Preparation and Permeability of a Block Copolymer Dialysis Membrane by Poly(γ-methyl-L-glutamate) and Poly(ethylene glycol)

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ABSTRACT: The block copolymer (PMLG-*b*-PEG) of poly(γ-methyl-L-glutamate) (PMLG) and isocyanate-terminated poly(ethylene glycol) was synthesized. Membranes were prepared by casting 2% 1,2-dichloroethane solutions of the polymer onto a glass plate and by evaporating the solvent at room temperature. The structure and microdomain morphologies of the membranes were observed with IR spectroscopy and scanning electron microscopy, respectively. Measurement of the contact angles of deionized water on polymer membrane surfaces was made. The mechanical properties of the membranes were also determined. The permeability of the PMLG-*b*-PEG and PMLG membranes toward urea and creatinine was studied in a dialyzer. In all cases, the block membranes showed improved permeability toward those solutes in comparison with the PMLG membranes. The permeation coefficients of urea, through the PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes, were about 2.3 and 3.2 times larger than that of PMLG membranes, and for creatinine through PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes, were about 1.0 and 2.0 times larger than that of PMLG membranes. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci 68: 75–82, 1998

Key words: PMLG; PMLG-*b*-PEG; dialysis rate; permeation coefficient

INTRODUCTION

Block copolymers of the A–B diblock and A–B–A triblock types are of special interest from the standpoint of molecular designing. These copolymers are capable of forming organized structures (i.e., microheterophase structures) when cast from solutions, and the resulting membranes are expected to exhibit specific functionalities. Chen et al.[1] studied the mechanical properties and water permeability of A–B–A triblock copolymer membranes consisting of poly(γ-benzyl-L-glutamate) as the A component and polybutadiene as the B component. Otsuki et al.[2] reported a detailed study on the synthesis of polyoxyethylene–polyamide multiblock copolymers by a diisocyanate method. The solubility, thermal behavior, and mechanical properties of the multiblock copolymers were also described. Shi et al.[3] investigated the block copolymers of PMLG and isocyanate-terminated polyester. The block copolymer membranes showed permeability for Na⁺, K⁺, and Mg²⁺ at moderately low concentration. However, the PMLG membrane shows no permeability for alkali ions. In this article, we investigated the effect of different molecular weights of PEG in PMLG-*b*-PEG on the permeabilities of solutes through PMLG-*b*-PEG membranes.

EXPERIMENTAL

Materials

L-Glutamic acid was manufactured by the Hefei Monosodium Glutamate Factory, and before use,

L-glutamic acid was dissolved in boiled water and the solution was cooled. At the same time, an appropriate amount of ethanol was added to the solution. The crystals of L-glutamic acid formed were collected on a No. 4 glass filter and then dried *in vacuo.*

Poly(ethylene glycol) (PEG) was supplied by the Nanjing Synthesis Resin Factory, and before use, the PEG was dehydrated using molecular sieves of type A. Titration by the Karl Fisher method showed that it did not retain more than 0.1% water. Reagent-grade 2.4-diisocyanatoluene was produced by the First Shanghai Chemical Reagent Factory.

Synthesis of Poly(γ-methyl-L-glutamate) (PMLG)

PMLG was prepared by the polymerization of γ-methyl-L-glutamate–N-carboxy-2-amino acid anhydride (MLG–NCA) in dichloroethane using triethylamine as the initiator.[4] The product was recrystallized from dichloroethane/methanol and then extracted with methanol using a Soxhlet extractor to remove low molecular weight polymers. The PMLG molecular weight, $M_n = 177,000$, was determined by GPC.

Isocyanate-terminated Poly(ethylene glycol) (PEG)

PEG with a molecular weight of 300 (PEG300) and 1000 (PEG1000) were used this work. Six grams (0.02 mol) of PEG300 (or PEG1000) and 6.96 g (0.04 mol) of 2,4-diisocyanatotoluene were added in 60 mL of dichloroethane (DCE) to a flask and the reaction was carried out, protected with nitrogen gas at 40°C, for 5 h. The α,ω-isocyanate-terminated PEG (ITPEG) solution was used for the following synthesis:

Preparation of the Block Copolymer

The designed amount of PMLG was dissolved in DCE and the resultant solution was added to the above-mentioned solution in a flask and the block copolymerization was carried out under a nitrogen atmosphere at 70°C for 8 h. The reaction solution was extracted with toluene to remove any remaining traces of ITPEG. The block copolymer was precipitated by cooled methanol and then dried *in vacuo* at 60°C.

Preparation of Membrane

The membranes were made from about 3% (wet %) solution in DCE. The casting solution was poured onto a glass plate and the solvent evaporated at room temperature. Membranes of 20–40 μm in thickness were obtained.

Structure and Morphology

The structures of the membranes were studied by a VECTOR22 FTIR recording spectrophotometer.

Wide-angle X-ray diffraction (WAXD) profiles were determined by a Rigaku D/MAX-rA X-ray diffractometer. ^{1}H-NMR spectra of PMLG and PMLG-*b*-PEG polymers were determined by a Varian EM-360L 60 MHz spectrometer. The morphology of the membrane was observed by a Hitachi X-650 scanning electron microscope (SEM).

Contact Angle

The measurement of the contact angles of deionized water on the copolymer membrane surfaces was made with a Modle JY-82 contact angle technique at 25°C. According to the equation of Achimi et al.,[5] the γ_p, γ_{pw}, and W_{pw} are obtained from

$$\gamma_p = \frac{\gamma_w(1 + \cos\theta)^2}{4} \tag{1}$$

$$\gamma_p = \gamma_{pw} + \gamma_w \cos\theta \tag{2}$$

$$\gamma_{pw} = \gamma_p + \gamma_w - W_{pw} \tag{3}$$

where θ, γ_p, γ_{pw}, and W_{pw} are the contact angle, surface free energy, interfacial free energy, and work of adhesion for PMLG and PMLG-*b*-PEG membranes, respectively. γ_w is the surface free energy of water (72.8 er cm^2). The values of θ obtained in this study are averages of at least five membranes prepared independently.

Mechanical Properties

The tensile-strength measurements of the membranes in the dry and wet states were carried out at room temperature with an Instron-1122 universal electronic tensile strength machine. The size of the membranes was 100×10 mm.

Permeability Experiments

In this permeation, initial concentrations of the solutes were $[\text{urea}]_0 = 8.3 \times 10^{-3}$ mol/L, $[\text{creatinine}]_0 = 1.8 \times 10^{-3}$ mol/L, $[\text{Na}^+]_0 = 0.1$ mol/L, and $[\text{Ca}^{2+}]_0 = 0.1$ mol/L.

The PMLG-*b*-PEG membrane (or PMLG mem-

brane) was fixed in a quartz dialysis cell as a partition membrane. An aqueous solution with the initial concentration of the solute was put into the left compartment of the cell and deionized water was put into the right compartment. The cell was immersed in a constant temperature bath set at 30°C. The cells were not stirred during the permeation test.

The concentration of urea (or creatinine) in both the left and right cells was determined by UV spectroscopy. The concentrations of Na^+ and Ca^{2+} were measured with an atomic absorption spectrophotometer (IL951 Model).

The solute permeability coefficient P was calculated from the following equation, which was obtained from a mass balance equation of Kim et al.[6]; that is,

$$P = \frac{-d}{A(1/V_1 + 1/V_2)t} \ln\left[\left(1 + \frac{V_1}{V_2}\right)\frac{C_t}{C_0} - \frac{V_1}{V_2}\right] \quad (4)$$

where V_1, V_2, A, d, C_0, and C_t were the volumes of the concentrate and the dilute compartments, membrane area, thickness, and concentrations in the concentrate compartment at times 0 and t, respectively.

Water Content

The PMLG and PMLG-*b*-PEG membranes were immersed in distilled water in a beaker at room temperature for 24 h, and water on the membrane surfaces was blotted with filter paper. Then, the water content of the membrane weight (Ww) was determined. By drying the membrane at 60°C under a vacuum (10 mmHg) for 7 h, giving the dried membrane weight (Wd). The water content was calculated by the following equation:

$$\text{Water content}(\%) = (Ww - Wd)/Wd \times 100 \quad (5)$$

RESULTS AND DISCUSSION

Structure of the Membrane

Shoji et al.[7] reported that the IR characteristic bands of PMLG for the α-helix are 1656 and 1545 cm^{-1} and those of the β-sheet form are 1630 and 1530 cm^{-1}. Masuda[8] reported that the position of the amide V absorption band for the α-helix structure of PMLG molecular chains is 610–620 cm^{-1}.
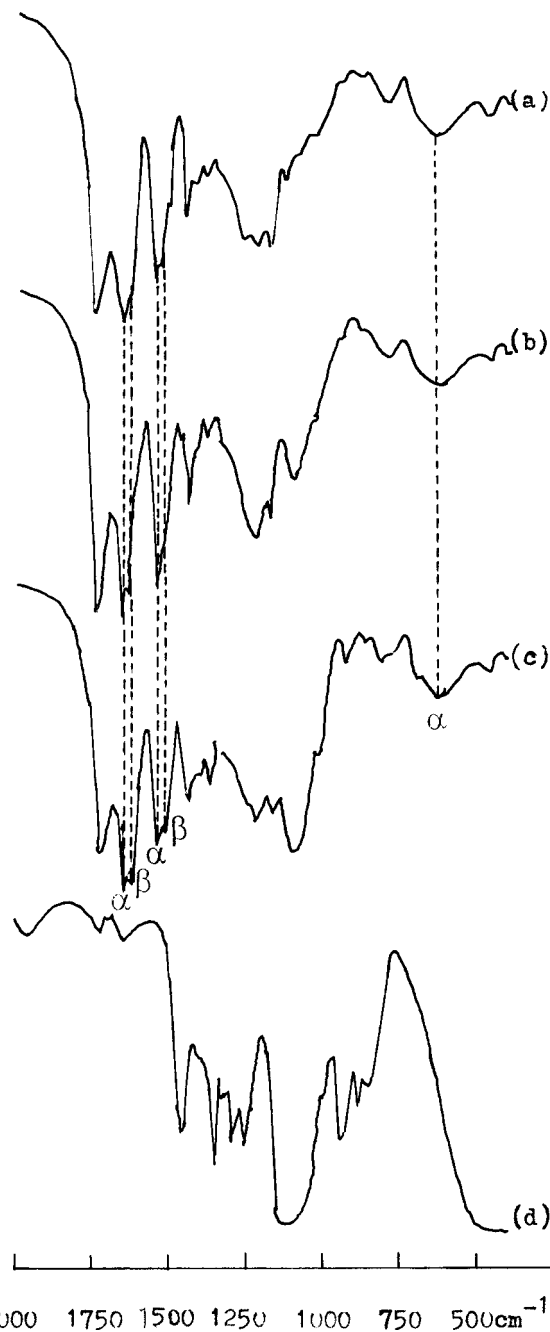
Figure 1 IR spectra of PMLG, PMLG-*b*-PEG300, PMLG-*b*-PEG1000, and PEG400: (a) PMLG; (b) PMLG-*b*-PEG300; (c) PMLG-*b*-PEG1000; (d) PEG400.

Figure 1 shows the IR spectra for PMLG, PMLG-*b*-PEG, and PEG400 polymers. In Figure 1(a), the positions of the amides I, II, and V absorption bands in the IR spectrum of PMLG were substantially identical with those reported for PMLG by refs. 7 and 8. From Figure 1(b,c), it is seen that the positions of the amides I, II, and V absorption bands of the PMLG-*b*-PEG300 and

PMLG-*b*-PEG1000 block copolymers are consistent with those in Figure 1(a). The IR spectra of Figure 1(a–c) are compared; it is seen that in the spectra of Figure 1(b,c) one new absorption band appears, at broader 1120 cm^{-1} (C—O—C), and the broader strong band at 1120 cm^{-1} increased with increasing molecular weight of PEG. The positions of two new absorption bands are in accord with the absorption band at 1120 cm^{-1} (C—O—C) in Figure 1(d). The above-mentioned results prove that the PEG component was blocked onto the PMLG molecular chain and the α-helix and β-form structures of PMLG molecular chains coexist in the PMLG-*b*-PEG copolymers.

The WAXD patterns for the PMLG and PMLG-*b*-PEG membranes cast from DCE are shown in Figure 2. In Figure 2(a), one main reflection corresponding to the intermolecular spacing of the α-helical chains has a spacing of 11.79 Å [9] for the PMLG membrane. When the WAXD patterns of Figure 2(a–c) are compared, it is seen that in the spectra of Figure 2(b,c) two diffraction peaks appear, one equatorial at about 10.78 Å and one meridional at about 4.40 Å. These values are in accord with the literature [9] values. This result indicates the transformation from the α-helical conformation to the β-pleated conformation of the PMLG molecular chain in the PMLG-*b*-PEG block copolymer. In addition, we found that the PMLG block portion in the PMLG-*b*-PEG membranes has less crystallinity and the orientation of the α-helical conformation is inferior to that in PMLG.

^{1}H-NMR spectra of PMLG and PMLG-*b*-PEG polymers in CDCL$_3$ are shown in Figure 3. In Figure 3, on the basis of the spectrum in Figure 3(a) of PMLG, peaks are assigned to β-CH$_2$ (2.25 ppm), γ-CH$_2$ (2.55 ppm), α-CH (3.77 ppm), —OCH$_3$ (3.80 ppm), and —(OCH$_2$CH$_2$) (4.00 ppm) protons, respectively, when the NMR spectra of Figure 3(a) are compared with 3(b,c), it is seen that in the spectra of Figure 3(b,c), two new peaks appear, one at 4.00 ppm (OCH$_2$CH$_2$) and one at 7.33 ppm (ϕH in the 2,4-diisocyanatotoluene molecule). This result proves that PEG is blocked onto the PMLG molecular chains.

Morphology of Membrane

Figure 4 shows scanning electron micrographs of the PMLG and PMLG-*b*-PEG300 and PMLG-*b*-PEG1000, membranes. When the scanning electron micrographs of Figure 4(a) are compared with 4(b,c), it can be seen that the superhelix structures of the molecule PMLG were distributed in the PMLG-*b*-PEG300 and PMLG-*b*-PEG1000
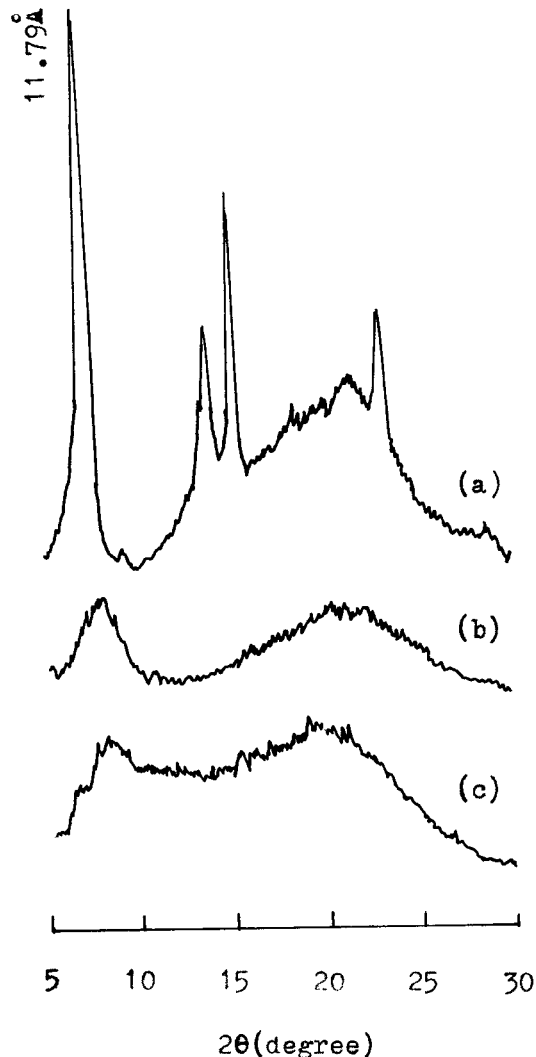

Figure 2 Wide-angle X-ray diffraction profiles of PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes: (a) PMLG membrane; (b) PMLG-*b*-PEG300 membrane; (c) PMLG-*b*-PEG1000 membrane.

copolymer membranes. The superhelix structures of PMLG are several helix structural units joined to form a bunched chain, and then two bunched chains are twisted together like a rope.[9] The interspace of two bunched chains of the PMLG in the block copolymer increases with increasing molecular weight of the PEG [see Fig. 4(b,c)].

Contact Angle

To obtain more information on the outermost surfaces, measurement was made of the contact angles θ of deionized water for the PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membrane surfaces, as shown in Table I. From Table I, it can be found that the contact angles for the PMLG-*b*-
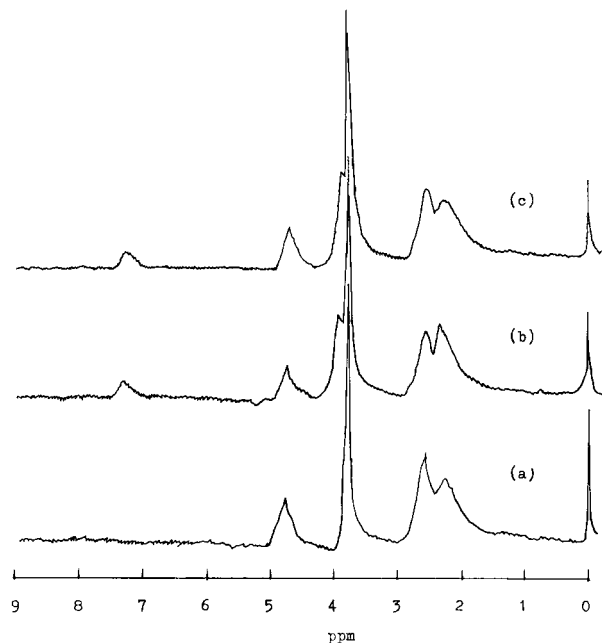
Figure 3 ^{1}H-NMR spectra of PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 polymers in CDCl$_3$: (a) PMLG; (b) PMLG-*b*-PEG300; (c) PMLG-*b*-PEG1000.

PEG300 and PMLG-*b*-PEG1000 block copolymers were seen to be smaller than for PMLG, indicating better wettability. This may be due to PEG components being more hydrophilic than PMLG components in the PMLG-*b*-PEG block copolymer. The change of contact angles was due to different contents of CH$_2$CH$_2$O units in PMLG-*b*-PEG300 and

PMLG-*b*-PEG1000 membranes: The content of CH$_2$CH$_2$O units of the PMLG-*b*-PEG1000 copolymer was much greater than that of the PLG-*b*-PEG300 copolymer. Therefore, the wettability of PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes by water is better than that of the PMLG membrane. The contact angles of the copolymer membranes had the following order:

$$PMLG > PMLG\text{-}b\text{-}PEG300 > PMLG\text{-}b\text{-}PEG1000$$

Using to the values of the contact angles, the surface free energy (γ_p), the interfacial free energy (γ_{pw}), and the adhesive work (w_{pw}) of PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes were calculated by eqs. (1–3). These results are listed in Table I. From Table I, it can be seen that increasing the molecular weight of PEG in the block copolymer gives a gradually increasing γ_p, decreasing γ_{pw}, and increasing W_{pw} for PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membrane surfaces.

Permeability

Figure 5 indicates the change in concentration of urea through the PMLG and PMLG-*b*-PEG membranes. The thickness and permeation area of the membranes are listed in Table II. In Figure 5, it can be found that the average permeation rates of urea through PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes are 1.27×10^{-4}
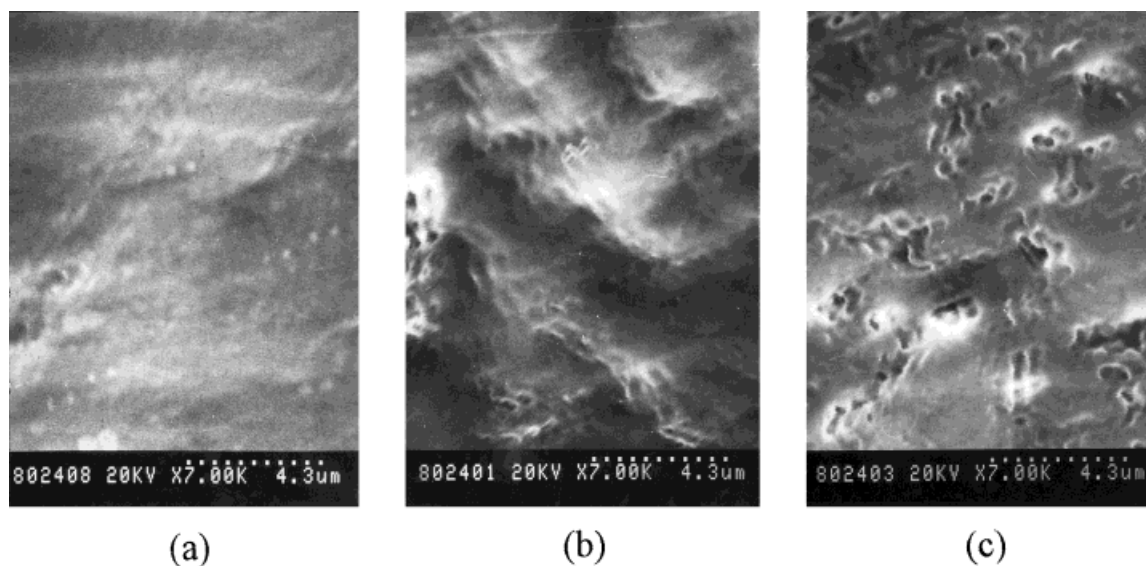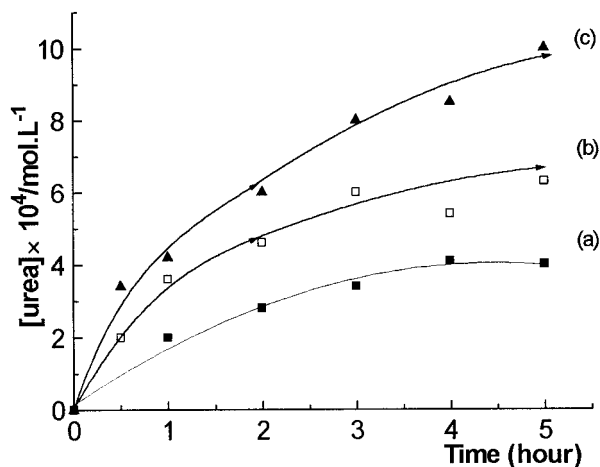

Figure 4 Scanning electron micrographs of PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes: (a) PMLG membrane; (b) PMLG-*b*-PEG300 membrane; (c) PMLG-*b*-PEG1000 membrane.

Table I   Contact Angles, Surface Free Energies, Interfacial Free Energies, and Adhesional Works of PMLG and PMLG-*b*-PEG Membranes

Polymer	θ (degree)	γ_p (erg/cm^2)	γ_{pw} (erg/cm^2)	W_{pw} (erg/cm^2)
PMLG	66	36.4	6.2	103.0
PMLG-*b*-PEG300	59	41.9	4.2	110.5
PMLG-*b*-PEG1000	48	50.6	2.0	121.4

mol/h, 2.94×10^{-4} mol/h, and 4.16×10^{-4} mol/h, respectively. The ratios of the permeation rates of urea through the PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes to that through the PMLG membrane are 2.3 and 3.3, respectively. These results are possibly due to water clusters in the block copolymer membranes being formed by hydrogen bonding between CH_2CH_2O in the PMLG-*b*-PEG copolymer and water. The solutes permeate only into the water region in the copolymer. The water clusters may play a significant role in helping the solutes to diffuse into the copolymer membranes. The poor permeability of the PMLG membrane was due to the absence of CH_2CH_2O units in the copolymer chains: The greater the content of CH_2CH_2O units in the copolymer chains, the more hydrophilic is the membrane and the easier is the diffusion of urea through the copolymer membrane. So, the permeability of the PMLG-*b*-PEG1000 membrane was much higher than that of the PMLG-*b*-PEG300 membrane.

Figure 6 shows that the permeation rates of creatinine through the PMLG, PMLG-*b*-PEG300,

Figure 5 Change in the concentration of urea through PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes in a dialysis cell at 30°C. [Urea]$_0$ = 8.3×10^{-3} mol/L. (a) PMLG membrane; (b) PMLG-*b*-PEG300 membrane; (c) PMLG-*b*-PEG1000 membrane.

and PMLG-*b*-PEG1000 membranes increased with time. The thickness and permeation area of the membranes are listed in Table II. When the permeation curves of Figure 6(a–c) are compared, it is seen that the permeability of creatinine through the PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes is improved compared to that through the PMLG membrane. This result may be due to the hydrophilic domains of CH_2-CH_2O units in the PMLG-*b*-PEG1000 copolymer chains being larger than those of the PMLG-*b*-PEG300 chains, making easier the diffusion of creatinine through the block copolymer membrane. Therefore, the permeation rate of creatinine through the PMLG-*b*-PEG1000 membrane is greater than for the PMLG-*b*-PEG300 membrane, which itself is greater than for the PMLG membrane.

The structure of the α and β conformations of PMLG is not known in atomic detail,[10] but it seems to be clear that in the α conformation the PMLG is intramolecular NH and CO hydrogen-bonded into an α-helix, while in the β conformation, it is intermolecular NH and CO hydrogen-bonded into a pleated sheet structure. Under these conditions, water molecules are not incorporated into the intramolecular and intermolecular hydrogen bonding of the α-helix and β-pleated sheet of the PMLG backbone; thus, the PMLG membrane showed no permeability for Na$^+$ and Ca^{2+}.

In addition, the interfacial zone of the microheterophase structure of the PMLG-*b*-PEG block molecular chain is made up of the coiled peptide residues near the end of the PMLG chain and the terminal residues of amine-terminated PEG. The NH, CO, and CH_2CH_2O groups in the interfacial zone and the PEG intermolecules can bind water through hydrogen bonds. Thus, the amount of the bonded water molecules should be related closely to the volume of the interfacial zone and the PEG intermolecules. These bonded water molecules in the PMLG-*b*-PEG membrane could act as a carrier, which prompted the permeation of ions through the PMLG-*b*-PEG membranes.

Table II   Permeation Coefficients of PMLG and PMLG-*b*-PEG Membranes

| Polymer | Water Content (%) | Tensile Strength (MPa) | | Elongation at Break (%) | | Thickness (μm) | Permeation Coefficients (cm^2/s) | | | |
		Dry	Wet	Dry	Wet		Urea $\times 10^7$	Creatinine $\times 10^8$	Na$^+$ $\times 10^6$	Ca^{++} $\times 10^6$
PMLG	1	20.4	14.0	67	62	28	6.8	3.4	0	0
PMLG-*b*-PEG300	5	14.0	11.2	75	81	36	15.7	5.3		
PMLG-*b*-PEG1000	15	6.6	4.9	115	126	38	21.5	6.8	1.5	1.1

The area of all membranes was 5.31 cm^2.

An example of the time change of concentration of Na$^+$ and Ca^{2+} is shown in Figure 7. The average permeation rates of Na$^+$ and Ca^{2+} through the PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes are 0×10^{-3} mol/h, 4.2×10^{-3} mol/h, and 2.5×10^{-3} mol h, respectively. In Figure 7, the permeation rate of Na$^+$ is greater than that of Ca^{2+}. This result is ascribed to the ion radius of Na$^+$ being less than that of Ca^{2+}.

The mechanical properties of PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes and the permeation coefficients of urea, creatinine, Na$^+$, and Ca^{2+} through the PMLG and PMLG-*b*-PEG membranes are listed in Table II. Also in this table are the ratios of the permeation coefficients of urea through the PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes to those through the PMLG membrane which are 2.3 and 3.2, respectively. The ratios of the permeation coeffi-
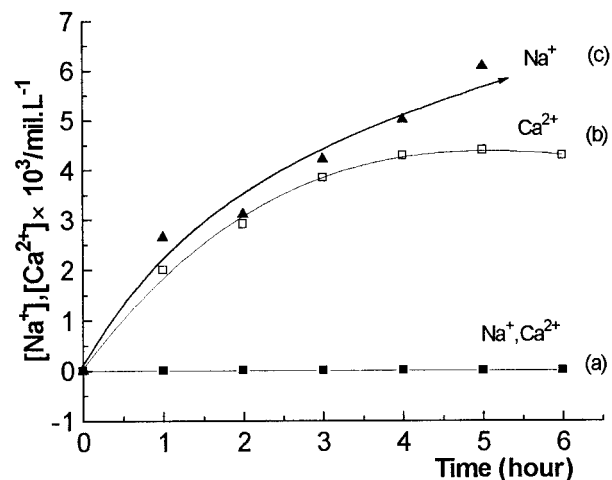
cients of creatinine through PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes to that through the PMLG membrane are 1.6 and 2.0, respectively.

CONCLUSIONS

1. IR, WAXD, and NMR spectra proved that the 300 and 1000 molecular weights of PEG were blocked on the PMLG molecular chains.
2. The scanning electron micrographs showed the molecular superhelix structures of PMLG in the PMLG-*b*-PEG membrane.
3. The changes of the contact angles were due to different contents of CH$_2$CH$_2$O units in the PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 copolymer membranes. Therefore, the contact angles of the copolymer membranes had the following order:
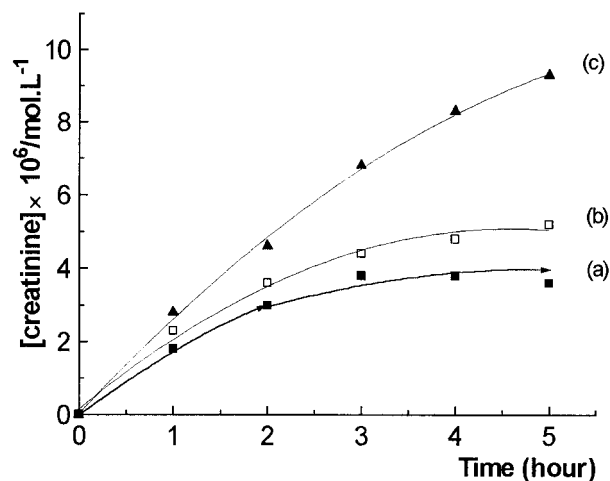
Figure 6   Change in the concentration of creatinine through PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes in a dialysis cell at 30°C. [Creatinine]$_0$ = 1.8×10^{-3} mol/L. (a) PMLG membrane; (b) PMLG-*b*-PEG300 membrane; (c) PMLG-*b*-PEG1000 membrane.

Figure 7   Change in the separation concentration of mixed Na$^+$ and Ca^{2+} through PMLG and PMLG-*b*-PEG1000 membranes in a dialysis cell at 30°C. (a) PMLG membrane; (b, c) PMLG-*b*-PEG1000 membrane. [Na$^+$]$_0$ = 0.1 mol/L; [Ca^{2+}]$_0$ = 0.1 mol/L.

PMLG $>$ PMLG-*b*-PEG300

$>$ PMLG-*b*-PEG1000

4. The ratio of the permeation rates of urea through the PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes to that through the PMLG membrane were 2.3 and 3.3, respectively.

5. The permeation coefficients of creatinine through the PMLG-*b*-PEG300 and PMLG-*b*-PEG1000 membranes were 1.6 and 2.0 times larger than that through the PMLG membrane, respectively.

6. The average permeation rates of Na$^+$ and Ca^{2+} through the PMLG, PMLG-*b*-PEG300, and PMLG-*b*-PEG1000 membranes were 0×10^{-3} mol/h, 4.2×10^{-3} mol/h, and 2.5×10^{-3} mol/h, respectively.

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