

Review

CONTROLLED SYNTHESIS OF AMPHIPHILIC BLOCK POLYMERS HAVING GLUCOSE RESIDUES AND THEIR STRUCTURE FORMATION

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Abstract Vinyl ether (VE)-based amphiphilic block copolymers with D-glucose residues as hydrophilic pendants were synthesized by $\text{CH}_3\text{CH}(\text{O}i\text{Bu})\text{Cl}/\text{ZnI}_2$ -initiated sequential living cationic copolymerization of 3-O-(vinylxy)ethyl-1, 2:5, 6-di-O-isopropylidene-D-glucopyranose (IGVE) and isobutyl VE (IBVE) and subsequent deprotection. The precursor block copolymers had a narrow molecular weight distribution ($M_w/M_n \sim 1.1$) and a controlled segmental composition. The solubility characteristics of the amphiphilic copolymer depended strongly on composition. Their solvent-cast thin films were examined, under a transmission electron microscope, and could be seen to exhibit various microphase-separated surface morphologies such as spheres, cylinders, and lamellae, depending on composition. The amphiphilic copolymers with the appropriate segmental composition were found to form a stable monolayer at the air-water interface, which was successfully transferred onto a substrate by the Langmuir-Blodgett (LB) technique. The layered structure of the built-up LB films was controlled by blending the homopolymer.

Keyword Glucose-substituted amphiphilic block polymer, Controlled structure

INTRODUCTION

Many studies have focused on synthetic polymers with pendant mono- and/or oligosaccharide residues for various functions such as biodegradability, high water-absorbency, and surface and pharmaceutical activities. Most of them were synthesized by chemical modification of a conventional polymer or by classical radical polymerization of sugar-containing vinyl monomers. By these methods, however, it is very difficult to precisely control the chemical structure and macroscopic morphology of the polymer. This paper reviews our recent works, in which we newly synthesized a well-defined amphiphilic block copolymer (**4** in Scheme 1) with a narrow molecular weight distribution by sequential living cationic polymerization^[1-3], and studied its monolayer-forming properties at the air-water interface to fabricate it into a ultrathin film with a supramolecular structure by the Langmuir-Blodgett technique^[4].

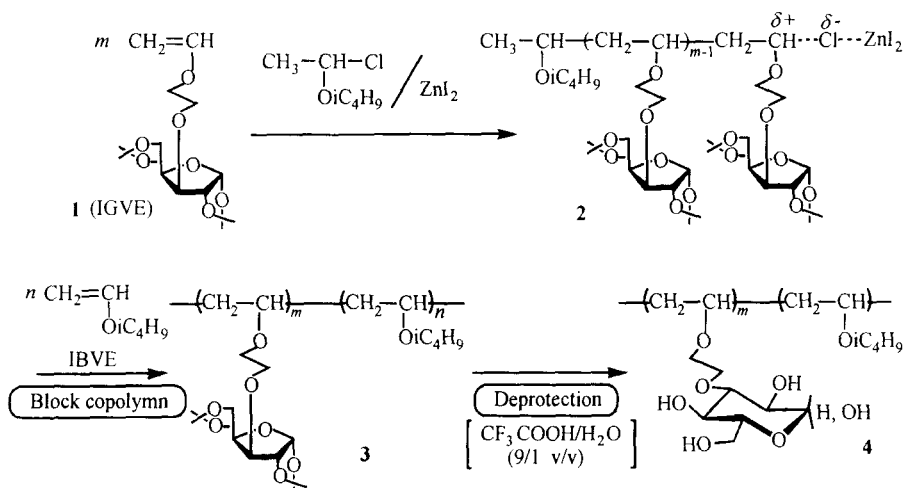
RESULTS AND DISCUSSION

Synthesis of Amphiphilic Block Copolymer

Amphiphilic block copolymer **4** was synthesized by sequential living cationic polymerization of a glucose-substituted vinyl ether (VE) and isobutyl VE (IBVE) followed by deprotection as shown in Scheme 1. In this study, 3-O-(vinylxy)ethyl-1,2:5,6-di-O-isopropylidene-D-glucopyranose (IGVE) was employed as the glucose-carrying VE because it was already proved to be more suitable for the

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Received October 3, 1997

living polymerization than the acetyl-protected counterpart^[1]. The polymerization was conducted with the HCl/ZnI₂ initiating system which has been widely used for the living cationic polymerization of a variety of functionalized VEs. We employed the adduct of IBVE with HCl, i.e. [CH₃-CH(OiBu)Cl] prepared separately as an initiator.



Scheme 1

The polymerization of IGVE was first carried out in toluene at -40°C to give a living polymer 2 quantitatively. After reaching 100% conversion of IGVE, the second monomer, IBVE, was added to the system and sequentially polymerized up to 100% conversion. Size exclusion chromatography (SEC) measurement of the resultant polymers revealed that the molecular weight distribution (MWD) of the precursor block polymer 3 is narrow ($M_w/M_n < 1.12$) and the MWD curve shifted to a higher molecular weight region without any detectable polymer remaining at the elution position of the IGVE homopolymer prepared in the first-stage polymerization. In this study, the degree of polymerization (m) of the IGVE segment was kept at ca. 20 whereas that (n) of the IBVE segment was varied by regulating the amount of IBVE. The results of the block copolymerizations are summarized in Table 1. The segment composition (m/n) was determined from the $^1\text{H-NMR}$ peak intensity ratio of the furanose ring protons of the IGVE segment to the pendant methyl protons of the IBVE segment. The degree of polymerization (m) of the glucose-substituted segment was calculated from the monomer (IGVE)/initiator [CH₃CH(OiBu)Cl] feed molar ratio. The observed segment compositions are in good agreement with the calculated values from the monomer feed ratio.

The precursor block polymer 3 was converted to the target amphiphilic block copolymer 4 through treatment with a mixture of trifluoroacetic acid and water. Comparison of the $^1\text{H-NMR}$ spectra of 3 and 4 has confirmed that the deprotection proceeded quantitatively. Furthermore, the observed segment composition of the deprotected polymer was in good agreement within experimental error with that of the precursor, suggesting that degradation of the polymer chain hardly occurred during the deprotection reaction. All of the precursor block polymer 3 with different segment compositions is soluble in common organic solvents but insoluble in water. In contrast, the solubility characteristics of the deprotected polymer 4 is different and strongly dependent on the segment composition. For example, copolymer 4a ($m/n = 20/20$) is as soluble in water as the deprotected product of a homopolymer of IGVE, while the copolymers 4b ($m/n = 20/48$) and 4c ($m/n = 20/89$) are no longer soluble in water but are soluble in some organic solvents.

Table 1. Characterization of Block Copolymer 3

Code	Structure	Composition ^a <i>m/n</i>	M_n^b	M_w/M_n^b
	Homo polymer	18/0	4000	1.05
3a	Block copolymers	20/20	6900	1.09
3b		20/48	11500	1.04
3c		20/89	15200	1.06

a. Determined by ¹H-NMR; b. Estimated by polystyrene-calibrated GPC

Morphologies of Solvent-Cast Thin Films of the Amphiphilic Block Polymer

Block copolymers consisting of incompatible components are known to exhibit microphase-separated structures with various morphologies. The morphologies at the surface are generally very different from those in the bulk. The surface characteristics of polymeric materials are closely related to their functions, especially in biological and biomedical applications. We examined the surface microstructure of thin films of amphiphilic copolymers **4** by transmission electron microscopy (TEM). To prepare a sample specimen, a thin film of **4** was cast from an aqueous or methanol solution and stained with uranyl acetate (2 wt% aqueous solution), which selectively stained the hydrophilic component. As seen in Fig.1, solvent-cast films of amphiphilic copolymers **4** exhibited various microphase-separated structure, such as spheres and cylinders. The morphology appears to strongly depend on the segment composition *m/n*. In this study, the hydrophilic segment length was fixed at *m* = 20, and an increase in *n* brings about an increase in size of the hydrophobic domains (the white regions in the images). The specimen of **4c** also exhibited a lamellar pattern with periodicity distance of ca. 16 nm (image D). These results indicate that the amphiphilic block copolymers **4** possess well-controlled chain architecture.

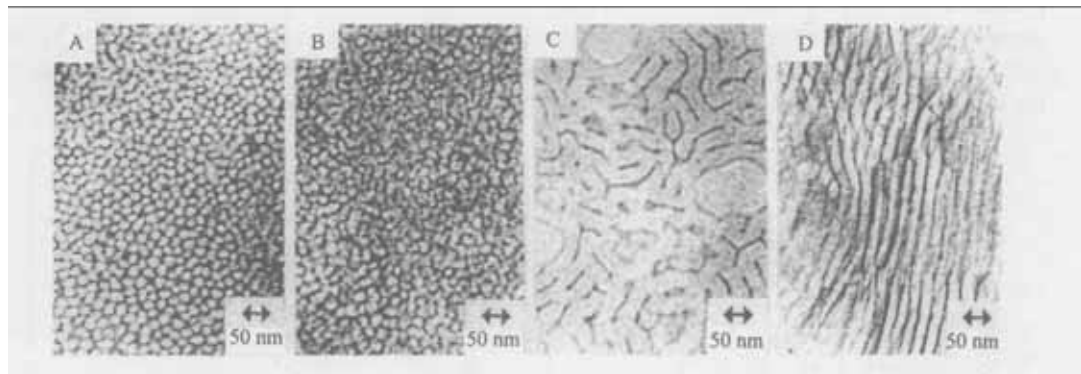


Fig.1 Transmission electron micrographs for amphiphilic block copolymers **4a** (A), **4b** (B), and **4c** (C and D)

The sample films were cast from methanol solutions. Segment compositions (*m/n*) are as indicated.

Langmuir-Blodgett Films of the Amphiphilic Block Polymer

The amphiphilic block copolymers **4** contain a poly(isobutyl vinyl ether) (PIBVE) subchain as a hydrophobic block. Since PIBVE has a monolayer-forming ability by itself, the block copolymer is expected to be fabricated into a glucose residue-carrying ultrathin film with a supramolecular structure by means of the Langmuir-Blodgett (LB) technique, which was proved to be a useful method to control molecular assemblies.

The block copolymers **4b** and **4c** with an appropriate segmental composition, spread from a mixed solution of methanol and chloroform on the water surface, were found to form a stable monolayer. It was also possible to prepare a blend monolayer by spreading a mixed solution of the

block polymer and PIBVE homopolymer ($M_n = 3900$, $M_w / M_n = 1.07$) on the water surface. The surface pressure (π)-area (A) isotherm for these surface monolayers measured at 10 °C are given in Fig.2, where A is the surface area per hydrophilic subchain in all cases. They exhibit a plateau region, suggesting that a structural change takes place on the water surface at a specific pressure. The stability of the surface monolayers was checked by measuring the time dependence of the occupied area at constant surface pressures. No change in the area was observed at both 20 mN/m (below the plateau) and 35 mN/m (above the plateau) for these surface monolayers. This means that the block copolymers and the blends form a stable monolayer without any structural relaxation at these surface pressures. The stability is also reflected on the collapse pressure as high as 45 mN/m.

With increasing number of IBVE units in the copolymer and those blended as a homopolymer, the plateau region expands; in Fig.3, A is plotted against n_T , where n_T is the total number of isobutyl vinyl ether (IBVE) units divided by the number of the hydrophilic subchains ($n_T = n$ for the block copolymer system without homopolymer). Below the plateau pressure ($\pi = 20$ mN/m), A is proportional to n_T . This proportionality suggests that only the hydrophobic segments of the block copolymer lie on the water surface and the hydrophilic segments have no effect on the surface area. This means that in the studied n_T range ($n_T \geq 48$), n_T is so large that the occupied surface area of the IBVE subchain is larger than that of the hydrophilic subchain in the water. From the n_T dependence of A (the slope of the line in Fig.3), the occupied area per IBVE unit at 20 mN/m (below the plateau) was determined to be 0.25 nm², which is almost equal to the area of IBVE unit evaluated from the space filling molecular model. This means that at low pressures, the IBVE segments essentially lie flat on the water surface, which is consistent with the n_T dependence of the layer thickness at low pressures (see below). On the other hand, A is almost constant at pressures above the plateau ($\pi = 35$ mN/m). This means that in this region, the hydrophobic segments make little contribution to the pressure, and the surface area is determined solely by the hydrophilic subchains, supposedly anchored to the interface, swollen and laterally compressed in the water phase.

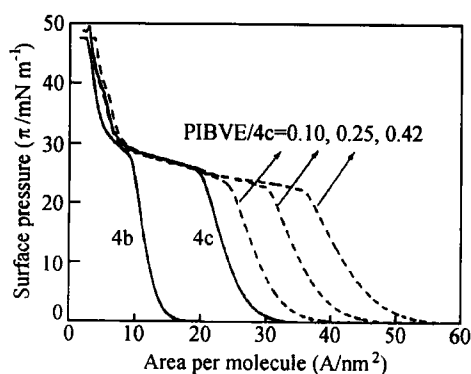


Fig.2 π - A isotherms of the block copolymers, 4b and 4c, and the blends, PIBVE/4c=0.10, 0.25, and 0.42

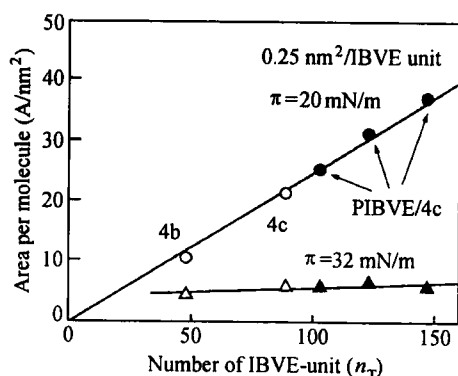


Fig.3 Plots of A vs. n_T for LB films of the block copolymers (open symbols), 4b and 4c, and the blends (closed symbols), PIBVE/4c=0.10, 0.25, and 0.42, measured at 20 and 35 mN/m

The surface monolayers were successfully transferred onto a substrate at 20 or 35 mN/m by the vertical dipping method. The transfer ratio, defined as the decrease of the water surface area after a dipping-in and lifting-up cycle divided by the substrate surface area, was evaluated to be approximately 2 in all cases, which indicates the formation of a Y-type multilayer film. Both below and above the plateau region, the total film thickness determined by SP spectroscopy^[5] and TEM^[6]

was proportional to the deposition number. This also confirms good transferability of the monolayers. Figure 4 shows the layer thickness d plotted against n_T , showing that d is apparently constant at 20 mN/m, while it increases linearly with increasing n_T at 35 mN/m.

The above arguments on the n_T dependence of A and d suggest the fine structure of the surface monolayers illustrated in Fig. 5; the IBVE segments, which essentially lie flat on the water surface at low pressures, aggregate at higher pressures, forming a thicker layer with hydrophobic and hydrophilic segments microphase-separated at the air-water interface. This is consistent with the fact that the surface pressure of the plateau is almost the same as the collapse pressure (22 mN/m) for the PIBVE homopolymer.

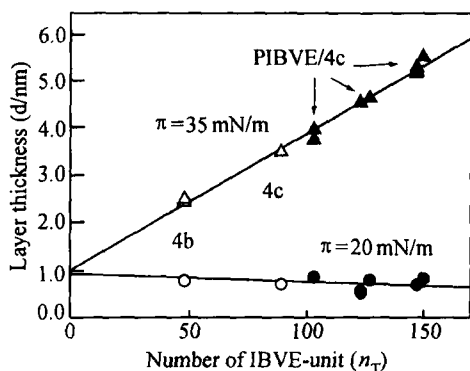


Fig.4 Plots of d vs. n_T for LB films of the block copolymers **4b** and **4c** (open symbols) and the blends PIBVE/4C (closed symbols) deposited at 20 and 35 mN/m

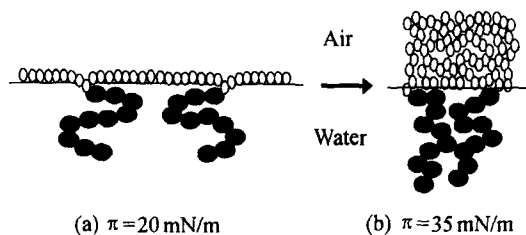


Fig.5 Schematic illustration of monolayers at the air-water interface

According to this model, the layer thickness extrapolated to $n_T = 0$ (about 1.0 nm; Fig.4) should correspond to that of the glucose residue-carrying hydrophilic segments: it is thus indicated that the LB film deposited at a high pressure consists of the hydrophilic layer with a thickness of 1.0 nm and the hydrophobic layer with a thickness proportional to n_T .

These results suggest a useful method to control the supramolecular structure of an ultrathin block copolymer film by blending it with a homopolymer. At lower pressures, it is possible to decrease the surface density of the hydrophilic segments in the water, and at higher pressures, where a microphase-separated structure is formed on the water surface (Fig. 5b), it is possible to adjust the hydrophobic layer thickness by blending the homopolymer.

EXPERIMENTAL

Glucose-substituted VE (IGVE) was prepared as reported previously^[1]. The IBVE was from a commercial source and purified by redistillation over calcium hydride before use. IBVE-HCl adduct $[\text{CH}_3\text{CH}(\text{O}i\text{Bu})\text{Cl}]$ was prepared as reported^[7]. Zinc iodide (Aldrich, purity > 99.99%) was used as received. Toluene and *n*-hexane (solvents) were purified by the usual methods and distilled twice over calcium hydride prior to use. Diethyl ether (anhydrous, Dojin) was distilled over calcium hydride before use.

The general procedure for the sequential living cationic copolymerization and subsequent deprotection has been previously reported^[2].

Measurements

Size exclusion chromatography (SEC) was carried out in tetrahydrofuran on a TOSOH HLC-802UR chromatograph equipped with polystyrene gel columns (TOSOH G2500H6 + G3000H6 +

G4000H6 and G2000H6 + G5000H6 + G6000H6; exclusion limit= 1.0×10^6 and 1.0×10^7 , respectively) and refractive index/ultraviolet dual-mode detectors. The number-average molecular weight (M_n) and polydispersity index (M_w/M_n) were estimated on the basis of a polystyrene calibration. $^1\text{H-NMR}$ spectra were recorded in CDCl_3 , D_2O , or CD_3OD on a Varian VXR-200 (200 MHz) instrument. The surface pressure (π) – area (A) isotherms were measured at a constant compression speed of $14 \text{ cm}^2/\text{min}$ and a subphase temperature of 10°C , after spreading the sample solution (0.01 wt%) on clean water, the solvent was left to evaporate off for 20 min. TEM images were obtained on a Hitachi H-300 (80-kV) electron microscope. The surface plasmon resonance curves^[8] were recorded using a He-Ne laser ($\lambda = 632.8 \text{ nm}$) and a prism coupler with the Kretschmann configuration^[10]. The detailed procedure of the measurements has been described elsewhere.

REFERENCES

- 1 Minoda, M., Yamaoka, K., Yamada, K., Takaragi, A. and Miyamoto, T., *Macromol. Symp.*, 1995, 99: 169
- 2 Yamada, K., Yamaoka, K., Minoda, M. and Miyamoto, T., *J. Polym. Sci. Part A: Polym. Chem.*, 1997, 35: 255
- 3 Yamada, K., Minoda, M. and Miyamoto, T., *J. Polym. Sci. Part A: Polym. Chem.*, 1997, 35: 751
- 4 Yamamoto, S., Tsujii, Y., Yamada, K., Fukuda, T., Miyamoto, T. and Ito, S., *Langmuir*, 1996, 12: 3671
- 5 The thickness of the built up film was evaluated by analyzing a plasmon curve obtained for a multilayered film deposited on a gold coated substrate^[8].
- 6 The cross-sectional image of a multilayered film deposited on a Pt-Pd coated carbon film was observed using the folding method^[9].
- 7 Kamigaito, M., Sawamoto, M. and Higashimura, T., *Macromolecules*, 1992, 25: 2587
- 8 Raether, H., “Surface Plasmons on Smooth and Rough Surfaces and on Grating”, Springer, Berlin, 1988
- 9 Itoh, T., Tsujii, Y., Suzuki, H., Fukuda, T. and Miyamoto, T., *Polym. J.*, 1992, 24: 641
- 10 Kretschmann, E., *Opt. Commun.*, 1972, 6: 185