Surface Grafting of Poly(l-glutamates). 1. Synthesis and Characterization

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The ring-opening polymerization of N-carboxyanhydrides (NCA) of γ-benzyl L-glutamate and γ-methyl L-glutamate from (γ-aminopropyl)triethoxysilane (APS) pretreated substrates such as silicon wafers and quartz slides was investigated. FT-IR transmission spectroscopy, circular dichroism measurements, and UV/vis spectroscopy confirmed the pure α-helix conformation of the grafted polypeptide layers. FT-IR spectroscopy also showed that the most important part of the polymer growth took place in the first 5 h of the polymerization. The average orientation of the rather rigid α-helical polypeptides, grown during a short period of time, was more perpendicular with respect to the substrate than the orientation of the polymers grown over a longer reaction time. For concentrations up to 2.0 M, the polymer growth from both NCA monomers showed a pronounced dependence on the monomer concentration. Moreover, it appeared that the higher the monomer concentration, the more perpendicular the average orientation of the helices with respect to the substrate. The thickness of the grafted polypeptide layers up to 400 Å was determined with ellipsometry and small-angle X-ray reflection measurements. The absence of chemical chain termination was demonstrated by additional polymer growth in a renewed polymerization.

Introduction

The surface grafting of polymers in general has been studied intensively during the past decades because of its great importance for improving adhesion in composites,1 dispersion of pigments,2 for biomedical applications of polymers,3 chromatography,4 and wettability of fibers.5

Among the different methods for attaching polymers to surfaces, surface grafting by initiating a polymerization on the surface through an immobilized initiator has drawn relatively little attention. This method, however, can lead to higher grafting densities than other available techniques. It requires the immobilization of an initiator that will be incorporated in the chain after initiation, a high initiating efficiency, and polymerization conditions under which the polymer chains remain dissolved during the whole polymerization process.

Especially interesting in this respect is the preparation of functional thin films using the surface-grafting process, and particularly the surface grafting of α-helical synthetic polypeptides. In this respect, the use of l-glutamic acid derivatives is quite interesting, and has been studied quite well.6–10 The unique features of unidirectional aligned large dipoles of the stable right-handed α-helical polypeptides, as indicated by Hol,11 and experimentally confirmed by J aworek et al.,12 in combination with flat silicon or metal substrates that can be used as electrodes, and the possibility of tuning the polymer film properties by functionalization of the glutamic acid monomer unit, might lead to promising new applications in the fields of optoelectronic devices13 and liquid crystal displays.14

In general, two different methods have been developed to obtain chemically grafted, highly ordered polypeptide films. The first approach, the so-called “grafting-onto” method14–21 uses well-characterized preformed polymers. The end groups of the polymer chains react with active, specially designed surface groups. When the grafting density is high enough, the helices stretch themselves away from the surface and take on a more or less perpendicular orientation with respect to the surface.22 A large disadvantage of this “grafting-to” method is the relatively low surface coverage. Due to steric hindrance...
by neighboring helices and unfavorable dipolar interactions between already grafted and still nongrafted helices, not all grafting sites can be reached and, therefore, holes will be formed in the film. It is also possible that during the grafting process nongrafted helices diffuse into the film in an antiparallel way to cancel the dipole moment. When these films are washed in the proper way, these nongrafted helices will be removed from the film. This will result in a much smaller angle of the remaining grafted helices with respect to the substrate. Another drawback of this system is that the layer thickness is limited by the molecular weight of the used polymers.

To overcome these disadvantages some authors tried the so-called “grafting-from” method.12–29 This method uses relatively small monomers, which can easily reach the initiator sites on the substrate. So, these polymers actually grow from the substrates. Although the determination of the molecular weight of these polymer chains is much more difficult than for the grafting onto method, these grafted layers are expected to have much higher grafting densities. Also a broad molecular weight distribution can be expected since not all chains will grow to the same length of end.

For example, Whitesell23,24 published the polymerization of L-alanine and L-phenylalanine N-carboxyanhydrides (NCAs), initiated by specially designed aminothiol-functionalized gold and ITO substrates. This initiator molecule exactly meets the spatial requirements of an α-helix. They have prepared polypeptide films of about 1000 Å in thickness, with α-helices oriented more or less perpendicular to the substrate.

Simultaneously Oosterling et al.25,26 studied the surface polymerization, conformation, and orientation of various (co)-polyglutamates and (co)polyaspartates polymerized in solution from (γ-aminopropyl)triethoxysilane (APS) coated Aerosil, glass slides, and silicon wafers. Heise et al.27 used mixed amine monolayers of long aliphatic trichlorosilanes produced by the SAM technique in order to control the initiator surface concentration and studied the effects of grafting density on the orientation of the helices. The thin polypeptide layers, with a thickness of less than 150 Å, prove how delicate these polymerizations are. Inert reaction conditions, purity of the monomers, and dryness of the solvents require special attention.

Chang and Frank28 studied three different approaches: The grafting-onto reaction between the N-terminus of poly-(γ-benzyl glutamate) (PBLG) molecules with preformed sulfonate chloroformate groups in low grafting densities with the PBLG molecular axis parallel to the surface. In the second method, the triethoxysilane headgroups of the PBLG molecules initiated by (γ-aminopropyl)triethoxysilane (Acros, 99%) was vacuum distilled before use according to standard procedures. The coupling agent (γ-aminopropyl)triethoxysilane (Acros, 99%) was vacuum distilled before use (55 °C, 0.3 mHg). γ-Benzyl (Sigma, 99%), γ-methyl L-glutamate (Acros, 99%) and triphosgene (Acros, 99%) were used without further purification.

Various substrates were used depending on the intended characterization technique. Silicon wafers (Topsil Semiconductor Materials A/S, Frederikssund, Denmark, both sides polished, 900 μm) were used for Fourier transform infrared (FT-IR) transmission spectroscopy, X-ray photoelectron spectroscopy (XPS), and small-angle X-ray reflectometry (SAXR) measurements. Quartz slides (Heraeus) were used for UV/vis and circular dichroism (CD) measurements.

**Monomer Synthesis.** Benzyl L-glutamate–NCA (BLG-NCA) was synthesized by phosgenation of γ-benzyl L-glutamate using triphosgene in anhydrous tetrahydrofuran (THF) according to the procedure published by Dorman.33 The BLG-NCA was recrystallized from a warm mixture of THF/n-hexane (1/3 (v/v)). MLG-NCA was synthesized in the same way but recrystallized from warm 1,2-dichloroethane.

**Substrate Preparation.** The water used for cleaning was purified with a reverse-osmosis system (Elgastat spectrum SC 30) and by subsequent filtration through a Milli-Q purification system. The quartz slides and silicon wafers used as substrates were rinsed with Milli-Q water and ultrasonically cleaned with subsequently warm (30 °C) ethanol (Merck, p.a.) and dichloromethane (Lab-Scan, p.a.). After these precleaning steps, the substrates were treated with a mixture of H2O2 (Merck, 30%), NH3 (Merck, 25%), and H2O (1:1:5 (v/v)) for 25 min at 60–70 °C, washed several times with Milli-Q water, ultrasonically treated with a mixture of HCl (Merck, 37%), H2O (1:6 (v/v)) for 25 min, and subsequently warm (70 °C) hexane (1/3 (v/v)).

We published a new method by polymerizing γ-methyl L-glutamate N-carboxyanhydride (MLG-NCA) in the melt, providing the possibility of a solvent-free polymerization with a very high monomer concentration, leading to a film thickness up to 200 Å. Chang and Frank30 developed another solvent-free polymerization method. They polymerized NCA monomers with a vapor deposition technique. The layer thickness could easily be tuned by changing the temperature, pressure, and reaction time.

Very homogeneous and therefore pinhole-free polypeptide layers can be obtained using the surface-grafting polymerization of γ-benzyl L-glutamate N-carboxyanhydrides in solution from flat substrates such as silicon wafers and quartz slides.31 The electromechanical properties of these thin surface-grafted polypeptide layers between crossed aluminum electrodes were studied for the first time.

This study reports on the synthetic procedures to make these thin surface-grafted layers. It also gives some new insights into what happens with the orientation of the grafted helices during the polymerization and the ways to alter this orientation by varying the reaction time and monomer concentration. Part 2 of this series31 will describe a method to reveal the average angle between the grafted helices within these layers and the substrate by means of FT-IR transmission analysis. Part 3 will focus on the subject of surface-grafted block co-polypeptides.32

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(31) Wieringa, R. H.; Siesling, E. A.; Werkman, P. J.; Angerman, H. J.; Vorenkamp, E. J.; Schouten, A. J. Langmuir, the following paper in this issue (part 2).
washed with large amounts of Milli-Q water, and again ultrasonically cleaned with methanol (Merck, p.a.), a methanol/toluene (Merck, p.a.) mixture, and toluene for 5 min. After these steps the substrates were blown dry with a strong flow of nitrogen and immediately used in the silanization procedures.

Silanization. After the wafers and slides were cleaned, they were immediately silanized with freshly distilled (N-aminopropyl)-3-triethoxysilane. This silanization was performed according to the method published by Haller.34

Polymerizations. The solution polymerizations were performed in anhydrous N,N-dimethylformamide (DMF) (Acros, p.a.) at 40°C in specially designed glassware. The monomer solution (0.5 mol/L) was added to the silanized substrates. After the polymerizations, the films were washed with a mixture of dichloroacetic acid (Acros, p.a.) and chloroform (20/80 (v/v)) for 24 h to remove any nongrafted material and subsequently with chloroform for 1 h. The samples were dried in a vacuum before analysis. Various samples of the same silanized substrates were used for the experiments to study the polymer growth versus reaction time. These silanized samples were subjected to the same reaction mixture and withdrawn at different time increments.

Infrared Measurements. FT-IR transmission measurements were carried out on a Mattson Galaxy 6021 spectrophotometer using silicon wafers as substrates. Each spectrum is the average of 256 scans measured on five different spots per sample at a resolution of 4 cm⁻¹. The spectrum of a clean silicon wafer was used as the reference spectrum. Grazing incidence reflection spectra were recorded with a resolution of 4 cm⁻¹ on a Bruker IFS-88 equipped with a Spectra-Tech fixed-angle (80°) GIR accessory.

Calculation of the peak areas was done with the peak integration option of the Galaxy/FIRST data system software. The amide A (backbone N=O ester, amide I (after subtraction of the phenyl peak area centered at 1609 cm⁻¹ in case of PBLG) and amide II (mainly C=O stretching) peaks were integrated from 3400 to 3200 cm⁻¹, from 1795 to 1695 cm⁻¹, from 1695 to 1575 cm⁻¹ (after subtraction of the phenyl peak area centered at 1609 cm⁻¹ in case of PBLG), and from 1575 to 1500 cm⁻¹ (after subtraction of the phenyl peak area at 1498 cm⁻¹ in case of PBLG) and the amide II peak area at 1516 cm⁻¹ in both cases), respectively. Each peak area was integrated 10 times. The deviation from the average value was smaller than 2.5%.

X-ray Photoelectron Spectroscopy. XPS measurements were done on a X-3 probe 300 of Surface Science Instruments, using monochromatic Al Kα radiation with an energy of 1486.6 eV and a takeoff angle of 45°. Charges were compensated and peak positions were corrected on the basis of the C(1s) signal at 284.8 eV. An overall scan from 0 to 1000 eV (pass energy, 100 eV) is the average of 10 scans measured with an experimental resolution of 1.8 eV. The narrow scans of C(1s), N(1s), and O(1s) (pass energy, 100 eV) were the averages of 25 scans measured at three different spots on each sample with an experimental resolution of 0.4 eV. The atomic percentages were obtained by correcting the data using XPS sensitivity factors given by the instruments manufacturer (C, 1.0000; N, 1.6783; O, 2.4935).

Small-Angle X-ray Reflectometry. SAXR measurements were performed with a Philips PW 1830 generator and a Philips PW 1820 powder diffractometer, Cu Kα radiation (I = 1.542 Å) was used in a 0/2θ geometry with a starting angle of 0.8°. The simulations were carried out using a simulation program designed by A. Leuthe which uses a one slab model and two surface roughnesses.41 The polymer film thickness was corrected for a 28 Å SiO₂ layer and a 24 Å APS layer as determined before.

UV/Vis Spectroscopy. UV/vis absorption spectra of the polyglutamate layers were recorded with a resolution of 1.8 eV. The narrow scans of C(1s), N(1s), and O(1s) (pass energy, 100 eV) are the averages of 25 scans measured at three different spots on each sample with an experimental resolution of 0.4 eV. The atomic percentages were obtained by correcting the data using XPS sensitivity factors given by the instruments manufacturer (C, 1.0000; N, 1.6783; O, 2.4935).

Circular Dichroism. CD spectra of the polyglutamate layers on single quartz substrates were obtained with a Jasco J-720, J. J., AVIV circular dichroism spectrometer, model 62 A DS, by averaging over at least five scans.

Results and Discussion

Coupling Layer. The presence of the APS coupling layer on the substrate can easily be detected by means of XPS analysis. The existence of nitrogen as indicated by the N(1s) signal at 400 eV resulting from aliphatic free amine groups clearly proves the presence of the APS coupling layer on the silicon wafer. Compared to the overall spectrum of a clean wafer which contains no nitrogen signal at all, also a decrease in signal height for the Si(2s) and Si(2p) peaks at 150 and 99 eV can be seen. The atomic nitrogen concentration is roughly about 15%, which means that there are still some ethoxy groups left.

To determine the surface density of amine groups on the surface, we followed the method developed by Park’s group.33 The amine groups of the APS molecules are converted into imines in a reaction with 4-nitrobenzaldehyde. This reaction converts the nonabsorbing amine group into an UV/vis detectable nitrobenzyl substituted imine. From the imine absorbance of 0.0167 at 287 nm, an amine density of approximately 3.2 molecules/100 Å² can be calculated. This is lower than the density of OH groups of 5.0 molecules/100 Å², as determined by Zhuravlev,35 but very close to the values reported by Heinéy et al.36 In principle, there are more than enough amine groups available to start the polymerization, since one single PMLG helix requires 155 Å² of space (with a diameter of 14 Å).40

SAXR measurements on silanized silicon wafers and quartz slides reveal the layer thickness and surface roughness of the aminosilane layers. The reflection curve of a clean silicon wafer is shown in Figure 1a, and that of a clean quartz slide in Figure 1b. These curves can be fitted using a model of one layer on a substrate. The surface roughness of the silicon wafer is 3.5 ± 0.2 Å, and the surface roughness of the quartz slides was 3.9 ± 0.2 Å.

The reflection curves of the silanized substrates are shown in Figure 1c,d, respectively. From the Kiessig fringes a layer thickness of 24 ± 0.3 Å on silicon and 18 ± 0.2 Å on quartz can be deduced. These values agree very well with the thickness of 21 ± 3 Å obtained by means of ellipsometry and 21 ± 4 Å obtained by Kurth and Bein.41 The thickness of the coupling layer is exceeding the thickness of a monolayer. A monolayer will have a thickness of about 10 Å when the APS molecules are fully stretched.41 From our measurements it can be concluded that the coupling layer obtained with the method of Haller consists of two to three molecular layers resulting in a substrate with very high amine concentration. The surface roughness of the aminosilane films on both substrates did not exceed 6.5 Å. Thus, relatively smooth amino silane coupling layers can be obtained on silicon wafers and quartz slides with Haller’s method.

Therefore, ultradry solvents must be used for the monomer. Consequently, the polymer growth is blocked.

Polymerizations. The surface-grafting polymerizations from primary amine-coated flat substrates such as quartz slides or silicon wafers were performed with the synthesized NCA's according to Scheme 1. These nonaggregated polypeptide chains form aggregates, by growing in an antiparallel way, with the growing helices. The completely dissolved state of the growing helices, required for an ideal grafting-from polymerization, has been cleaved to an anhydride ring to start the formation of a polymer. These nongrafted polymer chains form aggregates, by growing chain leading to nongrafted polymeric material. These synthesized monomers should be stored under dry N₂ atmosphere at −20 °C. The calculated and experimental data match within 2.5%.

Small-angle X-ray reflection measurements (Figure 2a, b) reveal the film thickness and roughness. From the small variation in thickness between the polypeptide films obtained under the same reaction conditions was about 5%. The layer roughness was determined to be smaller than 20 ± 3 Å. The thickness determined with ellipsometry matches the values obtained with SAXR within 10%.

The measured UV/Vis spectra are consistent with results published in the literature for Langmuir–Blodgett (LB) films of the corresponding polypeptides on quartz slides. The spectra of the grafted PBLG and the grafted PMLG layers on quartz substrates show the characteristics of right-handed α-helices in both cases. The maximum at 190 nm and a minimum at 208 nm are due to exciton absorption.

(42) Block, H. Poly(-benzyl-L-glutamate) and Other Glutamic Acid Containing Polymers; Gordon and Breach Publishers: New York, 1983.

II), it can be concluded that only R PMLG, however, a substantial amount of polymeric oriented in the direction of the helix axis. The amide II spectra of a surface-grafted PBLG layer after a reaction time of 24 h and a PBLG LB assembly, fabricated following the procedure of Winter and Tredgold.49 The orientation of the substrate.

FT-IR Spectroscopy. The FT-IR spectra of surface-grafted PBLG and PMLG layers measured immediately after the polymerization are shown in Figure 3a, c. From the absorptions at 1650 (amide I) and 1546 cm\(^{-1}\) (amide II), it can be concluded that only \(\alpha\)-helices were formed during the polymerization of BLG-NCA.\(^{45}\) In the case of PMLG, however, a substantial amount of polymeric \(\beta\)-sheet material (amide I at 1630 cm\(^{-1}\) and amide II at 1530 cm\(^{-1}\)) was observed in addition to the \(\alpha\)-helix absorptions (amide I at 1652 cm\(^{-1}\) and amide II at 1548 cm\(^{-1}\)). The existence of only \(\alpha\)-helix material in the case of PBLG formation can be explained by the fact that the \(\alpha\)-helix is the most stable conformation for a PBLG molecule. A PMLG \(\alpha\)-helix on the other hand changes a lot easier into \(\beta\)-sheet material than a PBLG helix.\(^{42}\)

After the polymerization, the nongrafted polymer chains (\(\alpha\)-helix material in the case of PBLG and \(\alpha\)-helical together with \(\beta\)-sheet material for PMLG) were removed by the washing procedure and layers of pure \(\alpha\)-helical polymer chains remained on the substrates in both cases (Figure 3b,d). The formation of these nongrafted polymers is caused by thermal polymerization\(^{46}\) and/or initiation by water molecules.

Figure 4 compares the grazing incidence reflection spectra of a surface-grafted PBLG layer after a reaction time of 24 h and a PBLG LB assembly, fabricated following the procedure of Winter and Tredgold.\(^{49}\) The orientation of the helices in an Langmuir–Blodgett film is known to be parallel to the substrate.\(^{50}\) In grazing incidence reflection measurements only the transition dipole moment components perpendicular to the substrate can be observed. The transition dipole moments of the amide A \((A_a, 3290\text{ cm}^{-1})\) and amide I \((A_i, 1652\text{ cm}^{-1})\) vibrations are oriented in the direction of the helix axis. The amide II \(\perp\) band \((A_{\perp}, 1549\text{ cm}^{-1})\) has a perpendicular orientation with respect to the helix axis. The enlarged absorbances of the amide A and amide I peaks and the reduced absorbance of the amide II \(\perp\) peak for the surface-grafted PBLG film compared to those of the helices in the LB assembly (Figure 4b) clearly indicate a more perpendicular orientation with respect to the substrate.

Polymer Growth as a Function of Reaction Time. Polymer growth was studied by measuring the area of the \(\nu(C=O)\) absorption peak at 1735 cm\(^{-1}\) after different reaction times. This ester side chain carbonyl is randomly oriented because it is not involved in any H-bonding and connected to the helix by two methylene spacers. The area of this C=O stretching vibration can thus be used as a measure for the amount of polymer grown on the substrate. This was confirmed by independent ellipsometric measurements on various samples. A linear relationship was found between the amount of polymer and the ellipsometric layer thickness for both polymers (Figure 5). The larger helix diameter of PBLG of 15.5–26 Å,\(^{42}\) depending on the orientation of the sidechain phenyl group, compared to 14.0 Å for a PMLG helix, and the almost equal polymer density for both polymers (1.32 g/cm\(^3\) for PBLG and 1.29 g/cm\(^3\) for PMLG\(^{42}\)) explain why the same layer thickness is reached with smaller amounts (smaller ester carbonyl peak area) of grafted polymer in the case of PBLG.

To study the polymer growth as a function of time, several surface-grafting polymerizations on silicon wafers were performed in a 0.5 mol/L NCA monomer solution with different time increments (1, 2, 4, 6, and 24 h). The polymer films were characterized by FT-IR transmission

spectroscopy, and the results are shown in Figure 6. The
growth of PMLG (Figure 6a) is for unknown reasons
somewhat slower than that of PBLG, as can be seen by
the lower ester carbonyl absorbances in the first few hours.
Difference in monomer reactivity in this particular reaction
system is the most probable cause. At the end of both
polymerizations, however, layers of almost identical
thickness were obtained.

The most important part of the polymer growth takes
place during the first 5–6 h of the polymerization. During
this period, an almost linear dependence of the polymer
growth on time is observed. For longer reaction times,
this dependency becomes nonlinear and levels off. This
effect will be discussed later on.

Peak areas of the three specific amide absorptions
(amide I, amide II, and amide II\⊥) of the PBLG and PMLG
layers were obtained from FT-IR spectra and are listed
in Table 1. The ratio D of the peptide amide I and amide
II\⊥ peaks can give a good indication about the orientation
of the helical chains, because the amide I transition dipole
moment has an average orientation parallel to the helix
axis and the amide II\⊥ is more or less perpendicular to
that. Therefore, they have almost mutually perpendicular
transition dipole moments.\(^{35}\) For example, in Langmuir–
Blodgett films of polyglutamates, the helices are oriented
parallel to the substrate,\(^{50}\) and this results in a very high
amide I absorption and a very small amide II absorption.

The peak areas of the amide I, amide II, and amide II\⊥
were calculated and divided by the area of the ester
\(\nu(C=O)\) to normalize for the amount of polymer. In this
way, the peak areas of the analyzed absorbances of the
films obtained with various reaction times can be com-
pared with each other. Also the D (amide I/amide II\⊥) values
are shown. The experimental error in the D values
is about 5%.

The great change in the D value in the beginning of the
reaction can be explained by a slow initiation process,\(^{40}\)
during the first 1–2 h of the grafting process. During this
period, new chains will be initiated on the surface,
resulting in higher grafting densities and in a more
perpendicular orientation due to increasing steric hindrance
between neighboring chains.

After this start, propagation continues, as can be seen
by the increase of the ester C=O absorbances (Figure 6a),
but the D values hardly change over the next 2–4 h. That
can be explained by a continuous growth of all helices
collectively. The polymerization is first order in time
during this stage of the reaction (see the slope of 1 of the
straight line in Figure 6b.)

The D values slightly increase at the end of both
polymerizations because of the increasing polydispersity
of the grafted chains. The extending longer chain parts
might bend toward the surface of the film due to van der
Waals interactions to minimize surface energy.

A method was evaluated for the determination of the
average angle between the grafted helices and the
substrate by means of FT-IR transmission spectroscopy.
This will be reported in part 2 of this series.\(^{31}\) The results
of applying this method on the grafted layers in this study
are also shown in Table 1 and confirm the rough indication
about the helix orientation produced by the evaluation of
the D values.

The nonlinear polymer growth after a reaction time of
about 5 h seems hard to explain. The polymer growth is
expected to stay linear, due to the “living” character of the
polymerization. The observed nonlinear behavior can be
explained by partial chain growth termination. However,
we could not find any indication for the chemical termi-
nation steps reported in the literature, such as cyclization
of chain ends\(^{40}\) or nucleophilic attack of the primary amine
on the C-2 atom instead of the usual C-5 atom of the
anhydride ring, leading to an acid end group.

Termination of the helix growth in this case can be
explained by the gradual formation of nongrafted poly-
meric material. A thick aggregated layer of nongrafted
material is formed on top of the surface-grafted helices,
as can be seen in FT-IR experiments directly after
polymerization and before washing. This might lead to a
termination of the growing helices, although there is a
substantial amount of monomer left in the solution after
24 h, as was measured with FT-IR transmission spec-
roscopy as well.

**Polymer Growth as a Function of Monomer
Concentration.** To study the polymer growth dependence
on monomer concentration, several surface-grafting po-
lymerizations of BLG-NCA on silicon wafers were per-
formed using different monomer concentrations. A reaction
time of 1 h was maintained to avoid the formation of
nongrafted material as well as possible. The grafted
polymers were characterized by FT-IR transmission
spectroscopy. The normalized integrated peak areas of
the ester carbonyl absorbances versus monomer concen-
tration are displayed in Figure 7a.

A pronounced effect of the monomer concentration on
polymer growth was found within the investigated con-
centration range for PBLG as well as PMLG. Again the
growth of PMLG is somewhat slower than that of PBLG.
It is obvious that there is in both cases a more than linear
dependence of the polymer growth on monomer concen-
tration.

It is known from literature that the helix growth rate
is slow during the beginning of the reaction.\(^{40}\) After a
certain reaction time, it increases significantly. The exact
reason for this phenomenon is still unknown. During the
beginning of the surface-grafting polymerization, growth
of already grafted helices and initiation of new helices
occurs simultaneously. These new ones grow slowly for a
certain period. Therefore, the primary amine end groups
act in a similar way as the single-center, two-state cata-
lysts known in the olefin insertion polymerizations.\(^{51}\)
This can result in the order in monomer concentration of
1.7–1.8 (Figure 7b).

\(^{31}\) Fait, A.; Resconi, L.; Guerra, G.; Corradini, P. Macromolecules
1999, 32, 2104.
Mathematical evaluation of this equation (1) shows that for a specific value of \( k_i \) an order in [M] of about 1.7–1.8 can be deduced.  

\[
[\text{NH}_2] = [\text{NH}_2]^* - [P] 
\]

with [\( \text{NH}_2 \)] is the concentration of new initiating primary amine groups. Initiation is related to monomer concentration [M] according to

\[
 v_i = k_i[M][\text{NH}_2] 
\]

So

\[
 -d[\text{NH}_2]/dt = k_i[M][\text{NH}_2] 
\]

Integration over [\( \text{NH}_2 \)] to [\( \text{NH}_2]^* \) and from 0 to t results in

\[
[\text{NH}_2] = [\text{NH}_2]^*e^{-k_iM^*t} 
\]

combined with (A) gives

\[
[P] = [\text{NH}_2]^*[1 - e^{-k_iM^*t}] 
\]

Polymer growth is related to the monomer concentration according to

\[
 v_p = k_p[M][P] 
\]

combined with (E) gives

\[
 v_p = k_p[M][\text{NH}_2]^*[1 - e^{-k_iM^*t}] 
\]

So, the growth in film thickness is related to [M] \( e^{-k_iM^*t} \). Mathematical evaluation shows that for a specific value of \( k_i \) an order in [M] of about 1.7–1.8 can be deduced.
2. From the decreasing \( D \) values, we can conclude that the polymer chains are oriented in a more perpendicular way with respect to the substrate at higher monomer concentrations, pointing to higher grafting densities.

An increase in reaction time at higher monomer concentration leads to thick polypeptide layers. Using 1.5 mol/L and a reaction time of 24 h, a layer thickness of about 400 Å for the surface-grafting reaction of MLG-NCA was obtained.

**Renewed Polymerization.** The absence of chemical chain growth termination is demonstrated further by a renewed polymerization after the washing procedure. After 24 h of polymerization and subsequent washing, a freshly prepared BLG-NCA monomer solution was added. Polymerization was allowed for another 24 h. The increased absorption values in Figure 8 indicate that additional polymer growth occurred. The layer thickness increased from ±200 Å to about 280 Å. The reactive chain ends that had been enclosed by nongrafted material in the first polymerization period were able to grow again. This explains why the \( D \) value changes from 3.51 before the addition of new monomer to 3.11 after the renewed polymerization. This possibility of a renewed polymerization also opens the way for synthesizing surface-grafted block copolypeptides, which will be published in part 3 of this series.32

**Conclusions.** The surface-grafting polymerization of BLG-NCA and MLG-NCA in solution can be performed successfully, and the method described in this paper is a step toward a better controllable surface-grafting polymerization. FT-IR, UV/vis, and CD measurements of the grafted polypeptide layers on silicon wafers and quartz slides show that the layers consist of polypeptide material in the pure right-handed \( \alpha \)-helix conformation after the proper washing procedure.

Factors that influence the polymer growth and helix orientation, such as reaction time and monomer concentration, were studied by means of FT-IR measurements. The helices formed initially (<1 h) are oriented on average nearly parallel with respect to the substrate. During the next few hours the polymer growth is related to reaction time in a linear way. The helices formed are oriented in a more or less perpendicular orientation.

The monomer concentration plays a very important role. For short reaction times that prevent the formation of nongrafted material, FT-IR, ellipsometry, and SAXR measurements revealed that thicker polymer layers could be obtained with higher monomer concentration, within the same reaction time. The average orientation of the helices is more perpendicular with respect to the substrate when a higher monomer concentration is used.

Nongrafted polymeric material formed in solution aggregates between and on top of the growing helices and causes growth inhibition. After removal of this nongrafted material, the polymerization can be continued again. This opens a way for synthesizing surface-grafted block copolymers.

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**Supporting Information Available:** Figures showing XPS and UV/vis spectra and a table giving elemental composition of PBLG and PMLG films. This material is available free of charge via the Internet at http://pubs.acs.org.