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In situ modification on cellulose acetate hollow fiber membrane modified with phospholipid polymer for biomedical application

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Abstract

The hollow fiber membrane (HFM) made from synthetic polymers need improvement in terms of hemocompatibility or biocompatibihty, for use in the medical field. In this study, cellulose acetate (CA) HFM modified with the water-soluble amphiphilic 2-methacryloyloxyethyl phosphorylcholine (MPC) copolymer (poly (MPC-co-*n*-butyl methacrylate) (PMB80, MPC:BMA = 80:20 (mol%)) was prepared by a dry-jet wet spinning process. The PMB80 was coated on the CA HFM surface in situ during the phase inversion of the dope solution by using a PMB80 solution as an inner coagulant. The CA/PMB80 coating HFM showed no physical structure changes in comparison with the CA HFM prepared using the same preparative conditions. The structure and permeability of the CA/PMB80 coating HFM was controllable by changing the preparative conditions. From the results of the X-ray photoelectron spectroscopic (XPS) observations, the amount of modification was changed with the concentration of PMB80 in the coagulant. The XPS signal attributed to the phosphorus atom of the PMB80 remained even after 1 month of rinsing with distilled water. Also, the CA/PMB80 coated HFM showed good permeability and a low membrane fouling property in comparison with the non-modified CA HFM, due to the low protein adsorption property of the PMB80.
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Keywords: Cellulose acetate membrane; Protein adsorption; Membrane fouling; Phospholipid polymer; Hollow fiber membrane

1. Introduction

Hollow fiber membranes (HFMs) have been used in many biological purification systems, and their applicable extent has been broadened in the medical field with the improvement of biomedical technology. Some of the HFMs made from synthetic polymers, such as cellulose acetate (CA), polysulfone (PSf) and polyacrylonitrile (PAN), are also widely used in the biomedical field due to their good performance in permeability and mechanical stability. However, the protein adsorption on these HFM surfaces can induce a decreasing water and solute permeability and a series of biochemical reactions. Also, they cause many complement problems or decrease in their performance during medical therapy (the well known

example is hemodialysis) which has an impact on the patient's life and the quality of life directly or indirectly with long term therapy. Therefore, the protein adsorption on the HFM surface should be reduced for obtaining biocompatibility, particularly hemocompatibility [1–5].

Surface modification is a widely used method for the improvement of the biocompatibility and hemocompatibility of polymer materials for medical devices. A large number of membranes surface modifications have been suggested that are modified with some hydrophilic and hydrophobic polymers, and other materials with functional groups, such as hydroxyl groups, amino groups, and phosphorylcholine (PC) groups. Among them, the PC group-containing materials which have enhanced the biocompatibility and many clinical benefits in the application of medical devices have been demonstrated, because the fundamental concept of the PC group-containing polymers were inspired by the biomem-

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brane surface which is mainly constructed of a neutral phospholipid [6–13].

Since a bioinspired polymer, 2-methacryloyloxyethyl phosphorylcholine (MPC), and its copolymers with various molecular structures was synthesized [14,15], many studies have demonstrated that their polymers mildly interact with proteins and cells on the surfaces. The series of MPC polymers could improve the biocompatibility and hemocompatibility of medical devices by surface modification [15–21]. Also, we have reported that blending with the MPC copolymer is an effective treatment for both improving hemocompatibility and reducing protein fouling on the CA flat membranes and HFMs blended with the MPC copolymer in our previous study [22–24].

In this study, we prepared the CA HFM modified with water-soluble amphiphilic poly (MPC-co-n-butyl methacrylate) polymers (PMB80) during the dry-jet wet spinning process using the PMB80 solution as an inner coagulant solution. The performance and characteristics of the CA/PMB80 HFM such as the chemical surface property, protein adsorption resistance property, and its performance in permeability were evaluated. Moreover, the stability of the PMB80 coated on the CA HFM was also investigated in order to evaluate potential in practical biomedical applications.

2. Materials and methods

2.1. Materials and HFM fabrication

The CA (acetylation degree: 39.8%, $M_w = 1.0 \times 10^5$) powder was purchased from the Kanto Chemical Co., Tokyo, Japan. The PMB80 (MPC unit composition = 80 mol%, water-soluble, $M_w = 1.5 \times 10^6$) was prepared by a conventional radical copolymerization technique of MPC and BMA [14,15]. The chemical structure of the PMB80 is shown in Fig. 1.

Twenty weight percent of CA solution was prepared from the solvents such as dimethylsulfoxide (DMSO), acetone and 2-propanol. The compositions of the solutions are shown in Table 1. The HFM was fabricated using a double injection nozzle with an annular spinneret by the dry-wet spinning process. The spinneret diameters of the inner and outer tubes were 1.5 and 2.0 mm. The polymer solution was pumped at a constant speed (Table 2) while an inner coagulant (dis-
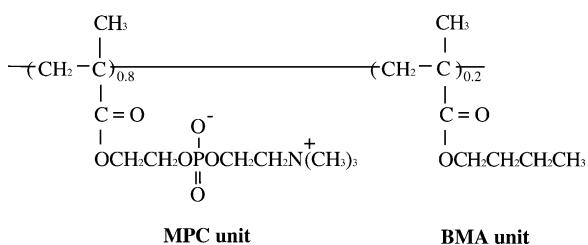
Table 1
Composition of the polymer solutions

Abb.	Composition (wt.%)				
	Polymer	Solvent			
	CA	DMSO	Acetone	2-Propanol	Water
CAI	20	50	15	15	0
CAII	20	66.5	0	13.5	0
CAIII	20	66.5	0	12.5	1

tilled water or PMB80 solution) was pumped at a constant speed (10 mL/min) using a metering pump. After leaving the spinneret, the nascent HFM freely dropped by gravity into an outer coagulant (2500 mL of distilled water) bath. The CA/PMB80 coating HFM was prepared using the PMB80 solution (from 1 to 0.1 wt.%) as the inner coagulant during which the CA dope solution was extruded from the spinneret (Fig. 2). The preparative conditions for the CA/PMB80 HFMs are summarized in Table 2. After preparation of the HFMs, they were rinsed with 1500 mL of distilled water for 48 h to remove solvent, and the distilled water was changed at least three times during this period. The HFMs were stored in distilled water before use.

2.2. Morphology observation and surface characterization

The obtained HFMs were freeze-dried in vacuo. The morphologies of the HFMs were observed with a scanning electron microscope (SEM, SM-200, Topcon, Tokyo, Japan) after gold coating with an ion coater (IB-3, Eiko Co., Ibaraki, Japan). The chemical composition of the HFM surfaces was analyzed using an X-ray photoelectron spectroscope (XPS, AXIS-HSi, Shimadzu/KRATOS, Kyoto, Japan). The releasing angle of the photoelectrons was fixed at 90°. The tensile strength of the HFMs was measured using an autograph (STA-1150, ORIENTEC, Tokyo, Japan) at a 2 mm/min crosshead speed.
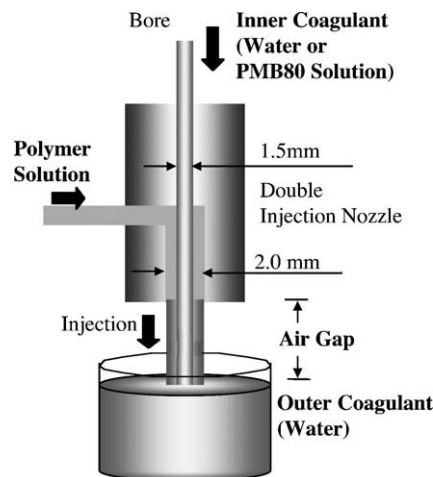

Fig. 1. Chemical structure of PMB80.

Fig. 2. Preparation of HFM by dry-jet wet spinning process.

Table 2
Preparation conditions of CA and CA/PMB80 HFMs

Abb.	Polymer solution feed speed (mL/min)	Polymer solution temp. (°C)	Inner coagulant temp. (°C)	Outer coagulant temp. (°C)	Air gap length (cm)
CAI	1.5	23	20	25	5
CAI/PMB80	1.5	23	20	25	5
CAII	1.2	35	20	35	12
CAII/PMB80	1.2	35	20	35	12
CAIII/PMB80	1.2	23	20	50	12

2.3. Permeability characterization

In order to determine the permeability of the HFM, a single hollow fiber permeability test module was prepared. The HFM was mounted through the external channel made from polypropylene T-tube connectors and a silicone tube, which test module was already reported in the previous study [24]. The test length of the HFM was set at 10 cm.

For characterization of the solute transport of the HFMs, fluorescein (molecular weight (MW) = 3.3×10^2), cytochrome c (MW = 1.2×10^4), bovine albumin (MW = 6.6×10^4), fluorescein isothiocyanate (FITC)-dextran (MW = 7.7×10^4), bovine γ-globulin (MW = 1.5×10^5) and blue-dextran (MW = 2.0×10^6) were used as permeation solutes. The concentrations of these solutes in the feed solution were adjusted to 0.125 mmol/L, 2.0×10^{-2} g/dL, 4.5×10^{-2} g/dL, 2.0×10^{-2} g/dL, 2.0×10^{-2} g/dL and 1.0×10^{-2} g/dL in a phosphate buffer solution (PBS, pH 7.4), respectively. The amount of permeated solute was determined using an ultraviolet/visible (UV) spectrophotometer (V-560, JASCO, Tokyo, Japan) after each experiment.

The permeability experiments were performed using the same process described in the previous study [24]. To compare the permeability and fouling property of the HFMs, the internal and external lumen flow rate of the HFM were set at a constant in each experiment flow condition. The flow conditions are shown in Table 3. In this study, the cross-flux ratio (F_p/F_{in} was set in very low values that remained below 0.05 in all experiment. The overall diffusive mass-transfer coefficient (K_o) was calculated using the following equation after 1 h dialysis condition experiment [24,25]:

$$K_o = \frac{J_s}{\Delta C\, A} \text{ (cm/s)} \tag{1}$$

$$J_s = Q_{ext} \frac{C_{ext}}{\Delta T} \text{ (g/s)} \tag{2}$$

where J_s is the transmembrane solute flux (Q_{ext} and C_{ext} are the volume and concentration of the external loop solution); A is the log mean membrane surface area ($2\pi(r_2 - r_1)z/\ln(r_2/r_1)$), where r_2 and r_1 are the outer and inner radii, respectively; z is the length of HFM; and AC is the bulk solution concentration difference between the inside and the outside of the HFM.

The observed solute rejection rate (R_o) was experimentally determined using the following equation after 2 h of filtration:

$$R_o = \left(\frac{1 - C_p}{C_f} \right) \tag{3}$$

where C_p and C_f are the permeated and feed solution concentrations.

The water flux of the HFM was measured in the filtration condition when the external loop was filled with distilled water.

$$J_w = \frac{Q_{ext}}{\Delta T} \text{ (g/h)} \tag{4}$$

To determine the membrane fouling property during the permeation experiment, the changes in J_s of CA and CA/PMB80 for cytochrome c were measured during 10 h of diafiltration with a protein mixture solution of albumin (4.5×10^{-2} g/dL) and cytochrome c (2.0×10^{-2} g/dL).

2.4. Characterization of protein adsorption

A protein adsorption test was performed on the CA and CA/PMB80 HFMs using the same process described in the previous study [24]. The HFMs were contacted with each protein solution at 37 °C for 3 h. A protein analysis kit (Micro BCA protein assay reagent kit, #23235, Pierce, Rockford, IL, USA) based on the bicinchoninic acid (BCA) method was used to determine the amount of protein adsorption on 1 cm of the HFM (1 unit). The mean value of the triplicate samples for each polymer was calculated using the standard

Table 3
Flow rate conditions of dialysis, filtration, and diafiltration at a HFM permeability characterization experiment

Abb.	Internal lumen flow rate (F_{in}) (mL/h)	External lumen flow rate (F_{ext}) (mL/h)	Transmembrane flow rate (F_p) (mL/h)
Dialysis	0	0	0
Filtration	45	None	0.1–1.0
Diafiltration	45	160	0.1–0.7

deviation, and the statistical error was calculated using the Student's *t*-test.

3. Results

3.1. Morphologies of the CA/PMB80 HFMs

The morphologies of the CA and CA/PMB HFM obtained with the same preparative conditions exhibit almost the same physical structure. The differences in physical structure between the CA and CA/PMB80 HFM were not observed in the SEM observation. The physical structures of the CA/PMB80 HFMs were largely changed with changes in the preparative conditions such as solvent composition, air gap and the temperature of the coagulant. Therefore, we could control the cross-sectional structure and porosity of the CA/PMB80 HFM in a similar manner to the CA/PMB30 blend HFMs [23]. The CAI/PMB80 prepared in a short falling time (the air gap length = 5 cm and dope polymer feed speed = 1.5 mL/min) showed a double skin layer structure where the dense skin layer was on the outer and inner sides of the HFM. However, both the CAII/PMB80 and CAIII/PMB80 prepared in a longer falling time (the air gap length = 12 cm and the dope polymer feed speed = 1.2 mL/min) showed a single skin layer structure

where the dense skin layer was in the inner side, and the porosity increased below the skin layer to the outer side of the HFM. The porosity of the outer side of the HFM was dependent upon the temperature of the outer coagulant. The acetone or water of the solvent composition and polymer temperature also affected on the thickness of the skin layer and porosity in the case of the CAI/PMB80 and CAIII/PMB80 HFM, respectively (Fig. 3).

The mechanical property changes in the HFMs are summarized in Table 4. The CA and CA/PMB80 HFMs obtained from the same preparative conditions showed almost the same dimensions and mechanical properties. The physical dimensions and structures of the HFM were changed by the preparative conditions and the mechanical properties of the HFMs largely depended on the preparative conditions because the thickness and cross-sectional structures of the HFMs are the most effective factors in mechanical property.

3.2. Surface characterization and protein adsorption of HFMs

The XPS charts of the CA and CAII/PMB80-0.25 HFMs (which is the HFM prepared using 0.25 wt.% of PMB80 solution as the inner coagulant) are shown in Fig. 4. In the case of the CA/PMB80 coating HFMs, the XPS signals were ob-
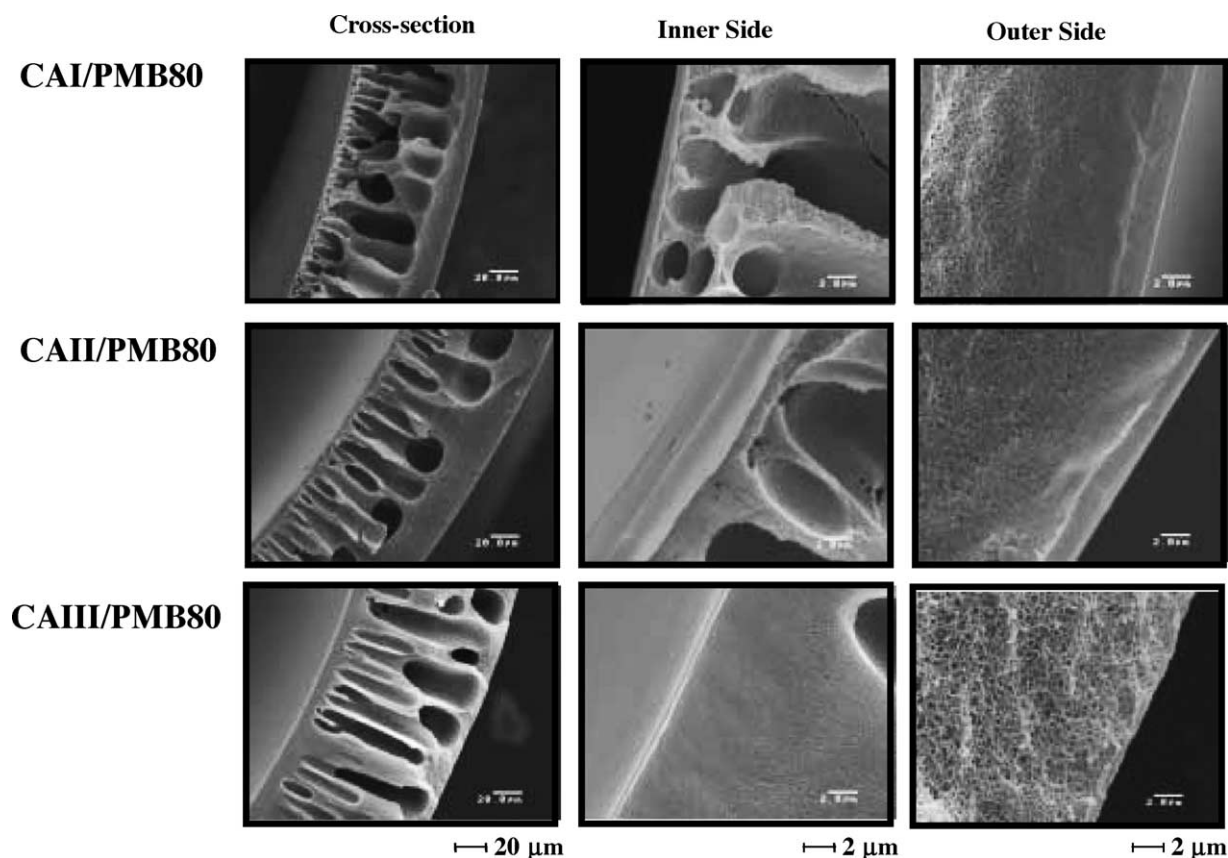

Fig. 3. SEM pictures of CA/PMB80 HFMs.

Table 4
Dimension and mechanical property of HFMs

Abb.	Inner diameter (mm)	Outer diameter (mm)	Young's modulus (MPa)	Strain max. (%)	Stress max. (MPa)
CAI	1.80	1.91	78	27	4.1
CAI/PMB80	1.80	1.91	77	28	3.9
CAII	1.60	1.72	57	34	3.3
CAII/PMB80	1.60	1.72	58	31	3.2
CAIII/PMB80	1.60	1.73	48	29	2.6
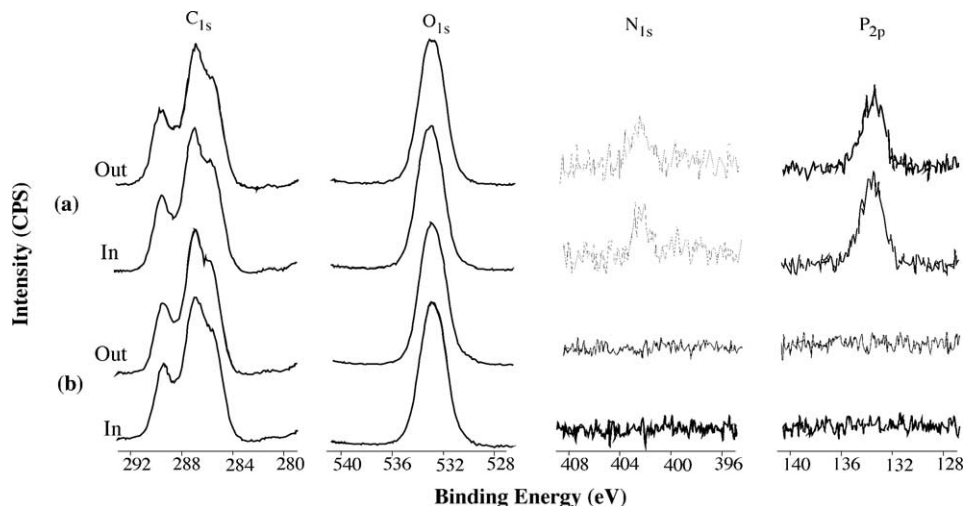
Fig. 4. XPS spectra of (a) CAII/PMB80-0.25 and (b) CAII HFMs.

served at 403 and 133 eV and are attributed to the nitrogen atom and phosphorus atom of the PMB80 in the inner and outer surfaces, respectively. We also prepared CAII/PMB80 HFMs that were coated with 1 wt.% (CAII/PMB80-1) and 0.1 wt.% (CAII/PMB80-0.1) of the PMB80 solutions used as the inner coagulant. To determine the amount of PMB 80 modified on the CA HFM, the number of phosphorous atoms related to the carbon atoms (P/C value) on the surfaces was calculated from XPS signals (Table 5). From the results of XPS chart and the P/C value, we knew that the amount of the PMB 80-modified HFM was changed and controlled with the concentration of the PMB 80 solution. The amount of PMB 80 modified on the inner surface of the CAII/PMB80-0.25 HFM was higher than that of CAII/PMB80-1. It was considered that the mobility of the PMB 80 chain in the coagulant solution during phase inversion was important for the amount of modification.

Fig. 5 shows the amount of adsorbed proteins on the inner surface of 1 unit (1 cm of the HFM) after contacting each protein for 3 h at 37 °C. The amount of each ad-

sorbed protein on the CA/PMB80 HFM is less than those on the CA HFM for all of the proteins examined in this study. It corresponded to the XPS signal for the MPC unit in PMB 80 exhibited on the surface of the CA/PMB80 HFM, and suppresses the protein adsorption. This result agrees with the previous results for the CA/PMB30 (MPC unit composition = 30 mol%) blend membranes and many reports that the MPC polymer coating is effective for reducing bioreactions (protein adsorption and platelet activation) [22,23].

Table 5
P/C value on CA/PMB80 HFMs

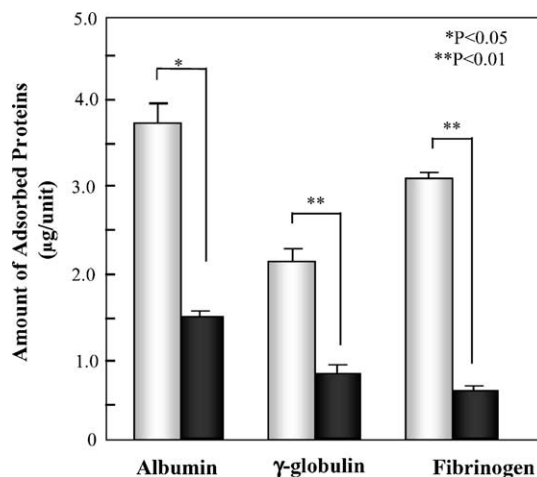| Abb.	P/C (%) from XPS data	
	Inner	Outer
CAII/PMB80-1	0.28	1.13
CAII/PMB80-0.25	0.98	0.92
CAII/PMB 80-0.1	0.82	0.68

Fig. 5. Amount of proteins adsorbed on the inner surfaces of CAII (white bar), CAII/PMB80-0.25 (black bar) HFMs.

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3.3. Stability of MPC polymers on HFM surface

To determine the stability of the PMB80 on the modified CA HFM, the XPS signals on the HFMs were measured, after rinsing for a constant period by distilled water under ultrafiltration conditions with a high speed of water flow rate (5 mL/min which is higher than that of the ultrafiltration experiment in this study). The XPS chart of the CAII/PMB 80-0.25 HFM measured after rinsing for 4 h, 1 week, and 1 month are shown in Fig. 6. The intensity of the signal on the surface of the CAII/PMB80-0.25 (P/C (%) = 0.52), measured after the rinsing experiment, decreased in comparison with the signal of CAII/PMB80-0.25 (P/C (%) = 0.98) in Fig. 3 that was measured after rinsing by just changing the water in the storage reservoir. However, the intensity of the XPS signal, attributed to a phosphorus atom of the PMB80, decreased no more after 1 week of rinsing (P/C (%) = 0.34), and the signal remained even after 1 month of rinsing (P/C (%) = 0.35).

3.4. Permeability of HFMs

The overall (apparent) rejection rate (R_o (%)) of the CA/PMB80 HFM was shown in Fig. 7 which was calculated
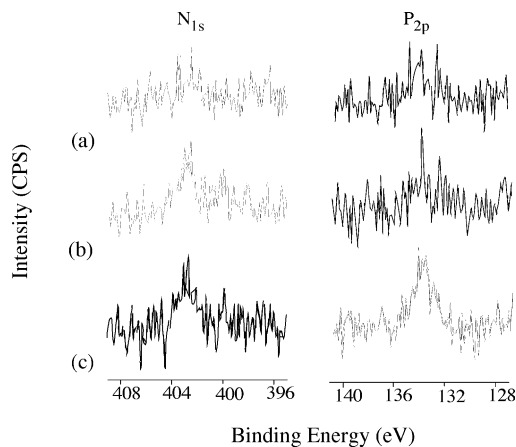

Fig. 6. XPS spectra on the inner surface of the CA II/PMB80-0.25 HFMs after rinsing for (c) 4 h (P/C (%) = 0.52); (b) 1 week (P/C (%) = 0.34); and (a) 1 month (P/C (%) = 0.35).
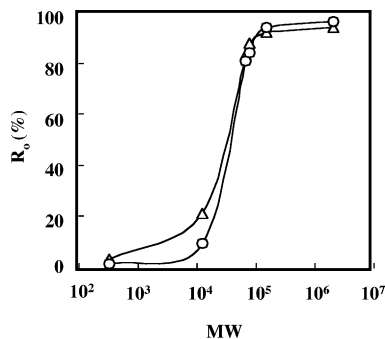

Fig. 7. The rejection (R_o (%)) of HFMs CAI/PMB80 (△) and CAII/PMB80 (○)).

by Eq. (3) after a 2-h filtration experiment with each protein solution. Each experiment was conducted at a constant flow rate through fiber lumen (45 mL/h) and the cross-flux ratio (F_p/F_{in}) was remained below 0.02 in all filtration experiment with protein solution. The F_p/F_{in}, which measured from the first 2 h of diafiltration experiment with the protein mixture solution of albumin and cytochrome c was shown in Table 6. The overall diffusive mass transfer coefficient (K_o) and transmembrane solute flux (J_s) for cytochrome c, and the water flux (J_w) of the CA and CA/PMB80 HFMs measured under the same dialysis and filtration conditions are also shown in Table 6. First, the R_o (%) and J_w of the HFM were strongly dependent upon all of the preparative conditions such as polymer solvent composition and the temperatures of the polymer solution and coagulant (compare CAI/PMB80 to CAII/PMB 80). The CAII/PMB80 could be obtained by controlling the preparative conditions with a sharp molecular weight cut-off property and good permeability. Also, we knew that CA/PMB80 HFMs showed an increasing of permeability for cytochrome c (MW = 1.2×10^4) and water flux in comparison with the CA HFMs that were prepared using the same preparative conditions. It was considered that the increasing of hydrophilicity of the HFM affected the water flux and solute flux, because the PMB80 modified on the CA HFM was a very hydrophilic polymer. As a result, the CA/PMB80 HFM showed excellent water and solute permeability in comparison with the CA HFM.

The SEM picture in Fig. 8 shows the inner surfaces of the HFMs after 10 h of diafiltration with a protein mixture solution of albumin and cytochrome c. In the case of CA HFM, many deposited and aggregated proteins were observed on the surface, however, the CA/PMB80 HFM showed little protein deposition on its surface. It is well known that membrane fouling, which decreases membrane performance, is due to the deposition of proteins on the membrane surface by adsorption and aggregation. As in our previous study, we demonstrated the same results that MPC polymers were effective in the prevention of membrane fouling during the permeation experiment [23,24].

The changes in the transmembrane solute flux (J_s) of CA and CA/PMB80 for cytochrome c during 10 h of diafiltration were shown in Fig. 9. The J_s for cytochrome c was calculated from the volume and concentration of the permeated solution in every 2 h diafiltration, with a protein mixture solution of albumin and cytochrome c, using Eq. (2). In case of CA HFM, J_s for cytochrome c dramatically decreased with the experiment time. However, the CA/PMB80 HFM showed little decreasing of J_s and sustained its high solute permeability in comparison with the original CA HFM during the experiment. This durability of the membrane surface and solute permeability (anti-fouling property) is a very important point for a blood purification membrane. The membrane permeability changes significantly by plasma proteins absorbed on the membrane surface. This deposition of the permeation pores of the membrane causes a marked decrease in the permeability or the clearance values [23].

Table 6
Overall diffusive mass transfer coefficient (K_o) and transmembrane solute flux (J_s) for cytochrome c, water flux (J_w), and cross-flux ratio (F_p/F_{in}) in diafiltration condition

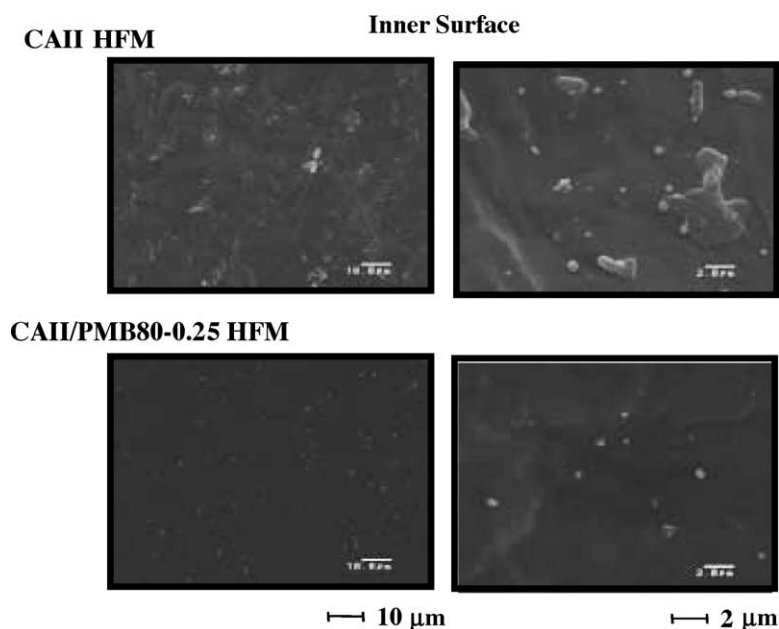| Abb.	Cytochrome c		J_w (g/h)	F_p/F_{in} in diafiltration (%)
	K_o in dialysis (10^{-6} cm/s)	J_s in filtration (10^{-8} g/s)		
CAI	3.51	0.75	0.27	0.44
CAI/PMB80	4.31	0.86	0.35	0.67
CAII	7.85	2.55	0.81	1.33
CAII/PMB80	8.15	2.89	0.95	1.56

Fig. 8. SEM pictures of the inner surfaces of CA II and CAII/PMB80-0.25 HFM after 10 h of diafiltration experiment with the protein mixture solution of albumin and cytochrome c.
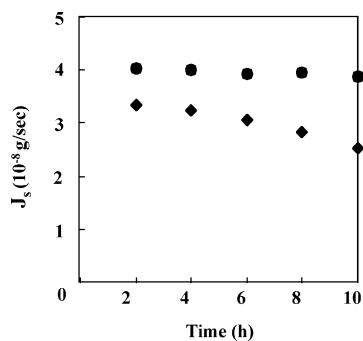

Fig. 9. Change in transmembrane solute flux (J_s) of CA II (♦) and CAII/PMB80-0.25 (●) for cytochrome c in 10 h of diafiltration condition experiment with the protein mixture solution of albumin and cytochrome c.

4. Discussion

In the dry-wet spinning process, many of the preparative conditions affect the characteristics of the hollow fiber such as dimensions, structure and permeability. Obtaining an HFM with the desired structure and permeability is not easy, because all of the preparative conditions comprehensively affect the structure and permeability of the HFM [25–30]. In this study, the HFM preparative conditions were determined from the experimental experience to obtain some desirable performances such as cross section structure and porosity, molecular cut-off property between cytochrome c and albumin, and water flux of the HFM. And then, the CA/PMB80 HFM with both good permeability and a desirable sharp molecular cut-off performance could be prepared by controlling the preparative conditions.

The modification effect of MPC polymer on the CA flat membrane and HFM has also been demonstrated in the previous study [22–24]. Most of the modification effects such as increasing the hydrophilicity, suppression of protein adsorption and the anti-fouling property on their surface are almost identical to the CA/PMB30 blend membrane. However, in the case of CA/PMB30 blend membranes, the large pores showed up on their surfaces, and the large pores through the thin active layer had to be controlled, because they affect the molecular weight cut-off property of the membrane. We knew that control of the large pores becomes more difficult in the preparation of the HFMs than in flat membranes. On the other hand, the CA/PMB80 HFM was very simple in prepara-

tion, control of the structure, and obtaining a high molecular cut-off membrane in comparison with the CA/PMB30 blend HFM, because the PMB80 does not affect the physical structure of the original CA HFM. The amount of modification could be controlled without the change in physical structure. We also knew that the amount of modification is changed with the concentration of PMB80 in the inner coagulant solution and the temperature of the coagulant solution.

Surface modification techniques such as coating, grafting and blending methods are valuable for improvement of the performance of biomaterials. Usually, coating is the easiest method for preparing a modified polymer surface. However, the stability of the coating has some problem that the modifier (polymer) may detach and elute from the surface. In this study, we prepared the CA/PMB80 HFM by a coating method where the PMB80 was modified at the simultaneously with the phase inversion of the dope solution in the dry-jet wet process. It was considered that this coating method enhanced the stability of PMB80 on the CA HFM in comparison with the HFM coated after the preparation. It is expected that the PMB80 could adsorb the CA polymer chains and entangle with them or at least stick to the CA HFM surface when the phase inversion occurs in a dry-jet wet process. In fact, the PMB80 on the CA/PMB80 HFM showed the good stability that the PMB80 remained even after 1 month of rinse under flowing distilled water. This point is important when the CA/PMB80 HFM is applied in practical medical treatments such as hemodialysis and hemofiltration therapies.

5. Conclusions

In this study, the CA/PMB80 HFM was prepared during a dry-jet wet spinning process where the PMB80 solution was used as an inner coagulant solution. The CA and CA/PMB80 obtained from the same preparative conditions did not show a difference in structure. However, the CA/PMB80 coating HFM showed improvement in both the flux and the suppression of protein adsorption in comparison with the CA HFM, because the hydrophilic and hemocompatible MPC copolymer (PMB80) existed on the surface of the HFMs. From the results of the XPS surface analysis, we knew that the amount of modification was changed with the concentration of the PMB80 solution. And, the XPS signal, attributed to phosphorus atom of the PMB80, was remained even after 1 month of rinsing. The CA/PMB80 coating HFM also showed the antifouling property that it suppress the protein adsorption and aggregation on its surface, and the solute permeability of the HFM were maintained in comparison with CA HFM during the permeation experiment.

Thus, it was expected that a hemodialyzer or hemofilter made of CA/PMB80 HFM could reduce the injection of anticoagulants in clinical therapy at least, and may be applied in a long-term therapy without decreasing its performance. Also, many research reports have already demonstrated that the polymer surfaces immobilized with a phosphohpid polymer (MPC polymer) have enhanced biocompatibility and many clinical benefits in the application of medical devices [10–21]. Therefore, it is considered that the CA/PMB80 HFM has a high potential in many medical applications, not only as a blood purification device, but also as an immunorejection device for a bioartificial organ or implantable device in cell encapsulation therapy.

Nomenclature

A	log mean membrane surface area (cm^2)
C_{ext}	concentration of the external loop solution (g/mL)
C_f	feed solution concentration (g/mL)
C_p	permeated solution concentration (g/mL)
CA	cellulose acetate
F_{ext}	fiber external lumen flow rate(mL/h)
F_{in}	fiber internal lumen flow rate(mL/h)
F_p	transmembrane flow rate(mL/h)
J_s	transmembrane solute flux (g/s)
J_w	water flux (g/h)
K_o	overall diffusive mass-transfer coefficient (cm/s)
MPC	2-methacryloyloxyethyl phosphorylcholine
PMB80	copolymer of MPC and *n*-butyl methacrylate
Q_{ext}	volume of the external loop solution (mL)
R_o	observed solute rejection rate
ΔT	experiment time

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