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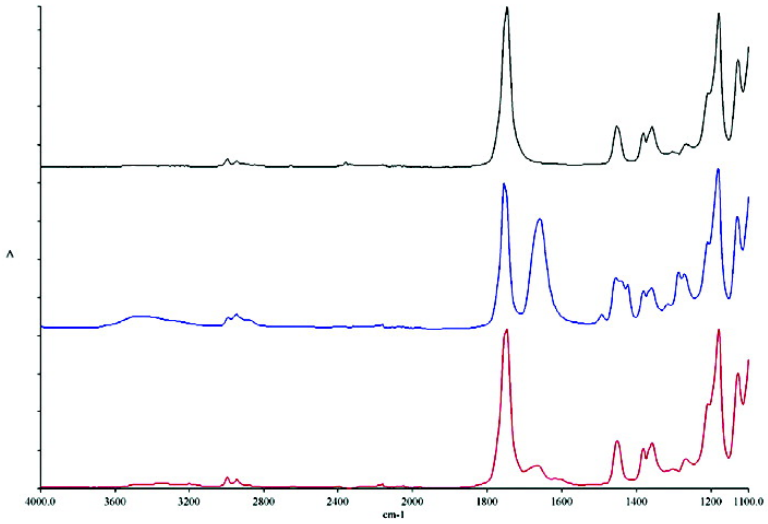

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Single-Step Covalent Functionalization of Polylactide Surfaces

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Abstract: A single-step, nondestructive, and versatile technique for the grafting and chemical surface modification of biodegradable polymers such as polylactide is described. The substrates are subjected to the vapor phase of any of three investigated vinyl monomers: acrylamide, maleic anhydride, and N-vinylpyrrolidone, and grafting is induced by photoinitiation of benzophenone under solvent free conditions. The modified surfaces exhibit higher wettability, and the grafting is verified by X-ray photoelectron spectroscopy, attenuated total reflection Fourier-transform IR, contact-angle measurements, and scanning electron microscopy. The graft-chain pendant groups remain functional and can subsequently be modified so that a tailor-made surface with desired properties may be achieved.

Introduction

Biological interactions between a polymeric implant and the host tissue are mainly taking place at the surface of the implant. Covalent surface modification is therefore crucial to increase the biocompatibility of the implant. First, an important limitation of many polymeric implant materials is their hydrophobicity, as low wettability is known to be an important factor impeding the attachment of cells.[1,2] Surface wettability can be markedly improved by covalent surface modification. Second, surface grafting opens up countless possibilities of tailor making the surface chemistry for biomedical purposes. When monomers are covalently bound to the substrate and polymerized, functional groups are generated in each graft chain that can subsequently be modified so that a surface with desired properties, perhaps bioactivity, may be achieved. The covalent attachment of functional groups is preferred over physical adsorption or coating because of its superior environmental stability. Hence, there is a strong need for a viable method for chemical modification of surfaces of biomaterials. Extensive studies have been performed in our laboratory in this regard.

Conventional grafting techniques for polymer substrates are based on either mutual or preparative irradiation techniques using γ, electron beam, X-ray, or UV light irradiation. Preparative irradiation involves high-energy irradiation of the substrates at which point free radicals are generated in the substrate. These free radicals may in a second step be brought to react with the desired vinyl monomer in solution, enabling graft chains, e.g., acrylamide, to be formed on the substrate surface.[3] The surface functional groups induced by grafting can be used for the covalent immobilization of bioactive substances such as heparin for enhanced biocompatibility.[4,5] A few biodegradable polymers, typically poly(ϵ-caprolactone), can be covalently modified by this technique.[6] High-energy irradiation can however cause additional chemical effects in the exposed polymers. If the generated free radicals recombine within the bulk, then cross-linking is the result. If chains are cleaved, the polymer degrades. These processes often occur simultaneously; which one is predominating depends on the polymer structure. High-energy radiation is therefore not a viable route of modification for most biodegradable polymers, especially polylactides, given their instability and susceptibility of degradation by chain scission as a result of irradiation, even at low dosage.[7−9]

Mutual irradiation involves the irradiation of the substrate in a monomer solution. This is a convenient one-step method but may be difficult to confine to the surface layer only. Often UV irradiation is used, as it has a much lower energy than γ or electron beam irradiation, minimizing deep penetration into the substrate, and the possible destructive effect of irradiation on sensitive substrates. Photografting is typically done by bringing the substrate in contact with a solution of monomer and photoinitiator under UV irradiation.[10−12] Alternatively, the substrate is presoaked in the monomer solution[13,14] or brought

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in contact with a mixture of solvent and monomer in the vapor phase.[13] The photoinitiator, benzophenone (BPO), for instance, is either precoated on the substrate[15] or present in the solution. When exposed to UV light, photons cause the excitation of BPO to a short-lifetime singlet state from where it relaxes to a triplet state. At this point, BPO can abstract hydrogen atoms from the polymer film by inelastic collision, thereby creating free radicals on the polymer surface which can serve as active sites for grafting. Photografting can be done under mild conditions for a wide range of monomers and substrates and is rather cheap.[12,16,17] The advantages of photografting were neatly used in the fabrication of microfluidic devices. A range of monomers could with this method be grafted within the microchannels of several commodity polymers creating either a single layer of functional groups in preselected patterns, or a multiple layered structure.[18] The available surface area of such devices could greatly be improved by the introduction of porous polymer monoliths, surface functionalized by photografting.[19] One other photografting method is based on bringing the substrate in contact with a mixture of molten monomer and initiator under UV irradiation.[20] For most monomers, this requires temperatures high enough to make degradable polymers such as polylactide lose its physical integrity. Unfortunately, all other presently known photografting methods involve solvents in one way or another. The choice of solvent has a great impact on the result and extent of grafting.[11] Solvent effects may have a detrimental impact on delicate and degradable materials such as polylactide and cause crazing in polymers such as PMMA. The presence of a solvent is also a source of contamination and distorts fine topographies on a polymer surface, such as sub-micro- and sub-nanopatterns. Conventional UV-grafting techniques are for these reasons not suitable for many polymeric biomaterials.

Other known surface activation methods such as ozonization,[21] flaming of the surface,[22] or photooxidation[23] are also unsuitable for most biodegradable polymers, as they will to some extent induce hydrolytic degradation of the substrate and may deteriorate its properties. For the same reason, chemical treatment with sulfuric acid or chloric acid solutions,[24] or alkaline hydrolysis with NaOH,[25] are too harsh of routes of modifying the wettability. Surface activation by hydroxylation with peroxydisulfate requires too high temperatures to be of use for most biodegradable polymers.[26] Various plasma treatments of biodegradable polymers have been described to increase the surface wettability,[27] but the changes in chemistry of the modified surfaces and the influence upon degradation is not fully known.[24] Plasma treatment may also cause etching of the surface[28] and fails to create an even modification of the substrate in small cavities,[29] for instance, on a nanopatterned surface. Plasma treatment has however been useful for many biostable biomaterials; for instance, it proved to be successful for the covalent functionalization of poly(dimethylsiloxane) to provide for heparin coupling.[30]

Among all biodegradable polymers, polylactide is today the most widely used within the field of biomedical materials. It has been extensively studied for temporary supports (e.g., sutures, orthopedic staples, stents, and scaffolds) and for the controlled release of drugs.[31−36] The design of devices is mainly focused on the bulk properties, optimizing them for a set of demands prevailing in an intended application. But as earlier mentioned, the surface properties could also affect the device performance in vivo.

The group of Prof. Albertsson has developed a technique for covalent surface modification of biostable polymers such as PET and PMMA.[37−39] The substrates are here subjected to the vapor phase of a mixture of a vinyl monomer and photoinitiator in a closed chamber under UV irradiation at very low pressure under solvent-free conditions. Our hypothesis is that a similar technique could be viable in the covalent surface modification of biodegradable polymers, which are more delicate than biostable materials. Our objective was thus to develop a single-step, nondestructive, yet viable technique for the grafting and covalent surface modification of biodegradable polymers, as for example poly(L-lactide) PLLA. We propose that grafting polymerization should take place under low-energy UV irradiation and under solvent-free conditions, thus eliminating the solvent effects of grafting and minimizing the degradation. Also, the low concentration of monomer in the vapor phase is thought to result in a very thin grafted layer on the substrates so that the topography, perhaps a nanopattern, is preserved throughout the process.

Experimental Section

Materials. N-Vinylpyrrolidone (VP) 97%, was purchased from Fluka and distilled at 100 °C and 25 mbar before use and stored cold. Acrylamide (AAm) 99+% (Acros), BPO 99+% (Acros), and Maleic anhydride (MAH) >99% (Fluka) were used as received. Chloroform 99.5% (Aldrich) and ethanol 99.5% (Lab-Scan) were used as received. PLLA in pellet form (M_n = 145 600, M_w = 191 400) was a kind gift from Tenova. Substrate films were prepared by dissolving 4 g of PLLA in 100 mL of chloroform and pouring the clear solution onto a leveled glass mould that was previously silanized. Silanization was done using dichlorodimethylsilane >98% (Fluka), triethylamine >99.5% (Fluka),

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and dichloromethane HPLC grade (Lab-Scan). The solvent was allowed to slowly evaporate from covered moulds, and the films were dried. Circular pieces with a diameter of 15 and 9 mm were cut from the films and used as sample substrates in the following grafting.

Vapor-Phase Grafting. Grafting was performed in a glass reactor consisting of two interconnected cylindrical compartments. The films were placed horizontally on a perforated Teflon disk in one compartment of the reactor, and this chamber was then covered with a horizontal quartz plate transparent to UV light. The monomer (AAm or MAH) and initiator (molar ratio of monomer to initiator = 10:1) was transferred to the other compartment of the reactor which was fitted to a vent. In case of using VP, the liquid monomer was added through a syringe. The horizontal tube connecting the two compartments was stuffed with glass wool to prevent anything but vapor transfer to take place between the two compartments. The reactor vent was fitted to a vacuum line with a rotary vane pump (Alcatel 2005) and a turbo pump (Alcatel 600 T) in series. The reactor was then evacuated and slowly filled with argon gas three times. Finally, the reactor was evacuated, sealed, disconnected from the pump, and finally immersed in a water bath thermostated at 50 °C (±0.2 °C). Care was taken to position the UV source at such a distance from the reactor so that the air and water between would eliminate the risk of heat radiation from the lamp affecting the temperature in the reactor (the temperature inside the reactor during UV illumination has been checked with a thermometer to ensure a stable temperature). The reactor was irradiated with UV light from an Osram Ultra-Vitalux 300-W lamp for predetermined times. The reaction was stopped by turning off the light, withdrawing the reactor from the water bath, and opening it. The grafted films were rinsed in deionized water, soaked in deionized water for 1 h, and then washed in ethanol (99.5%) for several hours including ultrasonication. Finally, the films were thoroughly dried under vacuum. For comparison, PLLA films (denoted PLLA blank) were also subjected to the grafting process, including UV irradiation and 50 °C for 30 min without the presence of initiator.

Electron-Beam Irradiation. To allow for comparisons with PLLA films subjected to vapor-phase grafting, PLLA films were irradiated with at dose of 2.5 Mrad per passage from a pulsed electron accelerator (Mikroton, Acceleratorteknik, The Royal Institute of Technology, Stockholm) operating at 6.5 MeV. During irradiation, films were placed in air on a glass surfaced cooling plate (LKB Multitemp. I.) operating at +2.5 °C.

Characterization. Fourier transform IR (FTIR) Spectrometry spectra were recorded on a Perkin-Elmer Spectrum 2000 FTIR equipped with an attenuated total reflectance (ATR) crystal accessory (Golden Gate) providing an analysis of the surface down to a depth of approximately 1 μm. All spectra were calculated means from 16 scans at 2 cm^{-1} resolution with correction for atmospheric water and carbon dioxide.

The molecular weights were determined from filtered samples with size-exclusion chromatography (SEC) on a system consisting of a Waters 717 plus auto sampler, a Waters model 510 apparatus equipped with three PLgel 10 μm mixed-B columns, 300 × 7.5 mm (Polymer Labs., UK) and an PL-ELS 1000 evaporative light scattering detector (Polymer Labs., UK). Chloroform, with a flow rate of 1.0 mL/min, was used at 25 °C as an eluent. Polystyrene standards with narrow molecular weight distributions ($M_w/M_n = 1.06$) were used for calibration.

The static contact angles of surfaces were measured on an apparatus purposely constructed at the department. The samples to be analyzed were placed on a flat and well-lit surface in front of a Sanyo VCC4100 Color charge-coupled device video camera, equipped with a Cosmicar 25 mm 1:1.4 television lens, connected by means of a 20-mm spacer in order to increase the optical magnification. The video signal was transferred to a computer using an IC-PCI frame grabber card from Imaging Technology Inc. The live feed from the camera was captured and processed with OPTIMAS 6.2 software from the Optimas Corporation. The contact angle data of each sample are averages of 4 individual measurements.

Chart 1. Structures of (a) PLLA, (b) AAm, (c) VP, and (d) MAH

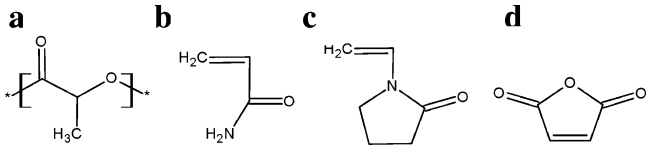

Table 1. Molecular Weights of PLLA and PLLA Films Treated in Various Ways

sample	M_n[a]	PDI[a,b]
PLLA pellets	163 000	1.3
PLLA film, untreated	145 600	1.3
PLLA film, electron beam irradiated	89 000	1.8
PLLA film, blank[c]	130 800	1.6
PLLA film, grafted with AAm for 10 min	127 500	1.4
PLLA film, grafted with VP for 17.5 min	135 800	1.5
PLLA film, grafted with VP for 30 min	137 100	1.6

[a] Measured by SEC with chloroform as an eluent. [b] Polydispersity index = M_w/M_n. [c] Film subjected to the UV-grafting process for 30 min without the presence of initiator.

X-ray photoelectron spectroscopy (XPS), also known as ESCA, was performed on an AXIS-HS X-ray photoelectron spectrometer (Kratos Analytical, Manchester, UK) with a monomchromatic Al Kα X-ray source at 15 kV and 20 mA. The takeoff angle to the substrates was 90°, the pressure was approximately 1.3×10^{-11} bar, and the pass energy used to determine the elemental compostition was 80 eV. Sensitivity factors were supplied by the manufacturer.

Surface topographies were examined by scanning electron microscopy (SEM) using a JEOL JSM 5400 scanning microscope. Samples were mounted on metal stubs and sputter coated with gold−palladium (Denton Vacuum Desc II).

^{1}H NMR spectra were recorded at 500 MHz on a Bruker DMX-500 NMR spectrometer, using Bruker software. Samples of about 40 mg were dissolved in $CDCl_3$ (Aldrich Chemical Co.) in 5 mm outside diameter sample tubes.

Results and Discussion

We describe a new method for the surface modification of PLLA films: UV-induced vapor phase grafting of AAm, MAH, and VP, in the presence of a photoinitiator, BPO, under solvent-free conditions. The structures of monomers and PLLA are shown in Chart 1.

A common approach for the chemical modification of polymeric substrates is the surface activation by means of preparative high-energy radiation. As previously discussed, this can cause chain scission and thereby polymer degradation. For comparison with the vapor phase grafting method elaborated in this paper, some PLLA films were subjected to electron beam irradiation and then analyzed with respect to molecular weight. Table 1 shows a marked decrease of molecular weight for the electron beam irradiated PLLA film as compared to the untreated film and the vapor phase grafted films. This is in accordance with more elaborate studies on the radiation effects of polylactides[7,9] and indicates that the radiation caused chain scission in the film. Unlike electron beam irradiation, UV light itself does not induce the grafting process on the irradiated films. As the PLLA films are not transparent, the irradiated light does not penetrate into the substrate leaving the bulk structure and properties intact. As seen in Table 1, the molecular weights of PLLA films are not significantly affected during vapor phase

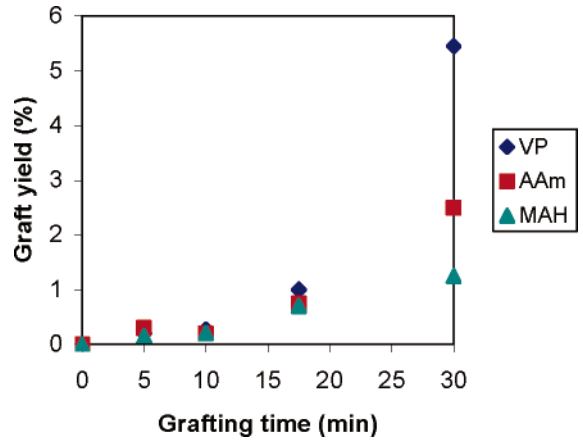

Figure 1. Graft yield as a function of grafting time during vapor phase grafting of (◆) VP, (■) AAm, and (▲) MAH on PLLA films.

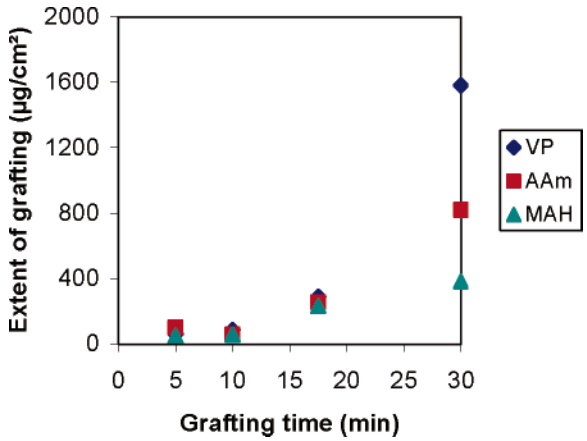

Figure 2. Extent of grafting as a function of grafting time during vapor-phase grafting of (◆) VP, (■) AAm, and (▲) MAH on PLLA films.

grafting, regardless of the grafting time within the investigated time frame.

The vapor phase grafted PLLA films were weighed prior to and after grafting to evaluate how successful the grafting process had been. The graft yield (the percentage increase in weight) was calculated from the weight of the films prior to grafting (W_0) and after grafting and drying (W_g)

$$GY = \left(\frac{W_g - W_0}{W_0}\right) \times 100$$

Another way of quantifying the result of grafting is to calculate the extent of grafting

$$EG = \left(\frac{W_g - W_0}{S}\right)$$

where S represents the surface area.

Figures 1 and 2 consistently show that the amount of grafted monomers on the PLLA films increases as a function of grafting time and that the yield increases in the monomer order of MAH < AAm < VP, although the differences between monomers are not significant until longer grafting times are reached. After 30 min of vapor phase grafting, an extent of grafting for AAm and VP has been reached that should be sufficient for full-surface coverage of larger molecules, albeit in a thin layer. Compared to photografting in solution, 30 min is quite a long

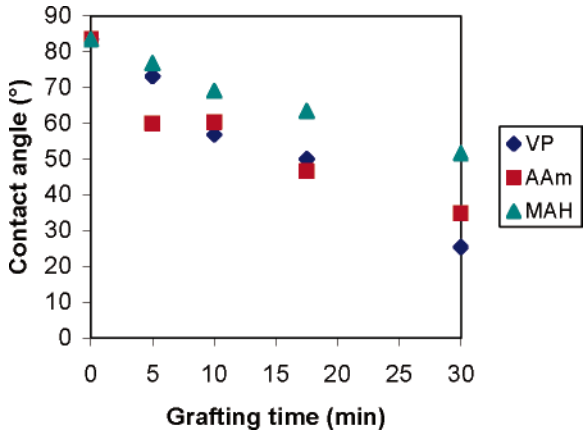

Figure 3. Contact angle of grafted surfaces as a function of time of vapor phase grafting of (◆) VP, (■) AAm, and (▲) MAH on PLLA films.

time. The photografting could theoretically proceed much faster, but then higher temperatures are required and, in our case, the glass transition temperature of PLLA sets a practical upper limit to the temperatures that can be used while preserving the physical integrity of the films. The differences in gained graft yield from the investigated monomers can be explained by considering that the concentration of monomer in the reactant vapor phase during grafting is given by the monomer vapor pressure at the grafting temperature. VP has a much higher vapor pressure[40] (1.64 mbar at 50 °C) than AAm (0.13 mbar at 50 °C) and is thus accessible to the site of grafting polymerization to a larger extent than AAm. The lowest graft yield is obtained with MAH despite the fact that this monomer has the highest vapor pressure (2.25 mbar at 50 °C)[40] of the investigated monomers in this study. This is explained by the still very low concentration of monomer vapor in the reactor during grafting at this temperature. At low concentration, depropagation is favored over propagation for MAH.[37] MAH will thus not homopolymerize but forms a grafted monomolecular layer of succinic anhydride on the substrate instead of the grafted chains yielded when AAm or VP was used as the monomer.

After the covalent attachment of grafted monomers upon the PLLA film surfaces, their wettability is expected to increase accordingly. The surface hydrophilicity is an important feature for polymeric biomaterials. Surfaces with a moderate wettability (~30−60°) have been shown optimal for the adhesion and proliferation of cells,[2] while surfaces too hydrophilic or hydrophobic, e.g., PLLA, are less cytocompatible in this respect. The contact-angle measurements show that the wettability of the vapor phase grafted PLLA films increases with the grafting time and in the monomer order of MAH < AAm < VP (Figure 3). The untreated PLLA has contact angle of ~80°, and films subjected to vapor phase grafting for 30 min show contact angles as follows, ~50° for MAH, ~35° for AAm, and ~25° for VP. The differences in wettability increase for the different monomers are consistent with the different graft yields, respectively. MAH gives a monomeric layer on the surface, while AAm and even more so VP gives a much higher extent of grafting. The grafts of the latter are thus able to influence the surface

(40) Vapor pressures were extrapolated from literature data. (a) Maleic anhydride: Stull, D. R., *Ind. Eng. Chem.* **1947**, *39*, 517−540, (b) Acrylamide: Carpenter, E. L.; Davis, H. S. *J. Appl. Chem.* **1957**, *7*, 671−675, (c) *N*-vinylpyrrolidone: *The Merck Chemical Databases ChemDAT, Merck KGaA, Darmstadt, Germany.*

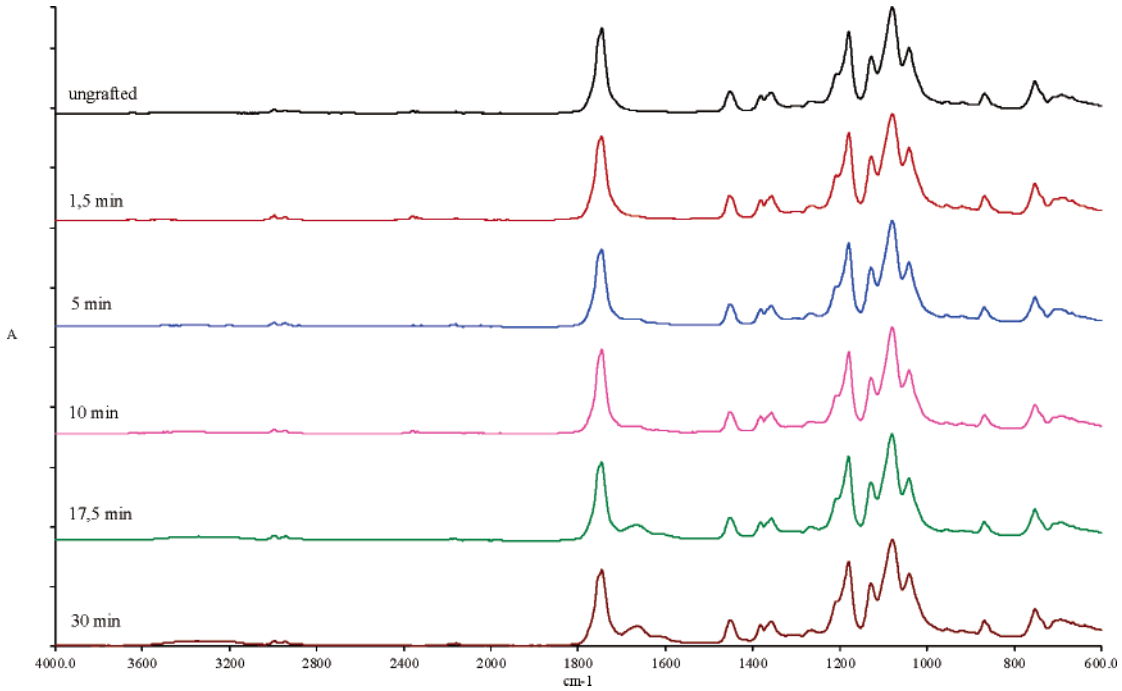

Figure 4. ATR-FTIR spectra of PLLA films, untreated and vapor-phase grafted with AAm for different times.

wettability much more. The contact angles do not level off during the period of up to 30 min of grafting, indicating that a fully continuous layer of polymer did perhaps not form on the surfaces. However, for all three monomers the vapor-phase grafting method effectively improves the surface wettability as compared to untreated PLLA. To reach the desired region of wettability, 30 min of grafting with MAH is required, while somewhat shorter grafting times are adequate for AAm and VP.

The graft yields and contact-angle measurements verify that the surface has been modified but not how the surface structure was changed. The structural features of the substrate surfaces were evaluated by ATR-FTIR analysis,[41] and the results are shown in Figures 4−6. The untreated PLLA film shows a characteristic ester C═O band at 1747 cm^{-1}. When AAm is grafted onto the PLLA film (Figure 4), another C═O band appears at 1663 cm^{-1} already after 5 min of grafting, consistent with the C═O stretching vibration band that primary amides in the solid state typically have in the 1670−1650-cm^{-1} region. Broad bands at 3450−3320 and 3220−3120 cm^{-1} also appear, assigned to the amide N−H stretching vibrations. Primary amides in the solid state have a weak-to-medium intensity band at ∼1620 cm^{-1} (amide II band). Such a peak indeed appears in the spectra of AAm-grafted PLLA films at 1618 cm^{-1}, which can be resolved from the amide C═O band. For the grafting of VP onto PLLA films (Figure 5), we also expect an amide C═O band (amide I band) to appear in the spectra, in this case in the 1680−1630-cm^{-1} region. Such a peak is visible at 1658 cm^{-1} even after short grafting times and increases in intensity with grafting time. There is also a broad band (amide N−H) in the 3600−3200-cm^{-1} region. For both AAm and VP grafts, there should also be C−N stretching bands (amide III) in the 1440−1200 cm^{-1} region. These bands are however difficult to single out as they are overlaid by the C−H and $-CH_2-$ and C−C bands in this region stemming from the main chains of the substrate and the grafts. In the case of MAH grafting, we expect monomeric attachment of the anhydride rings (as discussed above) on the PLLA surface and, because of the low extent of grafting, a low intensity of the peaks relating to the resulting succinic anhydride moiety. If the anhydride functionality is still intact, two C═O bands, separated by ∼60 cm^{-1}, in the 1840−1720-cm^{-1} region would appear. Such peaks could be hard to resolve from the PLLA C═O band, especially since they are of low intensity. In the spectra of MAH-grafted PLLA films (Figure 6), a shoulder at 1720 cm^{-1} on the C═O peak of the PLLA ester group is seen at longer grafting times, but no band is visible above 1800 cm^{-1}, implying that anhydride groups are not present on the PLLA surface. Because the anhydride functionality is not very stable, it may very well have hydrolyzed during the film purification step. The shoulder at 1720 cm^{-1} and the broad band around 1635 cm^{-1} implies that there are different C═O groups present, but because of an undetectable broad O−H band in the 3300−2500 cm^{-1} region, we exclude a higher extent of formation of free acid groups. Instead, adducts with ethanol may have formed. All together, the FTIR analyses effectively show that the monomers have been covalently attached to the PLLA surfaces and that the amount of grafted materials increases with grafting time. For comparison, PLLA film was subjected to the vapor phase grafting process with UV irradiation for 30 min at 50 °C without the presence of initiator. No weight increase could be recorded for these films after purification and the FTIR spectrum shows no trace of peaks other than those stemming from the PLLA bulk. This verifies that the monomers are not just physically deposited on or absorbed by the PLLA surface during the grafting process but covalently attached through the photoinitiation of BPO.

The surface composition of the grafted films was further determined by XPS[42] allowing for an elemental analysis of the outermost layer of the films (Figure 7). The XPS analyzes at a

(41) Socrates, G. *Infrared and Raman Characteristic Group Frequencies*, 3rd Ed., Wiley&Sons: England, 2001.

(42) Beamson, G.; Briggs, D. *High-Resolution XPS of Organic Polymers*, The Scienta ESCA300 Database, 1st ed.; John Wiley & Sons England, 1992.

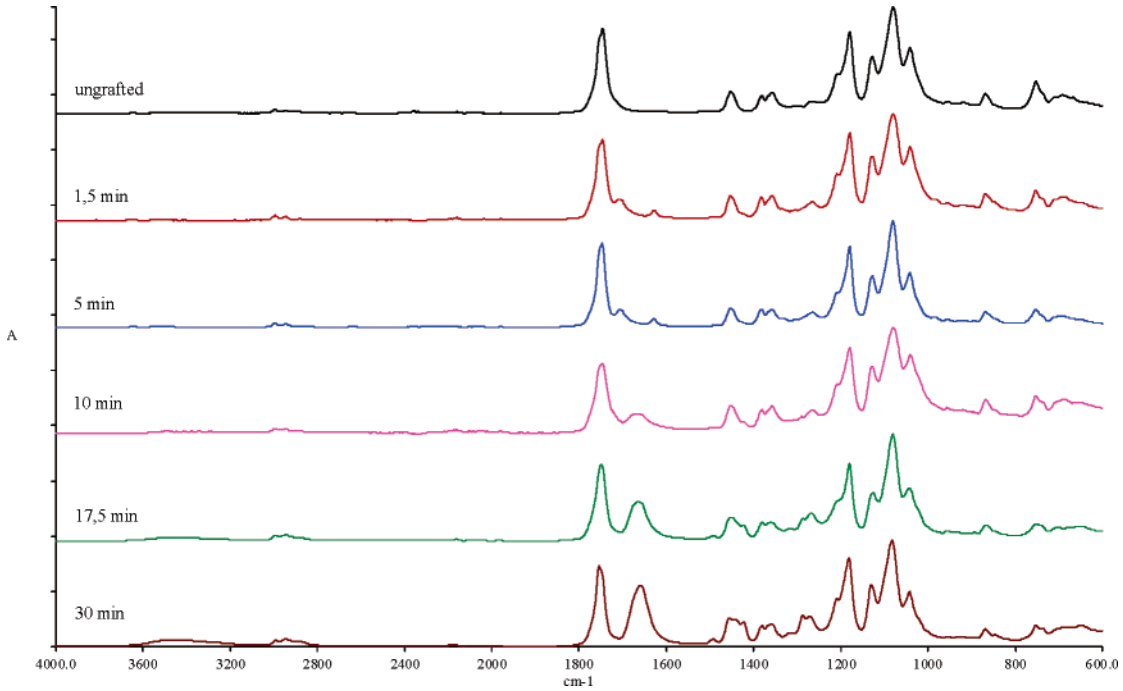

Figure 5. ATR-FTIR spectra of PLLA films, untreated and vapor-phase grafted with VP for different times.

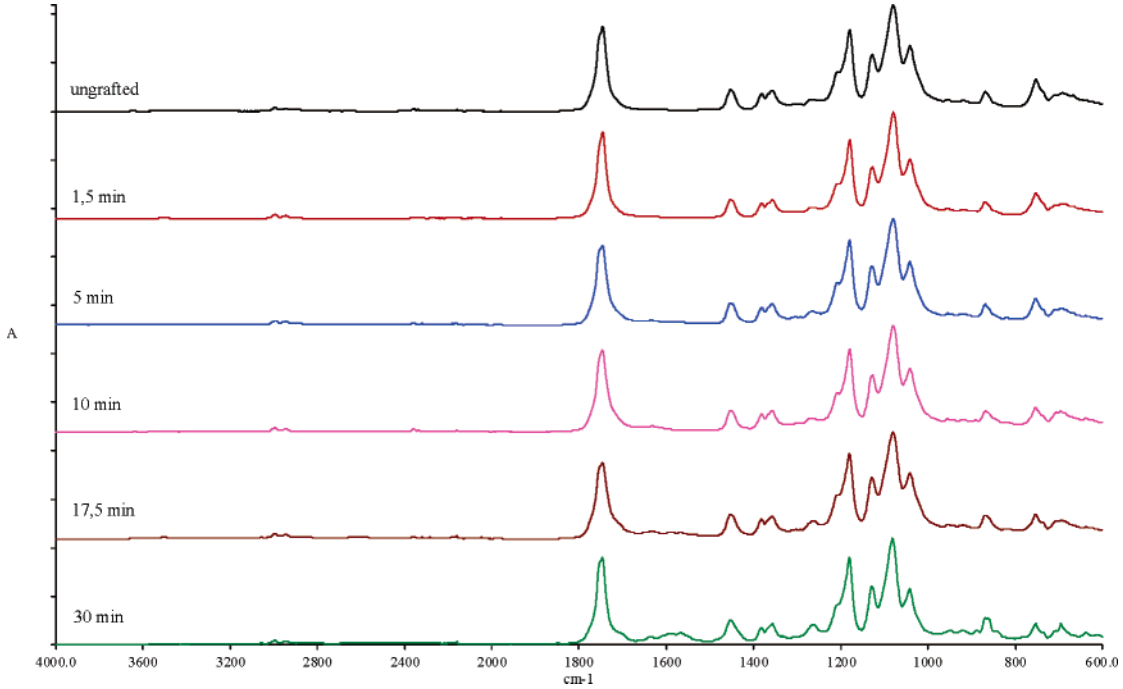

Figure 6. ATR-FTIR spectra of PLLA films, untreated and vapor-phase grafted with MAH for different times.

smaller depth compared to the ATR-FTIR. The XPS spectra revealed that the surface of the VP-grafted PLLA substrates contained nitrogen as expected. The surface composition (measured as at. % of present elements, H excluded) of the VP-grafted PLLA corresponded well with the theoretical values calculated with the assumption that the entire surface was covered with VP. The analysis of the AAm-grafted films also showed that the surface of the film contained nitrogen as was expected. The percentage of nitrogen was lower than the theoretical value, and the percentages of oxygen and carbon were higher than the theoretical values, which show that the substrate is either not fully covered with AAm chains or that the XPS analyses deeper into the substrate than the thickness of the AAm layer so that the PLLA bulk material of the substrate is included in the investigated layer of this analysis. This verifies previous results which shows that the VP gives a higher yield and extent of grafting than the AAm. It is difficult to evaluate XPS analysis of the MAH-grafted PLLA. There is no significant difference between the theoretical compositions of a fully covered MAH surface and a pure PLLA substrate, the hydrogen atoms cannot be seen in the XPS spectra, which also makes it more difficult. We can only conclude that, as expected, the MAH

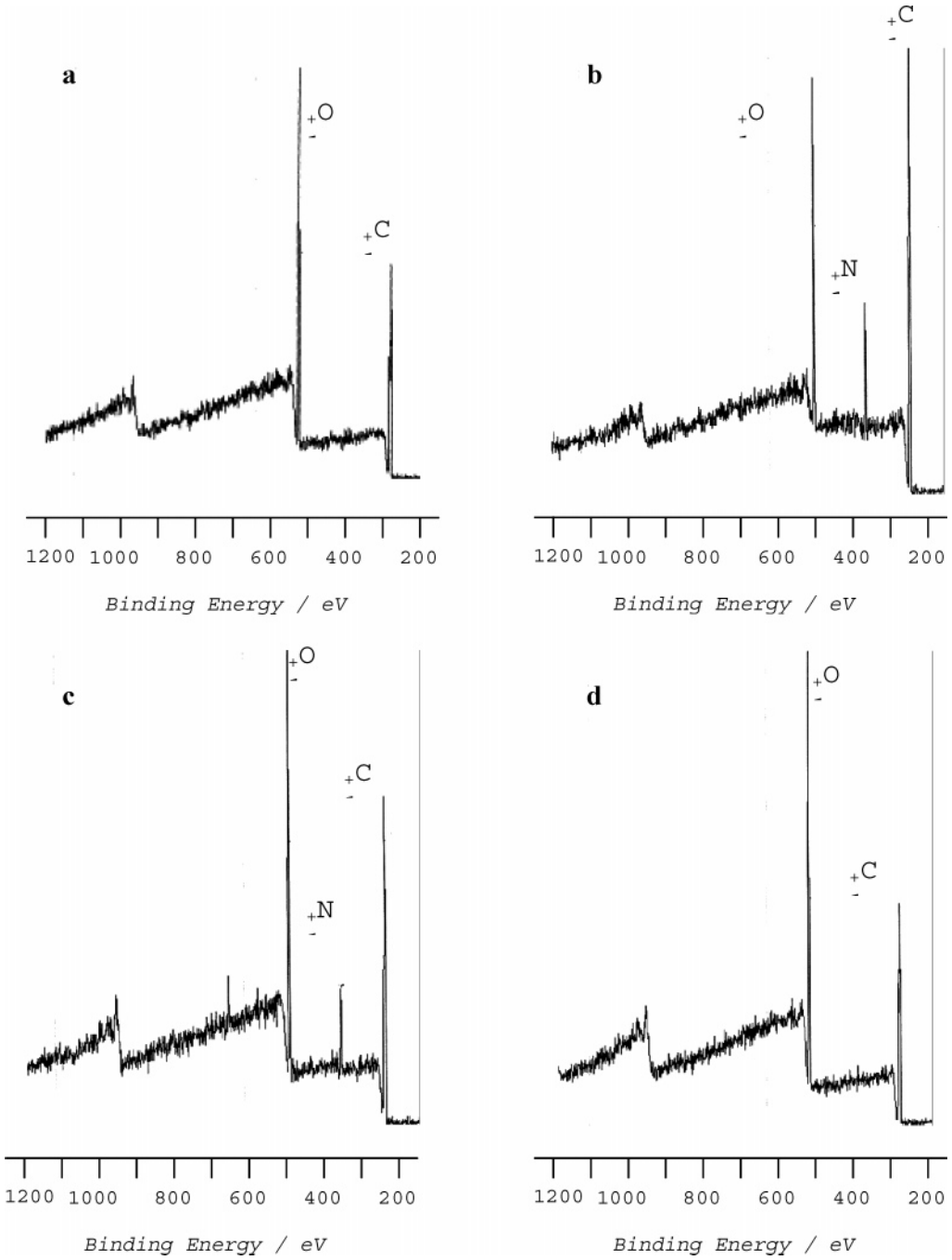

Figure 7. XPS data of (a) PLLA film, PLLA film grafted for 30 minutes with (b) VP, (c) AAm, and (d) MAH.

grafted substrates did not contain any nitrogen and that the ratio of carbon and oxygen corresponded well with the theoretical values of a fully MAH covered film.

The topographies of PLLA films could possibly change as a result of chemical modifications. SEM analyses showed (data not shown) that, while the original PLLA films hade a very smooth texture, the topographies changed to a somewhat rougher texture as they are subjected to vapor phase grafting. All grafted films have uniform textures suggesting that the grafting density at 30 min is high enough to provide full coverage, in a very thin layer, of the surface.

Conclusions

A method for the covalent surface modification of degradable polymers, here exemplified by PLLA, is presented. PLLA films were functionalized in one step with either VP, AAm, or MAH by subjecting the PLLA substrates to the solvent-free vapor phase of a mixture of a vinyl monomer and photoinitiator under UV irradiation. The extent of grafting and the wettability increases with treatment time. The static contact angle of pure PLLA (∼80°) changes to ∼50° for MAH, ∼35° for AAm, and ∼25° for VP after grafting for 30 min. The chemistry of the grafted surfaces was verified by ATR-FTIR and XPS.

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