Nonfouling Biomaterials Based on Polyethylene Oxide-Containing Amphiphilic Triblock Copolymers as Surface Modifying Additives: Synthesis and Characterization of Copolymers and Surface Properties of Copolymer–Polyurethane Blends

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ABSTRACT: The objective of this work is to develop nonfouling biomaterials by blending polyethylene oxide (PEO)-containing block copolymers with a polyurethane (PU) matrix; it is expected that the PEO component will migrate to the tissue-material interface. Three amphiphilic triblock copolymers, PEO-PU-PEO, in which the PEO MW was 550 (copolymer 1), 2000 (copolymer 2), and 5000 (copolymer 3), respectively, were synthesized. XPS data showed that the polymer/vacuum interfaces of copolymers 2 and 3 were enriched in the PU block, whereas that of copolymer 1 was enriched in the PEO block. In contact with water, the PEO blocks for all three copolymers migrated to the surface as indicated by water contact angles. Blends of the copolymers with a segmented polyurethane were investigated. Surface enrichment of the copolymers occurred and increased over time up to a limit; the degree of enrichment was dependent on PEO block size and copolymer content. At copolymer content <10%, enrichment decreased with increasing PEO block size. For the copolymer 2 and copolymer 3 blends, enrichment increased with increasing copolymer content; at 20% copolymer the surfaces consisted essentially of pure copolymer. For the copolymer 1 blends, the surface was completely covered by copolymer at content $\geq$ 1%. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 108: 1617–1628, 2008

Key words: polyurethanes; polyethylene oxide; proteins; block copolymers; blends; XPS

INTRODUCTION

The overall objective of this work is to develop ''nonfouling'' biomaterials, i.e. materials that resist the attachment of proteins, cells, and other species when in contact with a biological environment such as soft or hard tissue, blood, tear fluid, and others. The most common approach to nonfouling materials is via surface modification using hydrophilic polymers, e.g. poly(vinylpyrrolidone) (PVP), poly(2-methacryloyloxyethyl phosphorylcholine) (MPC), poly(ethylene oxide) (PEO or PEG), and polysaccharides of various kinds. PEO in particular has been widely investigated and has been shown to be among the most effective surface modifiers for this purpose.[1–4] Various methods of deploying PEO on biomaterial surfaces have been used including chemical grafting,[5–9] adsorption of PEO-containing block copolymers,[10,11] plasma deposition/polymerization of ethylene oxide analogs, e.g. tetraglyme,[12] and formation of self-assembled monolayers of PEO-thiols on gold.[13,14]

These different methods have advantages and disadvantages. Thus chemical grafting resulting in covalent attachment produces relatively stable surfaces; however grafting methods are complex and difficult to apply to complicated shapes. Plasma methods also produce stable surfaces, but generally they are of poorly defined structure and again are difficult to apply to complex geometries. Adsorption of copolymers is a relatively simple process, but the adsorbed species may be lost by desorption or exchange with species in biologic contacting media such as blood.[15] The thiol-gold materials have been used in biosensor and microarray applications, and in fundamental studies to elucidate mechanisms of protein resistance.[13,16]

A simple and effective approach for preparing PEO-containing surfaces is to blend small amounts of PEO-containing copolymers into a matrix or carrier material.[17–23] To be effective, the additive must

be hydrophilic and surface active so that it migrates to and modifies the material-biosystem interface. For example Lee et al.[17] blended Pluronics (triblock PEO-PPO-PEO copolymers) with a commercial segmented polyurethane and showed that the blends were resistant to platelet adhesion. A difficulty with this approach is that the additive may tend to leach from the surface and be depleted over time. Lee et al.[17] showed that this problem could be mitigated in the Pluronic-PU system by including a reagent that bonds the Pluronic covalently to the matrix.

In the work reported here we have pursued the surface modifying additive approach. Our system consists of a segmented polyurethane matrix based on a polytetramethylene oxide (PTMO) soft segment, and a triblock copolymer additive analogous to the Pluronics but with a PTMO/polyurethane middle block instead of PPO. We hypothesize that in these blends the amphiphilic copolymer will migrate to and accumulate at the aqueous-polymer interface to provide a PEO-containing surface with nonfouling properties. We further hypothesize that these surfaces will be relatively stable in biologic environments based on the similar chemical structures of the matrix and the middle copolymer segment, i.e. that interactions through chain entanglement and hydrogen bonding between this segment and the matrix will effectively anchor the PEO at the interface and prevent leaching.

In this article we report on the synthesis and characterization of the triblock copolymers, and on the formation and surface properties of copolymer-matrix blends. The solid state properties of the blends and their interactions with proteins are described elsewhere.[24,25]

MATERIALS AND METHODS

Materials

Dimethyl formamide (DMF) was obtained from Aldrich (Milwaukee, WI) and purified by vacuum distillation to remove trace amounts of water. Amino-terminated monomethoxy polyethylene oxides (MeO-PEO-NH$_2$, MW 550, 2000 and 5000) were purchased from Nektar Therapeutics (Huntsville, AL) and degassed *in vacuo* at 60°C for 6 h before use. Polytetramethylene oxides (PTMO) of MW 2000 and 980 were obtained from BDH Chemical (Toronto, Canada) and degassed *in vacuo* at 100°C for 3 h to remove trace amounts of water. Methylene di-*p*-phenyl diisocyanate (MDI) was obtained from Eastman Kodak (Rochester, NY) and vacuum distilled at 170°C and 1 torr to remove dimers and trimers. The distilled MDI was stored under nitrogen at −10°C. All other chemicals were of reagent grade and were used without further purification.

Synthesis of triblock copolymers (PEO-PU-PEO)

The two-step procedure for block copolymer synthesis is exemplified using PEO2000 as the end block.

Prepolymer formation

PTMO 2000 (348 g, 0.174 mol) was placed in a clean dry 500 mL round bottom flask and degassed/dried under vacuum at 100°C for 3 h. MDI (65.3 g, 0.261 mol) was placed in a clean dry 2L reaction kettle, under nitrogen, at 70°C. DMF (100 mL) was added to the dry PTMO. The PTMO/DMF solution was added dropwise to the MDI over a period of 15 min. The reaction was allowed to continue for 1 h under nitrogen. DMF (200 mL) was added during the course of the reaction. A small amount of the solution was taken for infrared and NMR analysis.

Reaction of PEO with prepolymer

PEO2000 was degassed/dried under vacuum at 60°C for 6 h. Dry PEO (348 g, 0.174 mol) was added to the prepolymer solution contained in the 2-L reaction vessel, under nitrogen. The reaction was allowed to continue for 1 h at 80°C. DMF (200 mL) was added during the course of the reaction. GPC analysis of the product showed only one peak (Fig. 1) indicating that no unreacted monomers remained and the yield of copolymer was ∼ 100%.

Three copolymers were synthesized: all three had the same middle block (based on the same prepolymer) but PEO end blocks of different MW, namely 550, 2000, and 5000. These are referred to as copolymers 1, 2, and 3, respectively.
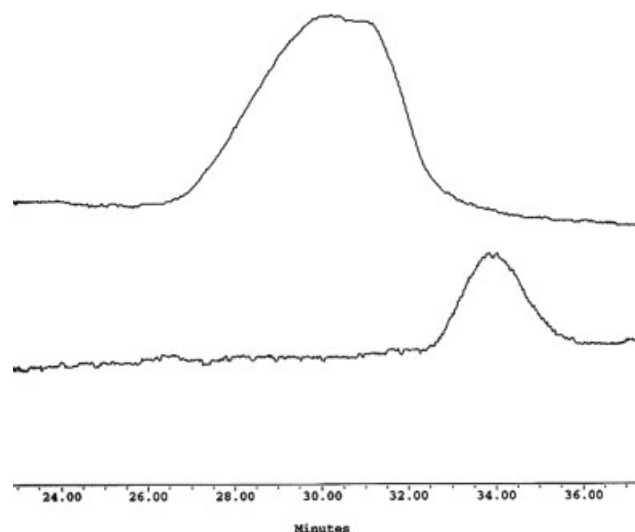

Figure 1 GPC traces of copolymer 2 (upper trace) and PEO2000 (lower trace).

Synthesis of matrix polyurethane

The segmented polyetherurethane urea (PU) used as the matrix for the blends was synthesized using a two-step method with methylene di-p-phenyl diisocyanate (MDI), polytetramethylene oxide (PTMO) of molecular weight 980, and ethylene diamine (ED) as chain extender as described elsewhere.[26] The molar ratio MDI: PTMO: ED was 2 : 1 : 1. The PU solid obtained from this procedure was washed with methanol for 2 days to remove low-molecular weight species and dried *in vacuo* at 60° overnight.

Preparation of copolymer/PU blends

The matrix PU was dissolved in DMF at a concentration of 5% (w/w). Solutions of the copolymers in DMF were added to the matrix solution such that the copolymer content of the final solutions ranged between 1 and 20% (w/w). Films of thickness ~ 300 μm were prepared by casting on clean glass from the matrix-copolymer solutions. The films were dried in air at 60°C for 24 h and then *in vacuo* at 60°C for 24 h. They were stored at room temperature in air prior to surface characterization. Surfaces referred to as ''aged'' were kept in air for at least 15 days, at which point migration of the copolymers to the surface was believed to be complete. The nomenclature used for the blend films is as follows: ''1% 1'' indicates the blend containing 1% (w/w) copolymer 1 and 99% matrix; ''20% 3'' indicates the blend containing 20% (w/w) copolymer 3 and 80% matrix.

Fourier transform infrared spectroscopy

Fourier transform infrared (FT-IR) spectra of the copolymers were obtained using a Bio-Rad FTS-10 FTIR spectrometer. Films were cast from solution in DMF on a sodium chloride window and dried *in vacuo* at 60°C for 24 h prior to taking spectra.

NMR spectroscopy

^{1}H NMR spectra were recorded on a Bruker 200 spectrometer using solutions of the polymers (5%, w/v) in a 1 : 1 (v/v) mixture of deuterated dimethyl sulfoxide (DMSO) and chloroform at room temperature. Tetramethylsilane (TMS) was used as internal standard.

Gel permeation chromatography

A Waters Chromatography 600 instrument was used for gel permeation chromatography (GPC) measurements. The system comprised four UltraStyragel columns with pore sizes of 1,000 Å, 10,000 Å, 10,000 Å, and 100,000 Å, respectively in series, a high-pressure pump and a differential refractive index detector. The mobile phase was a solution of LiBr (0.1M) in DMF (HPLC grade). The operating temperature was 80°C and the solvent flowrate was 1.0 mL/min. A typical chromatogram had a complete retention volume of ~ 50 mL. Copolymer solutions were filtered using Millex-SR 0.5 μm filter units prior to injection. Polyethylene oxide (PEO) standards were used for calibration.

X-ray photoelectron spectroscopy (XPS)

X-ray photoelectron spectra were obtained on a Leybold Max 200 system (LH, Cologne, Germany) using a nonmonochromatic Mg Kα source operating at 15 kV and 20 mA. The sampling spot was a 2 × 4 mm ellipse. Atomic compositions were obtained from spectra collected in low resolution mode over the 0–1000 eV range. High-resolution C1s spectra were also taken to obtain information on chemical bonding. Spectral fitting was performed using ESCA-TOOLS software (Surface/Interface Inc., Mountain View, CA). Spectra were obtained at take-off angles of 90° and 20° relative to the surface.

Water contact angles

Water contact angles were measured using a Ramé-Hart NRL C.A. goniometer.[27] The blend surfaces were investigated at different times in air after casting. Angles were determined using both the sessile drop and captive air bubble methods.

RESULTS

The copolymer synthesis scheme is outlined in Figure 2. The first step is the preparation of the isocyanate-terminated prepolymer. With a molar ratio MDI : PTMO2000 = 3 : 2 the expected prepolymer average molecular weight is 4750. MeO-PEO-NH$_2$ is then attached to both ends of the prepolymer by reaction between the amino and isocyanate groups. In this copolymer, the middle block has a polyurethane-like structure, and is relatively hydrophobic. The terminal PEO blocks are strongly hydrophilic. The copolymers may thus be described as amphiphilic triblock copolymers. Three such copolymers having the same middle PU block and PEO blocks of varying size (MW 550, 2000, and 5000) were synthesized. Their expected structures are listed in Table I.

Copolymer characterization

FT-IR spectra

The spectra of PEO2000, the prepolymer, and copolymer 2 are shown in Figure 3. For PEO2000, the
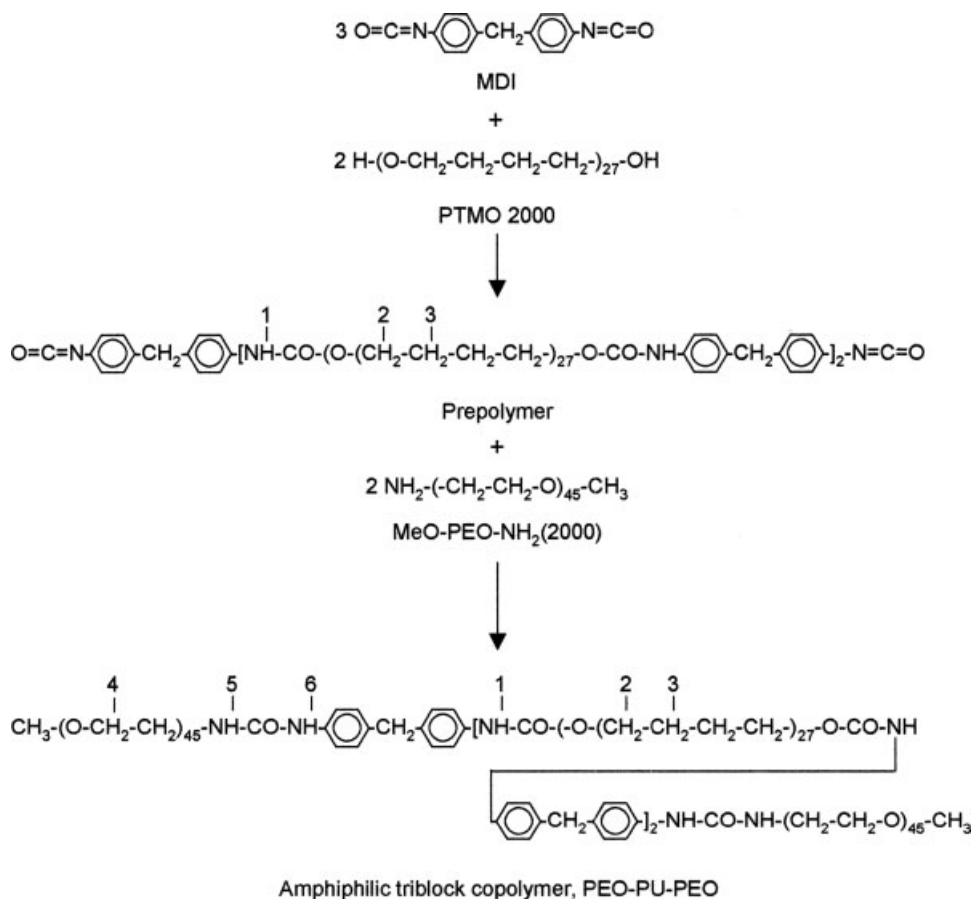
Figure 2 Reaction scheme for synthesis of triblock copolymers. Hydrogens are numbered for discussion of NMR spectra (see Figure 4).

very strong band at 1115 cm^{-1} is assigned to the ether group. Bands in the 3200–3500 cm^{-1} region, attributable to the NH$_2$ group in PEO2000, would be expected but were not observed, presumably because the amino content is too low. In the prepolymer the very strong band at 2276 cm^{-1} is assigned to the free isocyanate groups (—NCO). In the spectrum of copolymer 2, the —NCO peak is absent, indicating that the reaction between —NCO and —NH$_2$ went essentially to completion. At the same time, the ether peak at 1113 cm^{-1} and the CH$_2$ peaks near 2862 cm^{-1} increased significantly as expected. Five bands attributed to the PEO block of copolymer 2 are indicated in the spectrum. The spectra of the other copolymers were similar.

Proton NMR spectra

Figure 4 shows the spectra of PEO 2000, prepolymer, and the three copolymers. Figure 2 shows the assignments of the peaks. The peak at 3.59 ppm in PEO and the copolymers is assigned to the protons of —O—CH$_2$—CH$_2$— residues in PEO. For the prepolymer and copolymers, peak assignments are based on the standard spectra of polyurethanes.[28] The strong peaks at 3.35 and 1.54 ppm are due to the protons of PTMO in the PU block. The peak at 9.35 ppm is assigned to proton H1 in the urethane group formed by the reaction between the hydroxyl group of PTMO and the isocyanate group of MDI. The peak at 8.41 ppm is assigned to the proton H$_w$ in

TABLE I
Properties of Copolymers

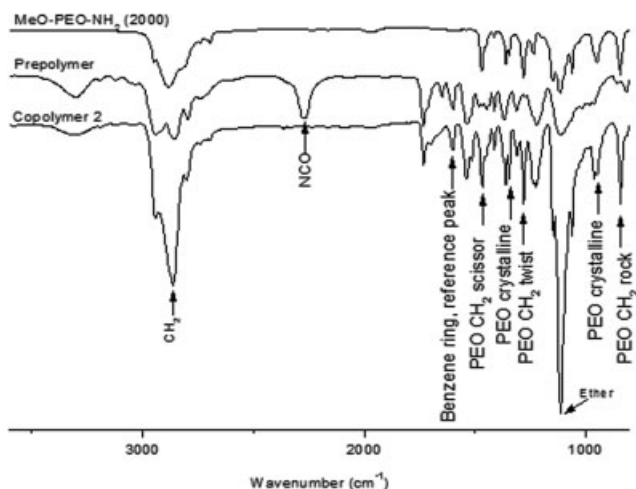|	Expected structure	PEO content (expected, wt %)	Expected M_n	Measured M_n	M_w/M_n
Copolymer 1	PEO550-PU4750-PEO550	19	5,850	6,200	1.2
Copolymer 2	PEO2000-PU4750-PEO2000	46	8,750	8,600	1.1
Copolymer 3	PEO5000-PU4750-PEO5000	68	14,750	11,800	1.1

Figure 3 FTIR spectra of PEO 2000, prepolymer, and copolymer 2.

"water urea" presumably formed by the reaction of water in the air with isocyanate during sample preparation. The peak at 8.14 ppm is due to the solvent chloroform.

The spectrum of copolymer 2 is shown in Figure 4(c). Compared to the prepolymer, there are three new peaks at 8.35, 6.10, and 3.59 ppm. The peaks at 8.35 and 6.10 ppm are assigned, respectively, to protons H6 and H5 in the urea residues formed by reaction of the amino groups of PEO2000 with the isocyanate groups of the prepolymer.

The spectra of the three copolymers are qualitatively similar. However, as expected on the basis of the different PEO block lengths, the intensity of the PEO peak at 3.59 ppm is the highest for copolymer 3 (PEO 5000) and lowest for copolymer 1 (PEO 550).
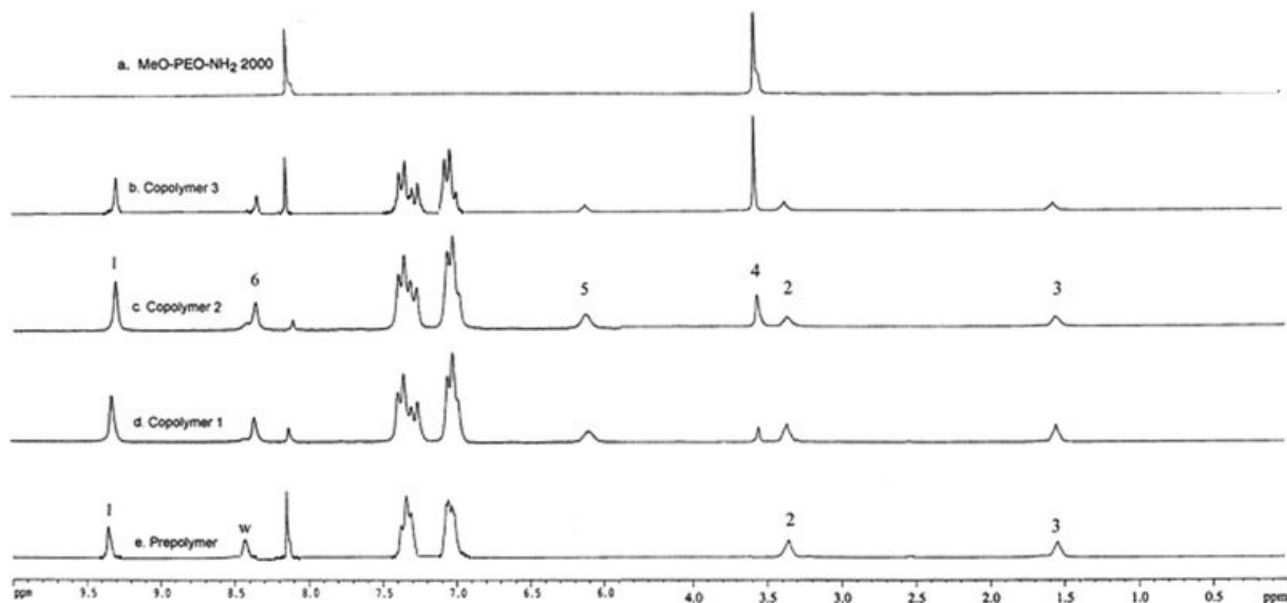
Since protons H1 and H5 are formed, respectively, by the reactions of PTMO and PEO with isocyanate groups, the peak intensity ratio, $I_{H5} : I_{H1}$, can be used to estimate the ratio of the PEO : middle (PU) blocks in the copolymers. From the NMR spectra, the PEO : PU ratios are estimated to be 1.96 : 1, 1.95 : 1, and 1.91 : 1 for copolymers 1, 2, and 3 respectively, i.e. close to the expected value of 2 : 1. This result confirms that the copolymers have the expected triblock structure, PEO-PU-PEO, and indicates that the reactions between the prepolymer and MeO-PEO-NH$_2$ went essentially to completion.

GPC

GPC traces for all three copolymers showed a single peak with no evidence of unreacted PEO, indicating that conversion in the copolymer synthesis reaction was close to 100%. Figure 1, showing chromatograms for copolymer 2 and PEO2000, exemplifies this result. The molecular weights determined by GPC are listed in Table I and are close to the expected values based on the triblock structures. The polydispersity index was in the range 1.1–1.2 for all three copolymers, indicating that the MW distributions were narrow.

Water contact angles

All three copolymers showed advancing contact angles of the order of 15°. These low values indicate that the copolymer surfaces are strongly hydrophilic, presumably due to the predominance of PEO rather than PU at the polymer film-water interface. In con-

Figure 4 ^{1}H NMR spectra of PEO, copolymers, and prepolymer. See Figure 1 for assignment of numbered peaks.

	Expected oxygen content	Expected oxygen content of PEO block	Expected oxygen content of PU block	Determined oxygen content	
				20°	90°
Copolymer 1	21.0	33	18.8	23.6 ± 0.5	22.7 ± 0.4
Copolymer 2	25.2	33	18.8	20.8 ± 0.6	22.2 ± 0.5
Copolymer 3	28.4	33	18.8	22.9 ± 0.3	24.5 ± 0.4

tact with water it is thus likely that the hydrophilic PEO segments predominate at the interface.

XPS

XPS survey spectra (take-off angle, 90°) showed three main peaks assigned to oxygen (O1s, 532 eV), nitrogen (N1s, 402 eV), and carbon (C1s, 285 eV), respectively. The oxygen content of the three copolymers at take-off angles of both 90° and 20° (Table II) is higher than that of pure PU block and lower than that of pure PEO block, suggesting that both the PU and PEO blocks are present at both sampling depths. The surface oxygen content of copolymer 1 is higher than that expected for the bulk material, implying that the copolymer 1 surface is enriched in PEO down to the sampling depth at a take-off angle of 90°. The surface enrichment of PEO is greater at 20° where the effective sampling depth is only 34% of that at 90°. The PEO concentration thus appears to increase as the vacuum-solid polymer interface is approached from the bulk. Copolymers 2 and 3 show depth concentration gradients opposite to copolymer 1. The surface oxygen content is lower than the expected bulk oxygen content, and is lower at 20° than at 90°, suggesting that the PU block concentration increases as the vacuum-copolymer interface

is approached. The surface of copolymer 3 has a higher oxygen content than copolymer 2, presumably due to the higher PEO content of copolymer 3.

Surface properties of copolymer/polyurethane blends

Water contact angles

Figure 5 shows the advancing water contact angles for the 20% blend surfaces as a function of time in air after film preparation. The angle on the unmodified PU control was 73 ± 2° and showed no change over time. Freshly prepared 20% 1 blend showed an initial contact angle of 65 ± 2° decreasing to 62 ± 2° and then remaining constant. Fresh 20% 2 and 20% 3 films showed higher contact angles than the PU control, i.e. 78 ± 3° and 81 ± 1°, respectively. This unexpected result may be due to the greater surface roughness of the blends compared to the unmodified PU. The contact angles of these blends decreased rapidly with time in air, stabilizing at about 20° after 4 days for 20% 2 and 6 days for 20% 3, suggesting migration of the copolymers from bulk to surface with an increase in surface concentration of the PEO-containing component. The leveling off at longer time suggests that the migration of the copolymers is complete. Thus it appears that migration of copolymers 1, 2, and 3 is complete after 1, 4, and 6 days, respectively, i.e. the migration rate decreases with increasing PEO MW. After copolymer migra-
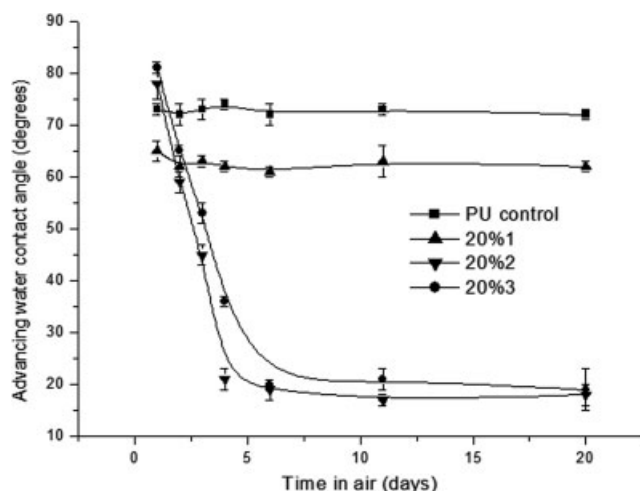

Figure 5 Advancing water contact angles of the 20% copolymer blends over time in air. Error bars represent one standard deviation (*n* = 6).
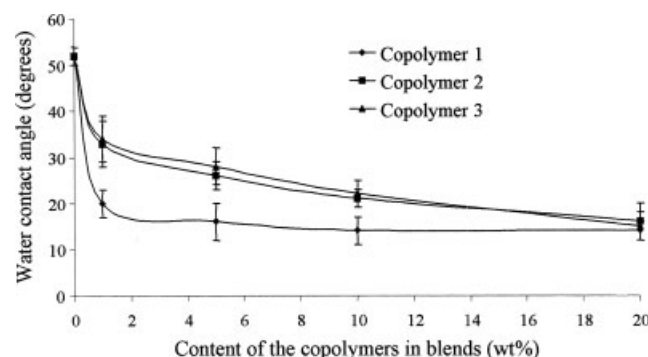

Figure 6 Water contact angles of the fully aged blends by captive bubble method. Error bars represent one standard deviation (*n* = 6).
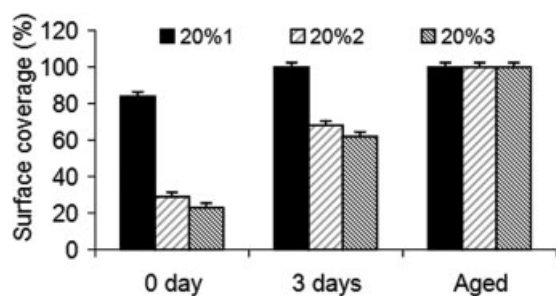
Figure 7 Percent surface coverage of copolymers on 20% blends at different times in air.

tion was complete, the 20% 2 and 20% 3 blends showed contact angles of ~ 20°, indicating high PEO surface concentrations on these two materials. On the other hand, the contact angle for the 20% 1 blend decreased by only 10° compared to the PU.

The water contact angles of the "aged" materials (time in air of at least 15 days) were also determined by the captive bubble technique (Fig. 6). For the PU control (0% copolymer) the angle determined by the captive bubble method was 53°, i.e. lower than the advancing contact angle of 73° measured by the sessile drop technique (Fig. 5), suggesting that a higher concentration of hydrophilic groups is present at the hydrated surface. For the copolymer 1 blends the angle decreased rapidly with increasing content of copolymer up to 1%, with no significant further decrease at higher content. For the copolymer 2 and copolymer 3 blends the angles decreased more gradually. At a copolymer content of 20% all three blend types showed contact angles of about 16°, close to the values found for the pure copolymer surfaces. This result suggests that at a copolymer content of 20%, and after ageing fully in air, the blend surfaces may be entirely covered by the copolymers.

The advancing and receding contact angles of the 20% 1 blend measured by the sessile drop technique were 62° and 35°, respectively, i.e. considerably higher than the value (15°) obtained by the captive bubble method, suggesting a higher PEO density at the hydrated surface. In contrast, the aged 20% 2 and 20% 3 blends showed contact angles of about 16° by the captive bubble method, similar to the advancing angles of about 20° determined by the sessile drop technique. It is clear that for the 20% 1 blend (and presumably the copolymer 1 blends of lower copolymer content) surface rearrangement occurs in contact with water as reflected in the much lower value for the captive bubble angle and in the large difference between the advancing and receding angles. It is likely that such rearrangement also occurs for the copolymer 2 and copolymer 3 blends but at a much faster rate such that the sessile drop angles give the same low values as the captive bubble.

XPS

In addition to oxygen, nitrogen, and carbon, XPS survey spectra showed small amounts of silicon (Si2p, 99 eV). High resolution C1s spectra showed four peaks assigned to —C—C— at 285 eV, —C—O— (ether) at 286.5 eV, —NH—CO—NH— (urea) at 288.8 eV, and —NH—CO—O— (urethane) at 289.5 eV.[29,30]

Migration of copolymer to surface: process of "ageing". Since the oxygen content of the copolymers is greater than that of the matrix PU, the surface oxygen content can be used to assess the migration of the copolymers to the surface. In all cases the surface oxygen content increased with time in air, indicating an increase in copolymer content. Copolymer enrichment was quantified as percent surface coverage defined as:

$$\text{Surface coverage}(\%) = [(\text{O\%}_{blend}) - (\text{O\%}_{PU})] \times 100/[(\text{O\%}_{copolymer}) - (\text{O\%}_{PU})]$$

where $\text{O\%}_{blend}$ is the surface oxygen content of the blend from XPS data; $\text{O\%}_{PU}$ and $\text{O\%}_{copolymer}$ are the expected oxygen contents of the PU and copolymer, respectively.

Figure 7 shows the fractional surface coverage of the 20% copolymers after different times in air. The fresh 20% 1, 20% 2, and 20% 3 surfaces showed coverages of 81%, 29%, and 23%, respectively, indicating that some migration of the copolymers took place during the two-day solvent removal period. After three additional days in air, the copolymer coverages on the 20% 1, 20% 2, and 20% 3 materials reached 100, 68, and 62%, respectively, suggesting that the migration rates of the copolymers decreased with increasing PEO chain length. All three materials showed 100% coverage when fully aged. These data are in agreement with the contact angles.

High resolution C1s data lead to similar conclusions. Spectra for the 20% 2 blend at different times after film preparation (Fig. 8) show that the ether carbon peak increased with increasing time in air. The ether carbon content was used to assess the migration of the copolymers to the surface based on expected values for the bulk materials (PU, 31.3%; 20% 2 blend, 38.1%; copolymer 2, 65.3%). The —C—O— contents of the 20% surfaces after different times in air are shown in Figure 9. The fresh surfaces showed higher ether carbon content than the bulk materials, again indicating that migration of the copolymers occurred during solvent removal. The ether carbon content of all three 20% blends increased with time in air.

Fully aged materials. Low resolution data for the fully aged blends at both 90° and 20° take-off angles are listed in Table III and high resolution C1s data in Ta-
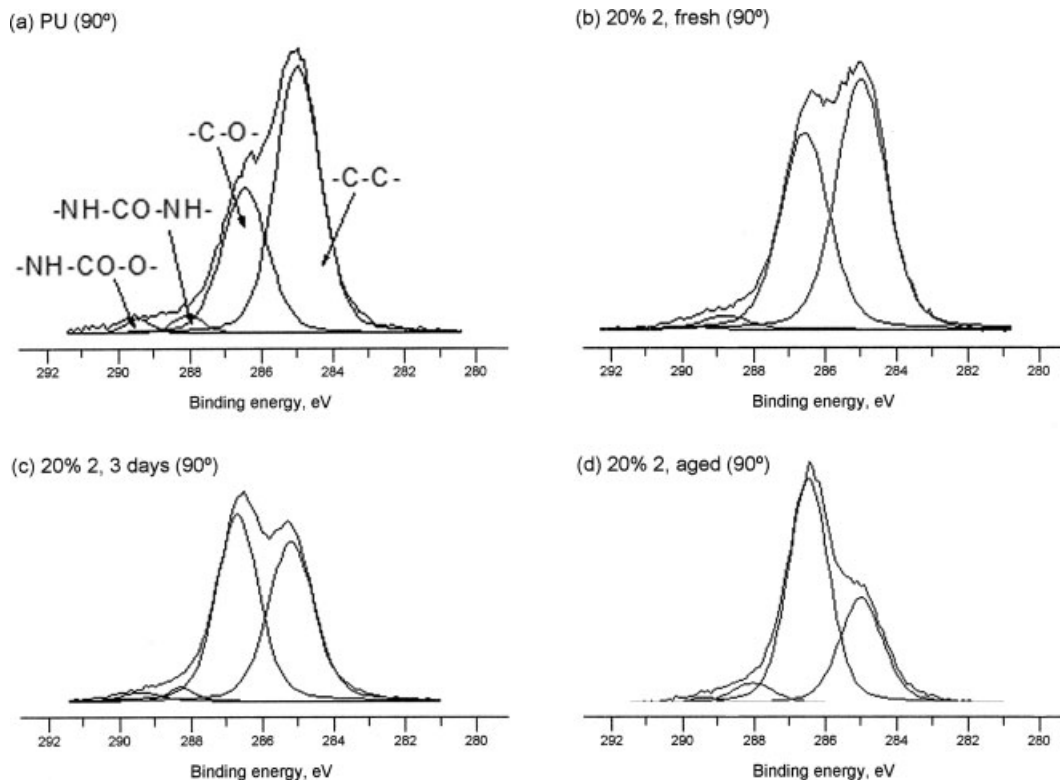
Figure 8 C1s spectra at a takeoff angle of 90°. (a) PU, (b) 20% 2, fresh, (c) 20% 2, aged 3 days, (d) 20% 2, fully aged. Assignment of peaks as shown in (a).

ble IV. The surface oxygen contents, as determined from both 90° and 20° data (Table III), were higher than the expected bulk values while the surface carbon and nitrogen contents were generally lower. These data indicate that the aged surfaces were, in general, enriched in the copolymers. It is also noted that the silicon content was consistently less than 2% implying minimal surface contamination.

The surface oxygen content of the fully aged copolymer 2 blends increased with increasing content of copolymer, and was higher at a take-off angle of 20° (more surface sensitive) than 90° for the 1, 5, and 10% blends. For the 20% 2 blend the take off angle dependence was reversed; this surprising result was confirmed for three different batches of the material, and is supported by the high resolution C1s data (Table IV). The oxygen content of the 20% 2 blend at 90° was 25.4%, close to the value of 25.2% expected for pure copolymer 2, suggesting that the 20% 2 surface was completely covered by copolymer. The oxygen contents of the other copolymer 2 blends were lower than 25.2%, indicating that copolymer coverage on these surfaces was less than complete. The copolymer 3 blends showed similar trends in the low resolution XPS data, and the 20% 3 surface, like the 20% 2, also showed higher oxygen content at 90 than 20°.

Like the copolymer 2 and 3 materials, the copolymer 1 blends were also surface-enriched in copoly-

mer (Table III). The surface oxygen contents at 90° increased with increasing content of copolymer 1, and the oxygen contents were in all cases greater at 20 than 90°. At 20° these surfaces showed oxygen contents in the vicinity of 21%, the value for pure copolymer 1. Thus it appears that even for a copolymer content of only 1% the surface was fully covered by copolymer.

Surface enrichment of the copolymers was quantified via estimates of percent surface coverage based on the oxygen content. The results (Fig. 10) indicate that coverage on the copolymer 1 blends was 100%
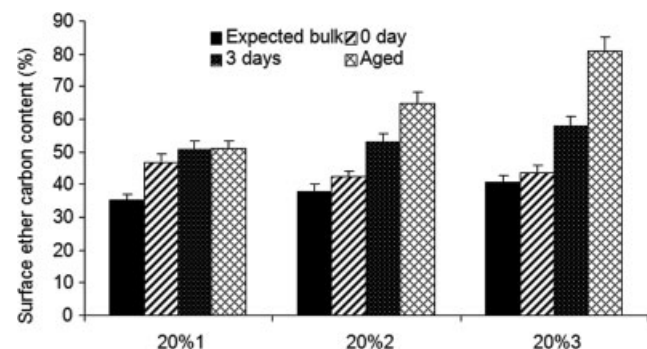

Figure 9 Surface ether carbon content of 20% blends after different times in air.

TABLE III
Low Resolution XPS Data for Aged Blend Surfaces

Surface	Carbon, atom %			Oxygen, atom %			Nitrogen, atom %			Silicon, atom %		
	Expected bulk	20°	90°	Expected bulk	20°	90°	Expected bulk	20°	90°	Expected bulk	20°	90°
PU	77.8	80.1	78.1	16.7	16.9	17.1	5.5	1.5	4.2	0	1.5	0.6
1% 1	77.8	75.1	76.9	16.7	21.6	19.6	5.5	1.5	3.0	0	1.8	0.5
5% 1	77.8	75.7	77.3	16.9	21.2	19.8	5.3	1.4	2.5	0	1.7	0.4
10% 1	77.7	76.4	77.1	17.1	21.4	20.5	5.2	1.2	2.1	0	1.0	0.3
20% 1	77.6	74.8	76.1	17.6	22.4	21.5	4.8	0.9	1.9	0	1.9	0.5
Copolymer 1	77.0			21.0			2.0			0		
1% 2	77.8	76.4	78.4	16.8	20.1	18.1	5.5	1.7	3.0	0	1.8	0.5
5% 2	77.6	76.4	77.1	17.1	20.4	19.5	5.3	1.6	3.0	0	1.6	0.4
10% 2	77.4	73.8	76.0	17.6	23.4	21.4	5.1	1.3	2.1	0	1.5	0.5
20% 2	76.9	73.5	72.7	18.4	23.7	25.4	4.7	1.2	1.4	0	1.6	0.5
Copolymer 2	73.5			25.2			1.3			0		
1% 3	77.7	78.9	78.1	16.8	18.3	17.8	5.5	1.9	3.9	0	1.0	0.2
5% 3	77.5	77.0	77.6	17.3	19.8	18.8	5.3	1.7	3.2	0	1.5	0.4
10% 3	77.1	72.3	74.9	17.9	25.5	23.3	5.0	1.3	1.5	0	0.9	0.3
20% 3	76.4	72.8	70.3	19.0	25.6	28.9	4.6	1.0	0.7	0	0.7	0.2
Copolymer 3	70.8			28.4			0.8			0		

Typical error limits: ±0.5 atom%.[31]

for all compositions. For the copolymer 2 and 3 blends coverage increased with increasing copolymer content. At the highest content of 20%, all three copolymers showed 100% coverage. For a given copolymer content, with the exception of 20%, coverage decreased with increasing PEO chain length.

The C1s data (Table IV) show that compared to the matrix, the —C—O— content increased and the —C—C— content decreased for all of the blends. The surface —C—O— content can be used to assess the surface enrichment of the copolymers in the blends. It is seen that the surface —C—O— content of the copolymer 2 blends increased with increasing content of copolymer. Surface —C—O— content higher than the expected bulk value (assuming a uniform distribution of the copolymer) indicates surface enrichment of the copolymer. Thus it can be seen that surface enrichment increased with increasing content of the copolymer up to 20%. The —C—O— content of the 20% 2 surface at a take off angle of 90° was 65.0% compared to the expected value of 65.3% for pure copolymer 2, suggesting that the 20% 2 blend surface was entirely covered by copolymer. As was found for the oxygen content of the 20% 2 material (Table III), the —C—O— content was higher at 90° than at 20° (Table IV). The trends in the C1s data for the copolymer 3 blends are similar to those for the copolymer 2 blends (Table IV). As was the case for the 20% 2 blend, the —C—O— content of 20% 3 at 90° was higher than at 20°.

TABLE IV
High-Resolution C1s Data for Aged Blend Surfaces

| Surface	C—C (%)			C—O (%)			Urea (%)			Urethane (%)		
	Expected bulk	20°	90°	Expected bulk	20°	90°	Expected bulk	20°	90°	Expected bulk	20°	90°
PU	64.0	66.5	64.2	31.3	37.0	34.7	2.3	1.0	1.9	2.3	1.0	1.8
1% 1	63.8	44.8	55.4	31.5	52.1	41.0	2.3	1.5	1.8	2.3	1.6	1.8
5% 1	63.2	46.6	52.6	32.3	50.3	44.2	2.2	1.4	1.7	2.3	1.7	1.5
10% 1	62.3	44.9	51.3	33.3	51.2	45.7	2.1	1.9	1.6	2.2	2.0	1.4
20% 1	60.7	43.5	49.3	35.2	53.2	48.4	2.0	1.8	1.0	2.1	1.5	1.3
Copolymer 1	47.3			50.8			0.6			1.3		
1% 2	63.7	47.8	51.4	31.5	49.1	45.7	2.3	1.6	1.2	2.3	1.5	1.7
5% 2	62.5	45.2	49.8	33.0	51.6	46.4	2.2	1.5	1.8	2.2	1.7	2.0
10% 2	60.9	42.5	44.9	34.7	54.2	51.3	2.1	1.6	2.0	2.2	1.7	1.8
20% 2	57.9	40.6	33.4	38.1	56.8	65.0	1.9	1.0	0.6	2.0	1.6	1.0
Copolymer 2	33.3			65.3			0.4			0.9		
1% 3	63.6	47.5	59.9	31.8	48.9	35.8	2.3	1.7	2.1	2.3	1.9	2.2
5% 3	61.8	45.9	51.8	33.7	50.7	44.3	2.2	1.5	1.9	2.2	1.9	2.0
10% 3	59.7	31.5	46.6	36.0	65.8	50.6	2.1	1.2	1.5	2.1	1.5	1.3
20% 3	55.3	29.7	16.5	40.7	67.9	80.9	1.9	1.1	1.2	2.0	1.3	1.4
Copolymer 3	20.7			78.4			0.3			0.6		

Typical error limits: ±5%.
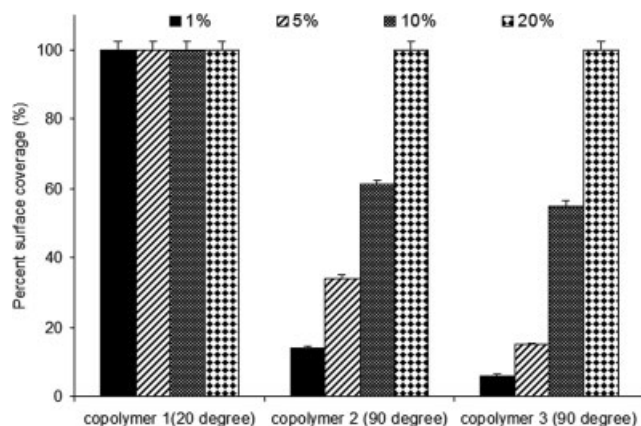
Figure 10 Copolymer surface coverage as a function of copolymer content.

The copolymer 1 blends showed different trends (Table IV). The —C—O— content of the 1% 1 blend at 20° was 52.1%, much higher than the expected value of 31.5% for the bulk material and close to the 50.8% expected for pure copolymer 1, suggesting that the 1% 1 surface was completely covered by copolymer 1. The addition of copolymer 1 beyond the 1% level did not increase the coverage of copolymer: the ether carbon content determined from data at a take-off angle of 20° did not increase. However, the —C—O— content determined at a take-off angle of 90° did increase with increasing content of copolymer 1 up to 20%. This suggests that the thickness of the copolymer "layer" at the surface increases with increasing content of copolymer 1. The ether carbon contents of the copolymer 1 blends at 20° were higher than those at 90° for all blend compositions.

DISCUSSION

The triblock copolymers were synthesized in two steps by the reaction of amino-terminated PEO with isocyanate-terminated prepolymer. The experimentally determined molecular weights are in good agreement with the expected values (Table I). The PEO : PU ratios of copolymers 1, 2, and 3 determined by ^{1}H NMR were 1.96 : 1, 1.95 : 1, and 1.91 : 1, respectively, i.e. very close to the expected value of 2 : 1. Thus both GPC and ^{1}H NMR data confirm that the expected triblock copolymer structures were obtained.

The angle-dependent X-ray photoelectron spectroscopy (AD-XPS) data indicate that the surfaces of copolymers 2 and 3 consist primarily of PU block, which is expected to have a low surface energy and to be relatively hydrophobic compared to the PEO block. The high vacuum environment of the XPS experiment is thus expected to favor migration of the low surface energy PU block to the outermost

layer. In contrast to copolymers 2 and 3, the AD-XPS data for copolymer 1 showed that its surface is enriched in PEO rather than PU. This unexpected surface enrichment of the higher energy PEO segment of copolymer 1 may be explained by the tendency for chain ends to localize at the surface.[32–34]

It seems likely that the copolymer-air interface has a structure similar to the copolymer-vacuum interface as in the XPS experiment, and thus the copolymer surface in air is expected to be enriched in PU block. The hydrated water contact angles for all three copolymers were about 15° independent of PEO chain length, i.e. similar to the value for PEO homopolymer, suggesting that in contact with water, the copolymer surfaces consist primarily of PEO. It is well known that the PEO chain is flexible and can rearrange rapidly. Such rearrangement apparently occurs upon exposure to water as suggested by the contact angle of 15°. This is important for the application of these copolymers as protein resistant surfaces. It may be anticipated that in contact with biological media the copolymers will rearrange similarly, resulting in a PEO-rich surface. Indeed, we have shown that protein adsorption on polyurethanes modified using these copolymers is low.[25]

When blended into the PU matrix material the surface-active block copolymers migrated to and became enriched at the surface as indicated by water contact angles and XPS. The decrease in water contact angles over time in air showed that for the blends containing 20% copolymer, migration to the surface was complete after 1, 4, and 6 days for copolymers 1, 2, and 3, respectively. Both the XPS and contact angle data showed that the migration rates of the copolymers decreased with increasing PEO block length. The reasons for this trend are not entirely clear but are most likely related to the relative sizes of the copolymer molecules and/or their aggregates. Other amphiphilic polymers have been shown to develop micellar morphology in blends.[35,36] The core of micelles or other domains in the copolymer/PU blends (an essentially hydrophobic environment) would be expected to consist predominantly of the PEO block, while the outer shell would consist mainly of the PU block. The formation of such domain structures in the blends is supported by electron microscope images discussed elsewhere.[24] If the sizes of the molecules and of the macrodomains formed by them are in the same order as the molecular weights, i.e., copolymer 1 < copolymer 2 < copolymer 3, then the dependence of migration rate on PEO chain length could be explained in terms of resistance to transport through the polyurethane matrix. Both the low and high resolution XPS data showed that surface coverage of the copolymers after complete migration increased with decreasing PEO chain length at low copolymer content (<10%).

At high copolymer content (20%) all three copolymers achieved 100% surface coverage. These materials are therefore expected to have surfaces that are rich in PEO when in contact with biological media.

The surfaces of the fully aged 20% 2 and 20% 3 blends appeared to be completely covered by the copolymers. However, the low-resolution XPS data for these materials showed lower oxygen content at 20° than 90°, and the high-resolution C1s data indicated lower —C—O— content at 20° than 90°. The expected O : C ratio for the PEO block of the copolymers is 0.5 and for the PU block 0.24. Thus it appears that the PU block was enriched on the outermost surface of the 20% 2 and 20% 3 blends, as was found for the pure copolymers. The PU block is hydrophobic compared to the PEO block, and should have a lower surface energy in contact with air. The PU block is thus expected to dominate the outermost surface layer to maintain the surface free energy at a minimum. While the XPS data showed that the outermost surface of the 20% 2 blend was enriched in the PU block of the copolymer, the water contact angle on this surface was 16°, i.e. closer to the PEO homopolymer than to the PU matrix. It can be inferred that, in contact with water (as opposed to vacuum), rearrangement occurs such that the surface consists primarily of PEO. The copolymer on the blend surface may rearrange similarly in contact with biological media, resulting in a PEO-rich surface.

The surface of the 20% 1 blend is also completely covered by the copolymer but its structure appears to be different from those of 20% 2 and 20% 3. The oxygen content of 20% 1 measured by XPS at 20° take off angle was higher than at 90°, suggesting that the outermost surface was enriched in the PEO vs. the PU block. Pure copolymer 1 showed a similar interfacial structure as discussed above. This unexpected surface enrichment of the higher energy PEO segment of copolymer 1 may be due to the tendency for chain ends to localize at the surface.[34] For copolymers 2 and 3, with longer PEO chains, the entropy loss involved in chain-end localization may prevent such an effect.

CONCLUSIONS

Three amphiphilic triblock copolymers having the general structure PEO-PU-PEO were synthesized. XPS data showed that the polymer/vacuum interfaces of copolymers 2 (PEO2000) and 3 (PEO5000) were enriched in the low surface energy PU block. In contrast, the PEO blocks were enriched in the copolymer 1 (PEO550)/vacuum interface. Upon contact with water, the hydrophilic PEO blocks came to the surface as indicated by the very low water contact angles. This rearrangement is important since the hydrophilic PEO block may minimize protein and cell interactions when the copolymers are used as surface modifiers for conventional biomedical materials, specifically polyurethanes.

Blends of the copolymers with a conventional segmented polyurethane (copolymer content from 1 to 20% by weight) were investigated. Surface enrichment of the copolymers occurred for all compositions, and the degree of copolymer enrichment (and other surface properties) was dependent on the structure and content of the copolymers. The rate of migration of the copolymers to the surface decreased with increasing chain length of the PEO block. Surface enrichment in blends of copolymer 2 and copolymer 3 increased with increasing content of the copolymers up to 20% by weight. In contrast, for copolymer 1 blends, the surface was already completely covered at a copolymer content of 1%. At low copolymer content (<10%) surface-enrichment of the copolymers decreased with increasing PEO chain length. For the 20% blends, migration was complete after times between 3 and 10 days depending on the PEO chain length and all three copolymers achieved complete surface coverage.

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