by GPC. For PVP, the $M_w = 6,180$ g/mol and PDI = 1.05. When the GVC was incorporated, the $M_w$ increased to 9,860 g/mol, and the PDI increased to 1.21. The polymers were also characterized by $^1$H NMR spectroscopy. There were some broad resonances due to the incorporation of GVC in the copolymer. There was some impurity in the spectrum, a pseudo triplet at 2.85 ppm [epoxide CH$_2$ group of impurity] as well as a multiplet at 2.64 ppm is overlapped with these, as is the doublet of doublet at ca. 4.5 ppm (O-CH$_2$-epoxide). The broad resonance at 6.67 ppm might be due to the N-H proton in the polymer or the impurity.
CHAPTER III
RESULTS AND DISCUSSION

Stimuli-responsive polymer brushes can be attached to a contact lens for surface property modification. The chemistry may be tailored to achieve lubricity, anti-fouling or anti-attachment characteristics. This thesis describes the synthesis of tethered polyampholyte polymer brushes utilizing 2- or 4-vinyl pyridine segments by surface-initiated ATRP. The “grafting from” strategy was performed on an oxidized silicon surface (Si/SiO$_2$/) using an $\alpha$-bromoisobutyrate initiator. AB diblock polyampholyte polymer brushes of acrylic acid and either 2- or 4-vinyl pyridine were prepared. The 4-VP segments in one of these polyampholyte polymer brushes were quaternized to form a permanently charged segment. The stimuli-responsive behavior of these brushes to solution pH was determined. Homopolymer brushes of 2- and 4-VP were also studied to compare the polyelectrolyte and polyampholyte behavior of the diblock copolymers.

3.1 Vinyl Pyridine Homopolymer Brushes Prepared by ATRP

Homopolymer brushes of VP were synthesized by surface-initiated ATRP using 1,1,4,7,10,10-hexamethyltriethylenetetramine (HMTETA), CuBr and CuBr$_2$ (Scheme 3).
Scheme 3. Preparation of homopolymer brushes of 4-VP by ATRP.

Cupric bromide was added due to the coordinating properties of pyridine. Preparation of these tethered brushes with control of MW and PDI requires the use of free initiator during ATRP. This results in concomitant formation of homopolymer in solution, which can be characterized by GPC in DMF. In the case of 2-VP, the homopolymers isolated had $M_w = 65,200$ g/mol and $M_n = 23,000$ g/mol with PDI = 2.83. Thus, the polymerizations were uncontrolled. The MW of the 4-VP block was not measured by GPC, but the MW would have to be nearly half that of poly(2-VP) to account for the difference in brush thickness. Thus, in the synthesis of the tethered diblock copolymers, the pyridine block was polymerized after the tert-BA since the latter polymerization was more controlled (vide infra).

These brushes were characterized by ellipsometry and tensiometry and the results are given in Table 1. The film thickness was 18 nm greater for poly(2-VP) than for poly(4-VP) and the surface polarity of these two films was significantly different. The surface of poly(4-VP) was more wettable than 2-VP. A possible explanation is that the nitrogen in the 4-VP is less sterically hindered and more available to compete with the ATRP ligand for chelation to a metal center. There might have been residual Cu$^{2+}$ that was more strongly bound to the poly(4-VP) brush. This would effect the brush height and
increase the surface wettability, since coordination of pyridine N to Cu$^{2+}$ has the same effect as protonation or quaternization.

On the other hand, within experimental error, there is a weak upward trend in both receding and advancing contact angles vs. brush thickness independent of the nature of the brush for the poly(VP) materials prepared in this section (this data is summarized in Tables 1-4 for neutral 2- and 4-VP or 2- and 4-VP-$b$-$t$-BuA brushes). This effect was much more pronounced for the thinner 4-VP vs. the 2-VP brushes, suggesting a fundamental difference between these two materials.

Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Film Thickness (nm)$^1$</th>
<th>Water Contact Angle$^2$</th>
<th>$\theta_a$</th>
<th>$\theta_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si/SiO$_2$</td>
<td>2</td>
<td></td>
<td>70</td>
<td>88</td>
</tr>
<tr>
<td>Si/SiO$_2$/SAM$^4$</td>
<td>5</td>
<td>70</td>
<td>88</td>
<td></td>
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<tr>
<td>Si/SiO$_2$/poly(2VP)</td>
<td>34</td>
<td>66</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(4VP)</td>
<td>16</td>
<td>54</td>
<td>68</td>
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<tr>
<td>Si/SiO$_2$/poly(4VP)</td>
<td>16</td>
<td>54</td>
<td>68</td>
<td></td>
</tr>
</tbody>
</table>

$^1$Thickness measurement of whole film ± 1 nm.

$^2$Contact angle measure with 10μL water droplet.

$^3$Contact angle not measured for freshly cleaned wafer.

$^4$Initiator layer.

The homopolymer brushes were characterized by ATR FT-IR spectroscopy and representative spectra appear in Figures 1 and 2. Characteristic absorptions for poly(2-VP) appear at 2960 (-CH), 2920 (-CH), 2850 (-CH), 1560 (C=N), 1500, 1470, 1440,
1380, 1340 (C-N), 1250 (C-N), 1230 (C-N), 1080, 1010, 970, 840 (aromatic ring), 750 and 640 cm\(^{-1}\) and at 2980 (\(-\text{CH}\)), 2900 (\(-\text{CH}\)), 1420, 1290 (C-N), 1190 (C-N), 1100, 970, 835 (aromatic ring), 740 and 655 cm\(^{-1}\) for poly(4-VP). As will be discussed, some of the absorptions shift for the polyampholyte brushes, due to protonation or alkylation at nitrogen (\textit{vide infra}). The 1740 cm\(^{-1}\) absorption must be due to residual initiator or the corresponding end-group.

The thickness of these brushes following exposure to aqueous HCl or NaOH solutions of differing pH and drying with a stream of air was monitored by ellipsometry; the results are presented in Figure 3 and 4 for poly(2-VP) and poly(4-VP), respectively.

Figure 1. IR spectrum of Si/SiO\(_2\)/poly(2-vinyl pyridine).
Figure 2. IR spectrum of Si/SiO$_2$/poly(4-vinyl pyridine).

Figure 3. Polymer brush thickness vs. pH for Si/SiO$_2$/poly(2-vinyl pyridine) brush.
Figure 4. Polymer brush thickness vs. pH for Si/SiO$_2$/poly(4-vinyl pyridine) brush.

Decreasing the pH led to an increase in film thickness. The pyridine segments became protonated, increased in fractional charge, experienced an electrostatic repulsion and adopted an extended coil conformation. The change in thickness was much more pronounced for the thinner poly(4-VP) brush. The brush thickness decreased by $>10$ nm vs. only $\sim4$ nm for the thicker 2-VP brush. The difference may be attributed to a saturation effect of the acid solutions by the thicker brush. This is supported by a change in the pH of these solutions after immersion of the brush. Since the pK$_a$ of these two pyridines was not very different, the extent of protonation and subsequent brush extension may also be subject to kinetic effects. The effects of temperature, immersion time and the stimuli-responsive behavior to pH in solution were not studied.
3.2 Synthesis of Polymer Brushes of poly(tert-butyl acrylate) by ATRP

The poly(tert-BA) polymer brush was synthesized by surface-initiated ATRP with \(N, N, N', N'\)-pentamethyldiethylenetriamine (PMDETA), acetone and CuBr (Scheme 4). This block proceeded to high conversion and reinitiated an additional aliquot of monomer. The poly(tert-BA) formed in the presence of free initiator was analyzed by GPC. The PDI (< 1.2) was narrow. The \(\overline{M}_n = 10.1\) kg/mol and 13 nm thickness suggested a densely covered polymer brush architecture as a result of employing the grafting-from method. The grafting densities of the tert-BA layer of the polymer brushes in Table 2 were 0.24 chains/nm\(^2\) for the brush extended with 2VP and 0.26 chains/nm\(^2\) for the brush extended with 4VP. Grafting density = \(\text{Th} \cdot F \cdot \frac{N_A}{\overline{M}_n}\), and Th is the thickness (nm), F is density (=1), \(N_A\) is Avogadro’s number, and \(\overline{M}_n\) is the number average molecular weight of the free polymer.

3.3 Synthesis of Diblock Copolymer Brushes of Poly(AA-b-2(4)-VP) by ATRP

In order to synthesize well-defined, diblock copolymers, the Si/SiO\(_2\)//poly(tert-BA) brush was extended with 2- or 4-VP. Based on the results presented in section 2.1, it was expected that these diblock copolymers did not feature controlled block lengths for the poly(2- or 4-VP) block. Pyrolysis of the tert-butyl ester groups in the tert-BA segment was achieved by placing the wafer bearing a poly(tert-BA-b-VP) diblock copolymer brush into a vacuum oven set to 190 °C for 45 min.\(^{18}\) The wafer was then immersed in deionized water, yielding the poly(AA-b-VP) polymer brush (Scheme 4). The free polymer in solution was analyzed by GPC for the poly(acrylic acid-b-2-vinyl pyridine) brush, and the \(M_w = 53.9\) kg/mol, \(M_n = 24.6\) kg/mol and PDI = 2.43.
Scheme 4. Preparation of a Si/SiO$_2$/poly(acrylic acid-b-2(4)-vinyl pyridine) brush.

The resulting polyampholyte brushes were characterized by ellipsometry, ATR-FTIR spectroscopy and tensiometry. ATR-FTIR confirmed the presence of both segments of the polyampholyte in the polymer brush and also confirmed the conversion of the tert-butyl esters to carboxylic acids. This was seen by the loss of the C(CH$_3$)$_3$ absorption at 2900 cm$^{-1}$, broadening of the ester C=O absorption at 1730 cm$^{-1}$ (formation of acid), and the appearance of a broad OH absorption between 3400 and 3000 cm$^{-1}$ (Figures 5 and 6). The film thickness decreased (Table 2) due to the volume loss of the tert-butyl ester groups and electrostatic attractions between segments; the AA segment is associated with the VP.

Figure 5. IR spectrum of Si/SiO$_2$/poly(AA-b-2VP) (9 nm).
Figure 6. IR spectrum of Si/SiO$_2$/poly(AA-b-4VP) (14 nm).

For a diblock copolymer of AA and 2-VP, given the pK$_a$ values for each block were (4.25 and 4.95, respectively), it can be estimated that the equilibrium will be favorable with $K \approx 5$ at the IEP ($K' \approx 14$ for AA and 4-VP with pK$_a = 5.39$). Therefore, the film thickness will be a function of relative block length (i.e. stoichiometry) and pH.
Table 2

Ellipsometry and Contact Angle Results for Si/SiO$_2$/poly(AA-$b$-VP) Brushes

<table>
<thead>
<tr>
<th>Sample</th>
<th>Film Thickness (nm)$^1$</th>
<th>Water Contact Angle$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\theta_a$</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(tert-BA)</td>
<td>13</td>
<td>78</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(tert-BA-b-2VP)</td>
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<td>61</td>
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<tr>
<td>Si/SiO$_2$/poly(AA-b-2VP)</td>
<td>9$^3$</td>
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</tr>
<tr>
<td>Si/SiO$_2$/poly(tert-BA)</td>
<td>13</td>
<td>77</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(tert-BA-b-4VP)</td>
<td>18</td>
<td>62</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(AA-b-4VP)</td>
<td>14$^3$</td>
<td>57</td>
</tr>
</tbody>
</table>

$^1$Thickness measurement of whole film ± 1 nm.

$^2$Contact angle measure with 10$\mu$L water droplet.

$^3$Thickness measured in bulk after exposure to aqueous solution at pH 7 for 16 h, 25 °C.

The diblock copolymer brushes had similar thicknesses for the AA segment and the 2- and 4-VP segments. The surface polarity appeared to be identical for the diblock copolymers as compared to the homopolymers, which had different polarities but this could be due to differences in film thickness as mentioned previously. The $M_n = 53.9$ kg/mol and PDI = 2.45 for the poly(AA-$b$-2-VP) diblock copolymer brushes.

The neutral annealed diblock polyampholyte brush was immersed in HCl or NaOH solutions at different pH values, dried with air and the brush thickness was recorded. The systems exhibited both polyelectrolyte and polyampholyte behavior depending upon the solution pH as shown in Figures 7 and 8 for the diblock copolymers of AA and 2-VP and 4-VP, respectively. The maximum thickness at low pH is about 2-3 times the minimum thickness for both 2- and 4-VP-$b$-AA brushes, with the latter about
40\% more extended; at high pH, the brushes had similar thickness. Thus, the response of the AA block to deprotonation is similar in both cases while the 2-VP shows somewhat greater extension on protonation than the 4-VP block.

Figure 7. Polymer brush thickness vs. pH for Si/SiO₂//poly(AA-b-2VP) brush.
Figure 8. Polymer brush thickness vs. pH for Si/SiO$_2$/poly(AA-\textit{b}-4-VP) brush.

The diblock copolymer Si/SiO$_2$/poly(AA-\textit{b}-2 or 4-VP) polyampholyte polymer brushes demonstrated polyelectrolyte behavior for each segment at high or low pH. When one of the blocks was charged, the thickness increased and the segment experienced electrostatic repulsions along one segment of the polymer chain. At intermediate pH, the thickness approached a minimum value and polyampholyte behavior was seen around the isoelectric point (IEP) of the chain. The brush collapsed as salt bridges formed between the oppositely charged segments. The IEP is the pH at which the net charge is zero along the polymer chain.

Vinyl pyridine was cationic at low pH (pK$_a$, 2-VP = 4.95 and pK$_a$, 4-VP = 5.39). Poly(acrylic acid) was anionic at high pH (pK$_a$,AA = 4.25) (Chart 1). The IEP was close to these pK$_a$ values. The IEP was around 5 for the poly(AA-\textit{b}-2-VP) polymer brush and 6 for the poly(AA-\textit{b}-4-VP) polymer brush.
The film thickness was at a minimum at the IEP. At low or high pH, polyelectrolyte effects dominated. At low pH, the cationic vinyl pyridine moieties caused electrostatic repulsion, as was observed for the corresponding homopolymers. As the pH increased, and approached the IEP, the acrylic acid groups were converted to carboxylate anions, increasing the anionic charges along the chain. Polyampholyte behavior dominated, and salt bridges formed between the opposite charges in the chain or between chains in close proximity. The chains adopted a collapsed conformation near the IEP. At higher pH, the vinyl pyridine segments were neutral, while the carboxylate anions in the AA segment showed polyelectrolyte behavior and the brush expanded.

The conformations adopted by these brushes depend on grafting density, block ratios and fractional charge. Since the chains are end-tethered in close proximity, electrostatic interactions occurred between the blocks. To investigate the influence of block ratio, a poly(AA-\textit{b}-2-VP) brush with longer block segments (by 54 and 28%,
respectively) was prepared. The length ratio differed by only 20%. This brush featured proportionately more AA than 2-VP but the difference was slight (cf. Table 3 vs. 2). The ellipsometry results are shown in Figure 9.

Table 3

<table>
<thead>
<tr>
<th>Sample</th>
<th>Film Thickness (nm)$^1$</th>
<th>Water Contact Angle$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si/SiO$_2$</td>
<td>3</td>
<td>$\theta_a$</td>
</tr>
<tr>
<td>Si/SiO$_2$/SAM$^4$</td>
<td>6</td>
<td>70</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly($t$-BA)</td>
<td>20</td>
<td>79</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly($t$-BA-b-2VP)</td>
<td>29</td>
<td>61</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(AA-b-2VP)</td>
<td>23</td>
<td>56</td>
</tr>
</tbody>
</table>

$^1$Thickness measurement of entire film ± 1 nm.
$^2$Contact angle measure with 10 $\mu$L water droplet.
$^3$Contact angle not measured for clean wafer.
$^4$SAM is deposited initiator.

Figure 9. Polymer brush thickness vs. pH for Si/SiO$_2$/poly(AA-b-2-VP) brush.
This brush was treated with both aqueous HCl or NaOH solutions and with buffer solutions that were prepared using commercial products that were mixtures of potassium biphthalate and sulphamic acid (pH 3), biphthalate / phthalate and/or biphosphate / monophosphate (pH 4-8) and bicarbonate / carbonate salts (pH 9). The thickness-response to pH only changed slightly with the nature of the solution for this thicker brush. Not only was the response reduced, the IEP was closer to a higher pH of 6 with this brush compared to the shorter brush with less AA. The brush in Figure 9 shows an extension of only 13% over the entire pH range vs. nearly 300% variation for the shorter brush in Figure 7. The origins of these profound effects are not well understood at this time but are obviously important for applications that require stimuli responsive surfaces.

The same trend can be seen for the HCl/NaOH solutions and the buffer solutions with this thicker brush. Initially, the film thickness decreased with increasing pH to some minimum pH value at the isoelectric point of the polyampholyte. With a further increase in pH, the film thickness increased. At every pH, the film thicknesses were greater after immersion in buffer solutions.

The buffers had a higher capacity to resist changes to pH compared to the salt solutions. The ionic strength of the buffer solutions was higher than that of the HCl/NaOH solutions. Both effects would tend to increase brush thickness at any particular pH though the effect is most pronounced at low pH where the 2-VP block is being protonated. Though the nature of the anions present would also influence extension of the 2-VP brush, since the low pH buffers all differed in ionic composition as well as ionic strength, it is not possible to state which of, or whether both of, these two effects are responsible for the difference seen.
3.4 Synthesis of poly(acrylic acid-b-quaternized 4-vinyl pyridine) by ATRP

The poly(vinyl pyridine) segments were quaternized with CH$_3$I (Scheme 5) to study the polyampholyte behavior when the VP block was quenched (permanently charged). The results in Table 4 were compared to the annealed polyampholyte.

![Scheme 5. Quaternization of 4-VP to form a poly(AA-b-Q-4-VP) brush.](image)

Table 4

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness (nm)</th>
<th>Water Contact Angle$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\theta_a$</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(t-BA)</td>
<td>11</td>
<td>77</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(t-BA-b-4VP)</td>
<td>15</td>
<td>55</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(AA-b-4VP)</td>
<td>17$^3$</td>
<td>55</td>
</tr>
<tr>
<td>Si/SiO$_2$/poly(AA-b-Q4VP)</td>
<td>9$^4$</td>
<td>64</td>
</tr>
</tbody>
</table>

$^1$Thickness measurement of whole film ± 1 nm.

$^2$Contact angle measure with 10 μL water droplet.

$^3$Thickness measured in bulk after exposure to an aqueous solution at pH 7.

$^4$Thickness after alkylation with MeI followed by sonication in methanol.
Figure 10. Polymer brush thickness vs. pH for Si/SiO$_2$/poly(AA-$b$-4-VP) in HCl/NaOH.

For the diblock copolymer in Figure 10, the $\tau$-BA block was approximately 11 nm. The 4-VP block was 4 nm. The total parent polymer poly(AA-$b$-4-VP) film thickness was 17 nm (including the initiator layer). The block copolymer in Figure 10 possessed a greater poly(AA) segment, as evidenced by the large film thickness change at high pH and the shifting of the curve minima to a lower pH value. The drastic change in the shape of the curve was not accounted for by the small difference in the length of the two segments. This poly(AA-$b$-4-VP) brush showed different behavior than the corresponding polyampholyte brush made previously. After quaternization, the thickness decreased to 9 nm. The thickness extended to 16 nm after exposure to 0.5 M NaBr solution. The electrolyte screened the electrostatic attractions between the quaternary amine groups and the carboxylate moieties (Table 4). The film thickness decreased with pH for the quaternized polymer brush as shown in Figure 11.
Upon quaternization, the film thickness only decreased with increasing pH about 4 nm. This behavior was explained by considering the nature of each block as the pH changed. At low pH, the acrylic acid was neutral. The Q-4-VP segment acted as a polyelectrolyte with electrostatic repulsions along the chain segment and adopted an extended coil conformation. The acrylic acid segments converted to carboxylate moieties with increasing pH. The carboxylate anions experienced electrostatic attraction with the permanently charged cationic pyridinium units, and the polymer chain collapsed. The IEP was much higher since the minimum of thickness was at a pH of 9.

The diblock copolymer in Figure 8 possessed a slightly longer tert-BA segment (13 nm) and 4-VP segment (5 nm) than that shown in Figure 10 which had a shorter tert-BA segment (11 nm) and a similar 4-VP segment (4 nm). The tert-BA segment was only slightly larger than the 4-VP segment for Figures 8 and 10. The calculated IEP for the
poly(AA-b-4-VP) was 4.82, which is the average of the IEP of each block segment and does not account for the block lengths. The actual IEP shifted to a lower pH value around four in Figure 10 and to a higher value around six in Figure 8.

In Figure 7, the tert-BA segment was about 13 nm while the 2-VP segment was also 7 nm. The calculated IEP for the poly(AA-b-2-VP) was 4.6 while the actual IEP was at a higher pH value of five for Figure 7. In Figure 9, the tert-BA segment was much larger at 14 nm than the 4-VP segment (9 nm). The actual IEP of poly(AA-b-2-VP) was also higher than expected at a value of six for that in Figure 9.

In Figure 11, there was a marked change in the behavior of the mixed annealed/quenched polyampholyte polymer brush. The film thickness only decreased with an increase in pH. Only polyampholyte behavior was seen as the anionic residues along the chain increased. The minimum thickness at the IEP was at a much higher pH when the VP segment was permanently charged. At low pH values, the poly(AA) segment was fully protonated and neutral. The quaternized 4VP segment acted as a polyelectrolyte. Upon increasing the pH of the solution, the poly(AA) segments were converted to carboxylate moieties. Increasing charge led to electrostatic interactions with the permanently charged pyridinium units and a collapse of the polymer coil by 4 nm.

In conclusion, diblock polyampholyte polymer brushes of Si/SiO₂//poly(acrylic acid-b-2(4)-vinyl pyridine) were successfully prepared. In order to obtain the acrylic acid segments, tert-butyl acrylate was polymerized as a protected form of acrylic acid. Following chain extension with vinyl pyridine the tert-butyl esters were converted to the corresponding carboxylic acids through pyrolysis, which afforded polyampholyte polymer brushes. The diblock polyampholyte polymer brushes demonstrated stimuli-
responsive behavior with respect to pH, showing both polyelectrolyte and polyampholyte effects. The response to the pH of HCl/NaOH and buffer solutions depended on the nature of the solution. The homopolymer brushes showed only polyelectrolyte behavior. The IEP point of these diblock polyampholyte polymer brushes depended on the block ratios. The thickness only decreased with pH when the vinyl pyridine segments were quaternized and salt bridges formed between the oppositely charged cationic pyridinium segments and the anionic carboxylate segments.

3.5 Synthesis of Polyelectrolytes and Polyampholytes by RAFT Polymerization

Conventional radical and RAFT polymerizations were used to synthesize amphiphilic random and block copolymers from cationic monomers. These monomers are soluble in lens solutions and increase the wettability of a lens. Monomers with epoxy functionality react with the aminated or hydroxylated lens surfaces. Thus, some of the copolymers synthesized included glycidyl methacrylate and N-vinyl glycidyl carbamate. Russell and coworkers reported ATRP of antimicrobial quaternary ammonium monomers to furnish cationic polyelectrolytes that can be applied to surfaces. Here \( N,N\)-dimethylaminoethyl methacrylate (DMAEMA) was reacted with alkyl bromides; monomer yields were \( \sim 80 \% \). These quaternary methacrylates were polymerized using the free radical initiators \( \alpha,\alpha'\)-azodiisobutyramidine dihydrochloride (V50) or azobisisobutyronitrile (AIBN) and the results are summarized in Table 5. Two RAFT chain transfer agents 8 and 9 were employed in some of these polymerizations, but since they lacked solubility in water, were only investigated in acetonitrile solution.
Table 5

Reaction Conditions and GPC Data for poly(quaternary methacrylates)\(^a\)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Monomer</th>
<th>CTA</th>
<th>Initiator</th>
<th>Solvent</th>
<th>T (°C)</th>
<th>t (h)</th>
<th>M(_w) (kg/mol)</th>
<th>PDI</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27</td>
<td>29</td>
<td>AIBN</td>
<td>CH(_3)CN</td>
<td>60</td>
<td>756</td>
<td>1.30</td>
<td>1.15</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>29</td>
<td>AIBN</td>
<td>CH(_3)CN</td>
<td>60</td>
<td>96</td>
<td>123</td>
<td>3.13</td>
<td>84</td>
</tr>
<tr>
<td>3</td>
<td>27</td>
<td>28</td>
<td>AIBN</td>
<td>CH(_3)CN</td>
<td>60</td>
<td>96</td>
<td>183</td>
<td>3.25</td>
<td>84</td>
</tr>
<tr>
<td>4</td>
<td>27</td>
<td>-</td>
<td>V50</td>
<td>H(_2)O</td>
<td>50</td>
<td>168</td>
<td>678</td>
<td>1.53</td>
<td>60</td>
</tr>
</tbody>
</table>

\(a\). Reactions feature 1 mol% initiator and 100:10:1 of monomer: CTA: initiator.

The initiator, solvent, temperature, CTA and reaction time determined the characteristics of the polymer. Monomer 27 was polymerized by RAFT using 28 or 29. Polymer was formed in low yield and GPC showed the MW was low after 756 h (Table 5, entry 1). Though this polymerization was controlled, in a separate experiment, after 4 days, polymer was formed in higher yield but with higher MW and a much broader MWD (Table 5, entry 2). Use of 28 vs. 29 had little effect on the latter result (entry 3).
The polymers were contaminated by residual monomer (Figures 12 and 13, $^1$H NMR resonances at $\delta$ 5.68 and 6.1 for the CH$_2$=) and CTA (resonances at 7.3 ppm). From a practical perspective, the reactions required high conversions of monomer for product isolation. Dialysis in water and precipitation in ethyl ether did not remove the monomer.

Figure 12. $^1$H NMR spectrum (400 MHz, CDCl$_3$) of polymer of 27 prepared using 29.
Polymerization in water was examined as the polymer could be dialyzed to remove residual monomer, and the polymer then isolated by freeze-drying the dialyzed solution. The V50 initiator was able to initiate polymerization of monomers 27 in water at 50°C though polymerization was slower at 50 °C (Table 5, entries 4 and 5). GPC analyses showed that the MW was high and the PDI was low compared to the samples prepared using RAFT polymerization; it is possible that the high MW materials were aggregated under the conditions of the GPC analyses in aq. MeOH. ¹H NMR spectroscopy showed that the material was free of monomer (Figure 14). The resonances for the polymer appear at 0.9 ppm (terminal CH₃), 1.0-1.7 (main chain CH₃ v. broad
resonance overlapped with $n$-hexyl $\text{CH}_2$ groups, 1.7-2.4 (main chain $\text{CH}_2$), 3.3 (NMe$_2$ overlapped with MeOH-d$_4$), 3.6 (NCH$_2$-C$_5$H$_{11}$), 4.0 (NCH$_2$CH$_2$O) and 4.5 (OCH$_2$).

Figure 14. $^1$H NMR spectrum (400 MHz, MeOH-d$_4$) of dialyzed polymer of monomer 27.

Though these homopolymerizations were uncontrolled, useful lens materials might still result through copolymerization with reactive monomers such as glycidyl methacrylate (GMA). Copolymerization with GMA was investigated in acetonitrile (Table 6). Copolymerizations of 27 with GMA were performed using V88 initiator at 80 °C. Crude products were obtained in ca. 50% yield.

GPC and $^1$H NMR spectroscopy showed residual monomer 27 in these low PDI materials as shown in Figure 15 (peaks at 6.15 and 5.72 ppm). Broad peaks at 2.75, and 2.90 ppm for the epoxy $\text{CH}_2$ protons due to incorporated GMA were observed in this
The incorporation of GMA was about 24 mol% based on integration of these resonances with respect to those due to monomer 27. Copolymerization with 27 yielded a high MW polymer with a high PDI, possibly due to the side chain decreasing solubility or inhibiting diffusion. The quaternary methacrylates polymerized slowly in an uncontrolled fashion. GMA separated the cationic units, allowing for monomer addition.

Table 6

Reaction Conditions and GPC Data for Copolymer Synthesis in Acetonitrile

<table>
<thead>
<tr>
<th>Entry</th>
<th>Monomer</th>
<th>Initiator</th>
<th>Solvent</th>
<th>T (°C)</th>
<th>t (h)</th>
<th>Mw (kg/mol)</th>
<th>PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>27 - r - GMA</td>
<td>V88</td>
<td>CH₃CN</td>
<td>80</td>
<td>96</td>
<td>30.5</td>
<td>1.31</td>
</tr>
<tr>
<td>2</td>
<td>27 - r - GMA</td>
<td>V88</td>
<td>CH₃CN</td>
<td>80</td>
<td>96</td>
<td>33.1</td>
<td>1.24</td>
</tr>
</tbody>
</table>

Figure 15. ¹H NMR spectrum (400 MHz, MeOH-d₄) of a random (76:24) copolymer of 27 and GMA.
3.6 Synthesis of Hydrophilic Copolymers by RAFT Polymerization

Hydrophilic monomers used for contact lenses can be polymerized using free radical initiation. Adding a RAFT agent can give better control over the products.

The synthesis of poly(acrylic acid) and poly(methacrylic acid) with RAFT agent 31 in methanol proceeded to ca. 75% yield. The polymers had narrow PDI but low MW (Table 7). The polymerizations were not studied further since it was proved impractical to obtain higher MW materials using 31. The amount of 31 may be decreased to obtain higher MW polymers in the future, or different RAFT agents may need to be employed.

Table 7

<table>
<thead>
<tr>
<th>Entry</th>
<th>Monomer</th>
<th>Solvent</th>
<th>Initiator</th>
<th>t (h)</th>
<th>Temp. (°C)</th>
<th>M_w (kg/mol)</th>
<th>PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>methacrylic acid</td>
<td>MeOH</td>
<td>AIBN</td>
<td>96</td>
<td>50</td>
<td>8.92</td>
<td>1.03</td>
</tr>
<tr>
<td>2</td>
<td>methacrylic acid</td>
<td>MeOH</td>
<td>AIBN</td>
<td>96</td>
<td>50</td>
<td>3.01</td>
<td>1.14</td>
</tr>
<tr>
<td>3</td>
<td>acrylic acid</td>
<td>MeOH</td>
<td>AIBN</td>
<td>96</td>
<td>50</td>
<td>2.22</td>
<td>1.02</td>
</tr>
</tbody>
</table>

a. Polymerizations were conducted using 1 mol% AIBN and 31:AIBN = (10:1).

Poly(NVP-b-GVC) was obtained in ca. 60% yield in 1,4-dioxane. The polymers produced were characterized by GPC and ^1^H NMR spectroscopy. The results are given in Table 8.
Table 8

Reaction Conditions and GPC Data for PVP Using 30

<table>
<thead>
<tr>
<th>Entry</th>
<th>Polymer</th>
<th>AIBN (mol %)</th>
<th>Temp. (°C)</th>
<th>t (h)</th>
<th>M_w (kg/mol)</th>
<th>PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PVP</td>
<td>1</td>
<td>60</td>
<td>96</td>
<td>6.18</td>
<td>1.05</td>
</tr>
<tr>
<td>2</td>
<td>PVP-b-GVC</td>
<td>1</td>
<td>60</td>
<td>96</td>
<td>9.86</td>
<td>1.21</td>
</tr>
<tr>
<td>3</td>
<td>PVP</td>
<td>1</td>
<td>60</td>
<td>96</td>
<td>6.72</td>
<td>1.93</td>
</tr>
<tr>
<td>4</td>
<td>PVP-b-GVC</td>
<td>1</td>
<td>60</td>
<td>96</td>
<td>6.75</td>
<td>2.37</td>
</tr>
<tr>
<td>5</td>
<td>PVP</td>
<td>1</td>
<td>60</td>
<td>96</td>
<td>4.80</td>
<td>1.75</td>
</tr>
<tr>
<td>6</td>
<td>PVP-b-GVC</td>
<td>1</td>
<td>60</td>
<td>96</td>
<td>5.22</td>
<td>2.27</td>
</tr>
<tr>
<td>7</td>
<td>PVP</td>
<td>0.02</td>
<td>60</td>
<td>96</td>
<td>77.7</td>
<td>1.72</td>
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<tr>
<td>8</td>
<td>PVP</td>
<td>0.02</td>
<td>60</td>
<td>96</td>
<td>81.4</td>
<td>1.72</td>
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<tr>
<td>9</td>
<td>PVP</td>
<td>0.02</td>
<td>60</td>
<td>96</td>
<td>45.6</td>
<td>1.27</td>
</tr>
<tr>
<td>10</td>
<td>PVP</td>
<td>0.02</td>
<td>60</td>
<td>96</td>
<td>42.5</td>
<td>1.23</td>
</tr>
</tbody>
</table>

When GVC was added, the MW and PDI increased for one reaction (Table 8, entry 2). Higher MW poly(NVP) with low PDI were obtained (entries 7-10). These polymerizations were not controlled in most cases.

\(^1\)H NMR spectroscopy was used to compare the homopolymer and the copolymer. In Figure 16 (a) is depicted the NMR spectrum of poly(NVP) while Figure 16 (b) depicts the spectrum of the copolymer. There is a low MW impurity in the latter spectrum that appears to contain a glycidyl group but is not residual GVC as there are no olefinic protons corresponding to the vinyl group in this spectrum.
There are also some broad resonances due to the incorporation of GVC in the copolymer. The pseudo triplet at 2.85 ppm [epoxide CH\textsubscript{2} group of impurity – see expansion in Figure 16 (b)] as well as the multiplet at 2.64 ppm is overlapped with these, as is the doublet of doublet at ca. 4.5 ppm (O-CH\textsubscript{2}-epoxide). The broad resonance at 6.67 ppm might be due to the N-H proton in the polymer or the impurity.

The synthesis of poly(DMA) was carried out using trithiocarbonate 31 or 32. Polymer was obtained in 85 % yield with low PDI using 32 (Figure 17 (a) and Table 9, entry 1). In the presence of 0.02 mole % of initiator and trithiocarbonate 31, the yield was 90 %, but the polymer had a lower MW and higher PDI after 16 hours (entry 2).
Several poly(DMA) homopolymers with higher MW and PDI were prepared by adding a higher concentration of initiator (0.2 mole %) and trithiocarbonate 31 (entries 3-4). The reaction took place at 60 °C and had 95 % yield.

Table 9

Reaction Conditions and GPC Data for DMA Polymerizations in Methanol

<table>
<thead>
<tr>
<th>Entry</th>
<th>Monomer</th>
<th>Mole % Initiator</th>
<th>CTA</th>
<th>Temp. (°C)</th>
<th>t (h)</th>
<th>M_w (kg/mol)</th>
<th>PDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DMA</td>
<td>0.2</td>
<td>32</td>
<td>50</td>
<td>16</td>
<td>15.2</td>
<td>1.55</td>
</tr>
<tr>
<td>2</td>
<td>DMA</td>
<td>0.02</td>
<td>31</td>
<td>50</td>
<td>16</td>
<td>13.0</td>
<td>1.96</td>
</tr>
<tr>
<td>3</td>
<td>DMA</td>
<td>0.2</td>
<td>31</td>
<td>60</td>
<td>6</td>
<td>77.5</td>
<td>2.97</td>
</tr>
<tr>
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<td>60</td>
<td>6</td>
<td>48.7</td>
<td>3.22</td>
</tr>
<tr>
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<td>DMA</td>
<td>0.2</td>
<td>32</td>
<td>60</td>
<td>6</td>
<td>6.62</td>
<td>1.54</td>
</tr>
<tr>
<td>6</td>
<td>DMA</td>
<td>0.2</td>
<td>32</td>
<td>60</td>
<td>6</td>
<td>6.04</td>
<td>2.30</td>
</tr>
<tr>
<td>7</td>
<td>DMA-b-GMA</td>
<td>0.2</td>
<td>32</td>
<td>60</td>
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<tr>
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<td>DMA-b-26</td>
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<td>32</td>
<td>50</td>
<td>23</td>
<td>6.28</td>
<td>1.85</td>
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<td>23</td>
<td>2.78</td>
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a. Polymerizations were conducted using 0.02 -1 mol% AIBN at 50 or 60 °C.

Trithiocarbonate 32 was used to prepare DMA homopolymers and gave similar results but the polymers had a lower MW after 6 hours (entries 5-6). The synthesis of poly(DMA-b-GMA) with 0.2 mole % AIBN in methanol was attempted, and crude material was obtained in ca. 75% yield. GPC showed the polymer had a high MW but broad PDI (Table 9, entries 7-8). 1H NMR spectroscopy confirmed that GMA was incorporated (Figure 17 (b), resonances at 3.8 and 4.3 ppm).
Trithiocarbonate 32 was used in an attempt to synthesize copolymers of DMA-\text{-}b-27 and DMA-\text{-}b-26 (Table 9, entries 9-11). $^1$H NMR spectroscopy (Figures 18 and 19) indicated no incorporation of 26 or 27 and showed residual 4° methacrylate comonomer (0.9 ppm for alkyl Me and 1.9 for Me). The synthesis suffered from the same problems as in homopolymerization of these 4° methacrylates. A narrow PDI and higher MW were obtained for 26 since 26 had higher solubility due to its shorter side chain than 27.
Figure 18. $^1$H NMR spectrum (400 MHz, MeOH-d$_4$) of Poly(DMA-b-27).

Figure 19. $^1$H NMR spectrum (400 MHz, MeOH-d$_4$) of Poly(DMA-b-26).
3.7 Conclusions

By studying the reactions conditions for RAFT polymerization of different monomers, it is possible to see how the products of the reaction depend on different factors such as reaction time and CTA and the concentration ratios of CTA: initiator. Different types of RAFT agents were selected based on the structure and reactivity of the monomer. Different solvents affected the yield (i.e. methanol increased the solubility) and molecular weight of the polymers. Lower concentrations of AIBN and shorter reaction times can be used for DMA than for PVP or the quaternary methacrylates. The polymers of DMA-\textit{b}-GMA and PVP-\textit{b}-GVC can be synthesized in a more controlled fashion using RAFT polymerization and may be able to be attached to a contact lens.

The quaternary methacrylates were polymerized by RAFT without achieving good control of the polymerization despite variations in time, temperature and the nature of the CTA, solvent or initiator. This made sequentially adding a GMA block impractical. Perhaps new charged, RAFT agents may be synthesized for use in aqueous media since polymerization occurred more readily in water using V-50 as the initiator.
REFERENCES


