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Preparation of molecular dispersed polymer blend composed of polyethylene and poly(vinyl acetate) by *in situ* polymerization of vinyl acetate using supercritical carbon dioxide

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Abstract

A novel polymer blend comprising polyethylene (PE) and poly(vinyl acetate) (PVAc) with a biocompatible surface was developed for fabricating medical devices. This blend was obtained by a new synthetic method using supercritical carbon dioxide fluid. Further, the acetyl group on the surface of this blend was converted to the hydroxyl group following the phosphorylcholine (PC) group. Surface analysis of the blend with attenuated total reflection Fourier-transform infrared spectroscopy, X-ray photoelectron spectroscopy and dynamic contact angle measurement revealed that the PC groups were located on the surface. Biocompatibility was evaluated by the adsorption of the bovine serum albumin and bovine plasma fibrinogen on the sheet surface. The hydrophilicity of the blend depended on the surface chemical structure introduced by surface reactions. Plasma protein adsorption decreased with the surface hydrophilicity. The PC groups were highly effective in reducing protein adsorption. We conclude that our process is a promising procedure for synthesizing new polymer materials including biomaterials.

Keywords: Polyethylene; Supercritical carbon dioxide; Phosphorylcholine

1. Introduction

The fundamental requirements for biomaterials used in the construction of high-performance medical devices and implantable artificial organs are biocompatible surfaces and favorable mechanical properties [1]. Advancements in medical treatment also demand substantial improvements in biomaterial properties. Conventional single-component polymer materials cannot satisfy these requirements. Therefore, multicomponent polymer systems have been designed and prepared for developing new multifunctional biomaterials [2].

A synthetic method for producing a new polymer blend using supercritical carbon dioxide fluid ($scCO_2$) has been developed [3]. Both the monomer and initiator dissolved in $scCO_2$ are impregnated into the polymer substrate and subsequently polymerized. We have already succeeded in obtaining miscible blends of isotactic polypropylene (iPP) or syndiotactic polystyrene (sPS) with poly(methyl methacrylate) (PMMA), even though these polymers are incompatible with each other and the polymer blend could not be obtained using conventional methods [4]. PMMA is blended with the amorphous region in a crystalline polymer (iPP or sPS) at a molecular level. Thus, it is expected that the polymer blend prepared using the $scCO_2$ method has favorable mechanical and surface

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properties. We have attempted to synthesize a polymer blend composed of a polyolefin and a biocompatible polymer such as poly(2-methacryloyloxyethyl phosphorylcholine (MPC)) [5,6] or poly(2-hydroxyethyl methacrylate (HEMA)) for use as biomedical polymer materials. However, the solubility of a polar molecule in $scCO_2$ is considerably lower than that of a nonpolar molecule [7]. Therefore, it is difficult to impregnate MPC and HEMA due to the presence of polar groups such as phosphorylcholine (PC) or hydroxyl groups.

The introduction of PC groups on the surface is an efficient technique to obtain biocompatibility and blood compatibility. Several studies on the introduction of PC groups on the surface have been conducted, such as coating, grafting, and reacting of the MPC polymer [8–15]. Further, direct surface reaction of the PC group has been studied [16]. These studies demonstrated the effectiveness of the PC group in preventing an unfavorable bioresponse at the surface. On the basis of the above-mentioned information, we considered that the introduction of PC groups on the surface of polyethylene (PE) after blending with PVAc and hydrolysis of acetyl group might be effective in developing new polymer biomaterials.

Fig. 1 shows the procedure for developing the novel PE/PVAc polymer blend with functional surfaces. The vinyl acetate (VAc) of the hydrophobic monomer easily dissolves in $scCO_2$. The PE/PVAc polymer blend was prepared by the polymerization of VAc in $scCO_2$ method. Finally, the acetyl group on the surface of the PE/PVAc polymer blend was converted to PC groups.

The products were characterized by attenuated total reflection Fourier-transform infrared (ATR-FTIR) spectroscopy, X-ray photoelectron spectroscopy (XPS), and dynamic contact angle measurement. The biocompatibility was evaluated by determining the adsorption of the plasma protein.

2. Experiment

2.1. Materials

A linear low-density PE substrate was prepared from a commercial pellet (Mitsui Chemical, Inc., Tokyo, Japan) by hot pressing at 170 °C. The substrate was cut into pieces with dimensions of $20 \times 20 \times 0.5$ mm^3, extracted with acetone for 24 h in a Soxhlet extractor, and dried *in vacuo* at room temperature. VAc, methanol, acetone, sodium hydrate (NaOH), dehydrated pyridine, and sodium dodecyl sulfate (SDS) were used without further purification, and tetrahydrofuran (THF) and trimethylamine (TMA) were used after distillation; these chemicals were purchased from Kanto Chemical Co., Tokyo, Japan. 2-Chloro-2-oxo-1,3,2-dioxaphospholane (COP) was synthesized and purified using the method reported earlier [17]. 2,2′-Azobisisobutyronitrile (AIBN) was purchased from Kanto Chemical Co. and used after recrystallization in methanol. Carbon dioxide (CO_2) with a purity of 99.5% was provided by Tomoe Shokai Co., Tokyo, Japan, and used as-received. Dulbecco's phosphate-buffered saline (PBS, ×10 concentrate) was purchased from Invitrogen Co., California, USA, and diluted (×1, pH 7.1) by distilled water before use. Bovine serum albumin (BSA) and bovine plasma fibrinogen (BPF) was purchased from Sigma–Aldrich Co., Saint Louis, USA, and used as-received.

2.2. Preparation of the PE/PVAc polymer blend using $scCO_2$

The apparatus for the preparation of the PE/PVAc polymer blend consisted of a 50 mL stainless steel vessel, magnetic stirrer, constant-temperature air bath (Model SCF-Sro, JASCO Co., Tokyo, Japan), thermocouple, and pressure gauge. The pressure gauge comprised a transducer (Model PTX1400, Druck Japan Co., Tokyo, Japan) and indicator; it had a precision of ±0.2% in the pressure range of 0–40 MPa. The PE substrate was suspended in the vessel by means of a wire mesh. No part of the substrate was in contact with the monomer solution or the vessel wall. The substrate, VAc (5 g), and AIBN (0.05 g, 1 wt% with respect to the monomer) were placed in the vessel and sealed [18]. Air in the vessel was replaced by CO_2 at atmospheric pressure. After the system reached thermal equilibrium (35 °C), the vessel was pressurized to a CO_2 pressure of 6.0 MPa by a CO_2 delivery pump (Model SCF-Get, JASCO Co.) and heated at the reaction temperature (80 °C) for approximately 0.5 h. After the reaction was completed, the vessel was cooled to 10 °C in an ice bath. The vessel was gradually depressurized to the ambient pressure. The PE/PVAc polymer blend sheet was dried *in vacuo* at room temperature after extraction with acetone

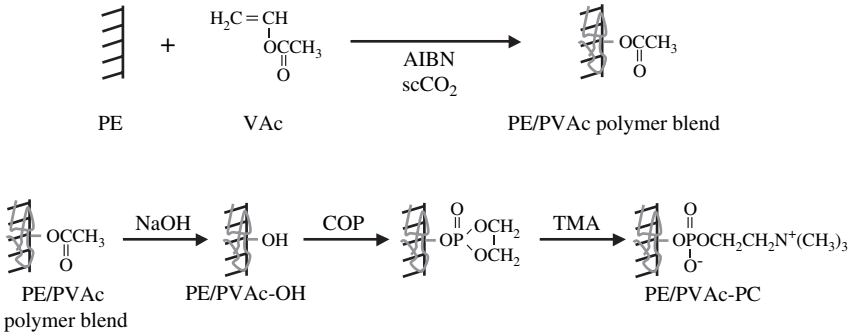

Fig. 1. Schematic representation of the introduction of phosphorylcholine group on the PE/PVAc polymer blend surface.

for 5 h to remove unreacted reagents and PVAc generated on the surface of the PE/PVAc polymer blend using the Soxhlet extractor. The mass gain was calculated by the following equation:

$$\text{Mass gain(wt\%)} = \frac{(W_t - W_0)}{W_0} \times 100 \quad (1)$$

where W_0 is the initial weight of the PE substrate and W_t is the weight of PE/PVAc polymer blend sheet after drying.

2.3. Preparation of PE/PVAc-OH: hydrolysis of acetyl group on the surface of the PE/PVAc polymer blend

The PE/PVAc polymer blend sheet was refluxed in 30 mL of 0.2 M NaOH/methanol solution for 3 h. The PE/PVAc-OH sheet was obtained after washing with methanol and water and dried *in vacuo* at room temperature.

2.4. Preparation of PE/PVAc-PC: introducing the PC group onto the PE/PVAc-OH sheet

The PE/PVAc-OH sheet was soaked in water overnight and then freeze-dried. It was then refluxed for 5 h in distilled THF (50 mL) containing COP (2.5 mmol) and pyridine (3.0 mmol) in order to introduce a cyclic phosphate moiety on the surface. The sheet was washed five times with distilled THF. The sheet and distilled THF (50 mL) were put in a flask and then cooled in an ice bath. TMA (10 mL) was added to the flask. After this flask was closed and allowed to heat up to room temperature, it was heated at 50 °C for 24 h to convert the cyclic phosphate moiety into the PC group. The PE/PVAc-PC sheet obtained was washed with methanol and dried *in vacuo* at room temperature.

2.5. Characterization

To analyze the functional groups on the surface of the product sheets, the ATR-FTIR spectra were measured using a FTIR spectrophotometer (Perkin–Elmer Spectrum One) equipped with universal ATR sampling accessory.

To confirm the chemical structure of the samples and assess the near-surface composition of the sheets, XPS was conducted on an AXIS-HSi (Shimadzu/KRATOS, Kyoto, Japan) employing Mg Kα excitation radiation (1253.6 eV). The take-off angle of the photoelectron for each atom was fixed at 90°.

2.6. Contact angle measurement by water

The hydrophilicity of the sample surface was characterized on the basis of water dynamic contact angle (DCA) measurements. By a sessile drop method, the contact angle with water was measured at room temperature (22 °C) using a contact angle goniometer (CA-W, Kyowa Interface Science Co., Tokyo, Japan) equipped with a video camera. The advancing (θ_A) and receding (θ_R) contact angles with water were measured for addition to and withdrawal from the drop (0–20 μL), respectively. The purified water was dropped on a dry sample using a microsyringe under atmospheric conditions. A minimum of 10 contact angles were averaged to obtain a reliable value. The mobility factor (Mf) used to evaluate the mobility of the polymer chains at the surface was calculated as follows [19]:

$$\text{Mf} = \frac{(\theta_A - \theta_R)}{\theta_A} \quad (2)$$

2.7. Protein adsorption test

To evaluate the amount of protein adsorption on the surface, sheets with a diameter of 15 mm were contacted with 4.5 mg/mL bovine serum albumin (BSA) or 0.3 mg/mL bovine plasma fibrinogen (BPF) in PBS at 37 °C for 60 min. The BSA and BPF concentration is 10% of the plasma concentration. After the sheet was rinsed five times with fresh PBS, the remaining protein adsorbed on the surfaces was removed with a 1 wt% aqueous solution of SDS. The amount of protein in the SDS solution was then determined by the micro-BCA method using a clinical test kit (micro-BCA protein assay reagent kit, #23235, Pierce, Rockford, IL, USA). The comparative analysis was performed using the Student's *t*-test.

3. Results and discussion

3.1. Preparation of the PE/PVAc polymer blend in $scCO_2$

The polymerization of PVAc was performed at 80 °C for different time periods. Fig. 2 illustrates the effect of reaction time on the percentage of mass gain and the final pressure after polymerization. It is evident that the mass gain increases

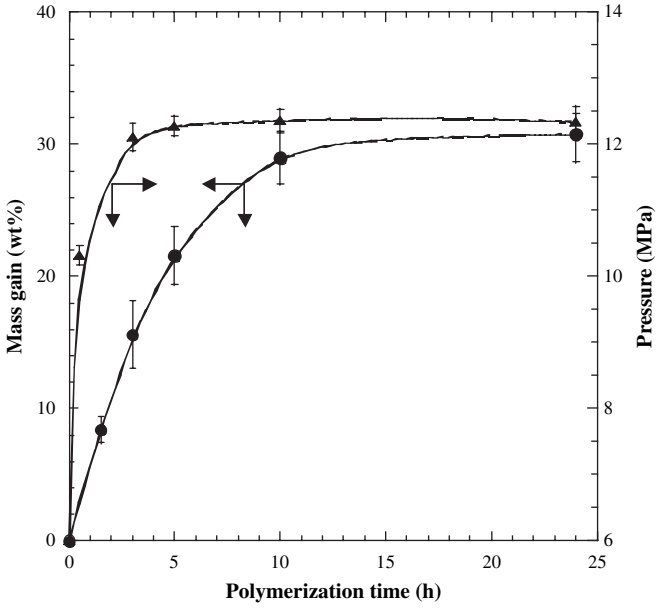

Fig. 2. Effect of polymerization time on the mass gain of PVAc into PE and the pressure after polymerization (circles: mass gain; triangles: pressure).

initially and reaches a plateau in 10 h. Similar results were obtained by Busby and co-workers using ultra-high molecular weight PE (UHMWPE) and methacrylate monomers [20].

Under this condition ($P < 15$ MPa, $T = 80$ °C), PVAc does not dissolve in $scCO_2$ [21]. When PVAc was generated on the exterior of the PE substrate, the pressure increased such that the volume of the gas phase in the vessel decreased. The primary stage of the polymerization process (polymerization time < 0.5 h) comprised the heating process up to 80 °C. The pressure at this stage increased with the temperature and polymerization. In the second stage (0.5 h < polymerization time < 5 h), the pressure and mass gain increased. This result indicates that PVAc was polymerized both in the interior and in the exterior of the PE substrate. The formation mechanism of the PE/PVAc polymer blend is as follows. The monomer was impregnated into the PE substrate by $scCO_2$ and polymerized *in situ* because PVAc does not dissolve in $scCO_2$. To further increase the mass gain, the amount of monomer in the PE substrate should be increased. For example, consider the changes in the soaking time and initial pressure. The amount of impregnated low-molecular weight components depends on the soaking time and attains an equilibrium value [22]. The soaking time results in equilibrium in the monomer concentration between the interior and exterior of the PE substrate. The pressure significantly affects the solubility of substance in $scCO_2$ [23] and the solubility of $scCO_2$ in the PE substrate [24,25]. It is known that the solubility of the monomer in $scCO_2$ and that of $scCO_2$ in the PE substrate increase with the pressure of $scCO_2$. It is thought that the polymerization of the monomer in the substrate can be enhanced further by changing the soaking time and the pressure.

3.2. Surface chemical structure of the PE/PVAc polymer blend

Fig. 3 shows the ATR-FTIR spectra of the original PE substrate, the PE/PVAc polymer blend with a mass gain of 23.2 wt%, differential spectrum ((PE/PVAc polymer blend)−(PE)), and PVAc. It is observed that the spectra of the original PE and PE treated with $scCO_2$ are almost identical (spectrum is not shown). This implies that $scCO_2$ does not affect the chemical structure of PE during the course of swelling [26]. The differential spectrum (Fig. 3(c)) almost corresponds to the spectrum of PVAc (Fig. 3(d)). In addition, the C=C stretch (1660 cm^{-1}) observed in VAc monomer disappeared. The spectra confirmed that PVAc was formed within the PE substrate. Fig. 4 shows the relationship between the ratio of ATR-FTIR intensities at 1725 cm^{-1} versus 719 cm^{-1} $\left([A]_{1725\ cm^{-1}}/[A]_{719\ cm^{-1}}\right)$ and the mass gain of PVAc. The ATR-FTIR absorption at 719 cm^{-1} $([A]_{719\ cm^{-1}})$, which was attributed to the methylene chain in the PE substrate, was almost the same even for larger values of mass gains for PVAc. On the other hand, new absorption was observed at 1725 cm^{-1} $([A]_{1725\ cm^{-1}})$ which was attributed to the carbonyl group (C=O) (Fig. 3(b)); further the intensity increased with the

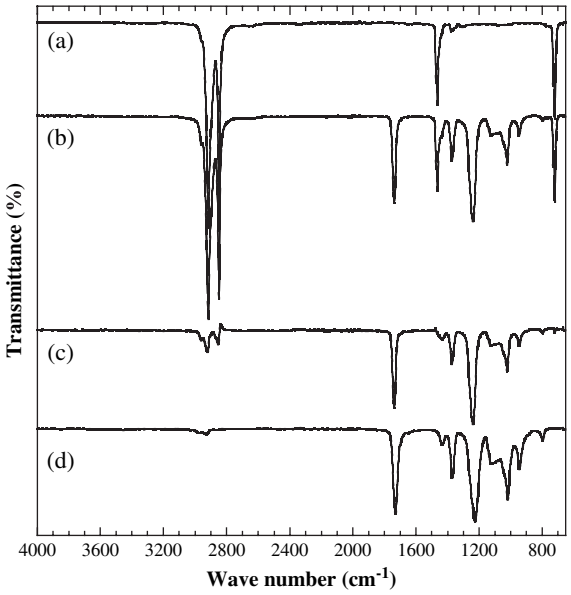

Fig. 3. ATR-FTIR spectra of (a) original PE, (b) PE/PVAc polymer blend (mass gain of 23.2 wt%), (c) differential spectrum ((PE/PVAc polymer blend)−(PE)), and (d) PVAc.

mass gain of PVAc. These results imply that PVAc near the surface could be controlled by the mass gain of PVAc, that is, the polymerization time.

Fig. 5 shows the change in the ATR-FTIR spectrum following the conversion of the functional groups on the surface of the PE/PVAc polymer blend sheet. The ATR-FTIR spectrum of the PE/PVAc polymer blend with a mass gain of 23.2 wt% exhibits stretching bonds at 1725 cm^{-1} for C=O groups (Fig. 5(b)). It was confirmed that PVAc was incorporated within the PE sheet. PE/PVAc-OH was prepared by hydrolysis of the acetyl group on the surface of the PE/PVAc

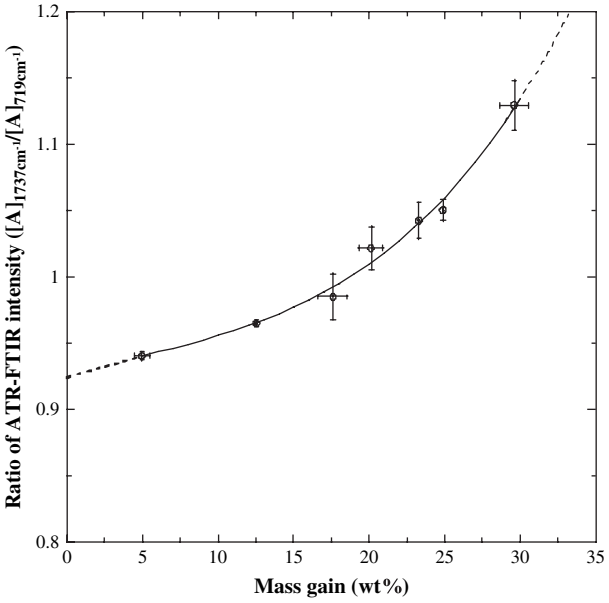

Fig. 4. Relationship between the ratio of ATR-FTIR intensity at 1737 cm^{-1} versus 719 cm^{-1} and mass gain of PVAc.

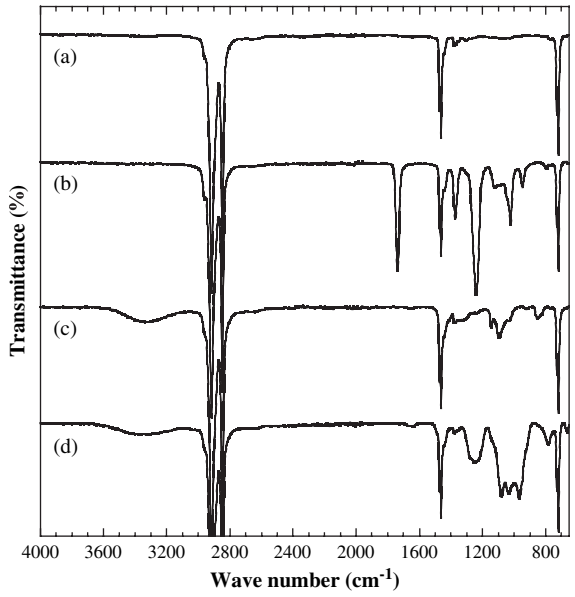

Fig. 5. Change in the ATR-FTIR spectrum by functional group conversion: (a) original PE, (b) PE/PVAc polymer blend (mass gain of 23.2 wt%), (c) PE/PVAc-OH (hydrolysis of (b)), and (d) PE/PVAc-PC (addition of PC group to (c)).

polymer blend. The spectrum of PE/PVAc-OH exhibits stretching bonds at 3500 cm^{-1}, which was attributed to the OH group (Fig. 5(c)). The absorption of the acetyl group of PVAc disappears and the absorption of the hydroxyl group can be observed. It was found that the acetyl group on the surface of the PE/PVAc polymer blend sheet was hydrolyzed. After the addition of the PC group on the surface of PE/PVAc-OH, new absorptions at 1200–1350 cm^{-1} (–P═O, C–N) and 960–1150 cm^{-1} (P–O–C, $-N^{+}(CH_3)_3$) were confirmed (Fig. 5(d)). The OH group on the surface of PE was reacted with COP followed by the addition of TMA to convert the PC group. This reaction procedure may also be applicable to introduce various functional groups using other acid chloride compounds.

Fig. 6 shows the XPS charts of the PE/PVAc polymer blend with various functional groups. In the case of original PE, a strong intensity is observed at 285 eV. This is attributed to the carbon atoms in the methylene chain. Further, a small peak is observed at 535 eV. This peak is attributed to the oxygen atoms and may arise from the oxidation or contamination of PE.

After the incorporation of PVAc into PE, the XPS peaks broaden in the carbon atom region and a new peak is observed in the oxygen atom region. This broad peak can be attributed to the acetyl group in the carbon atom region; the peak in the oxygen atom region can be attributed to the carbonyl group (C═O) in the acetyl group.

Due to the hydrolysis of the PE/PVAc polymer blend, the shape of the peak in the oxygen region changed. The change in the shape of the peak can be attributed to disappearance of the peak corresponding to the acetyl group and the appearance of the peak corresponding to the hydroxyl group by hydrolysis.

After the introduction of the PC group, the XPS chart changed dramatically. In the carbon atom region, the XPS peak broadened. This broad peak can be attributed to the carbonyl group (C═O and C–O–C). In the oxygen atom region, the increase in the peak intensity is caused by the increase in the number of oxygen atoms. The nitrogen and phosphorus peaks are observed at 401 eV and 134 eV, respectively. These peaks were attributed to the PC groups on the surface. These results confirmed that the introduction of PC groups on the PE/PVAc polymer blend surface was possible using the above-mentioned reactions.

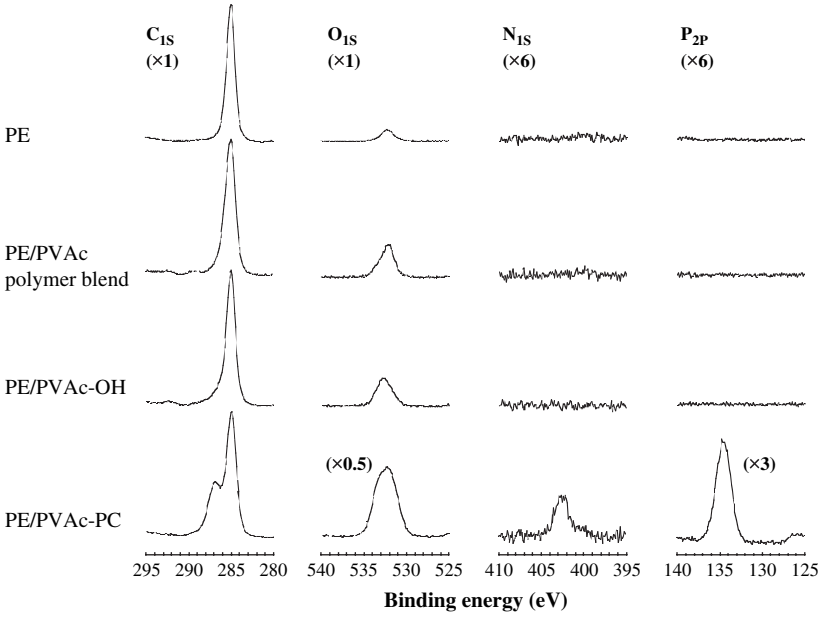

Fig. 6. XPS charts of original PE, PE/PVAc polymer blend (mass gain of 23.2 wt%), PE/PVAc-OH, and PE/PVAc-PC. The intensities of each atom were normalized by that of C_{1s} at 285 eV.

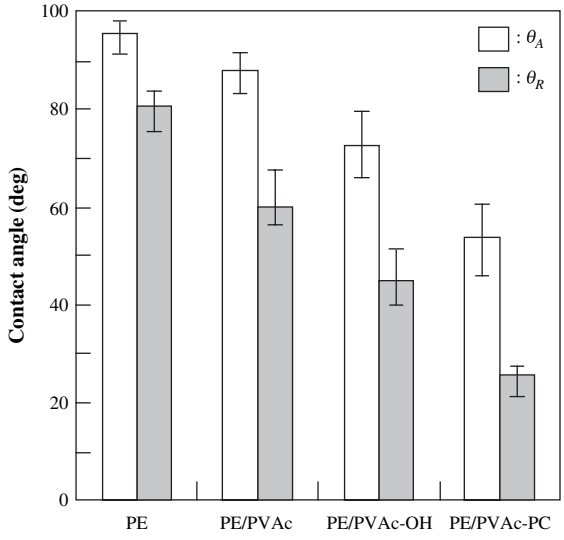

Fig. 7. Advancing (θ_A) and receding (θ_R) contact angles with water for PE and PE/PVAc polymer blend with various functional groups.

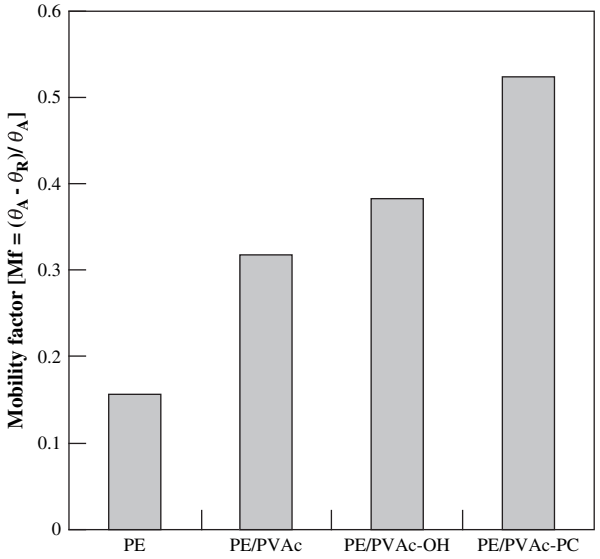

Fig. 8. Mobility factor of PE and PE/PVAc polymer blend with various functional groups.

3.3. Surface properties of the PE/PVAc polymer blend with various functional groups

Dynamic water contact angle measurement has been commonly used to characterize the relative hydrophilicity or hydrophobicity of the surface [27]. For surfaces with comparable structures, a relatively low contact angle value generally implies high hydrophilicity. Fig. 7 shows the results of the DCA measurements of the original PE and PE/PVAc polymer blend. The advancing (θ_A) and receding (θ_R) contact angles decreased with an increase in the polarity of the functional groups on the surface. In fact, poly(MPC) having PC groups in the side chain is a water-soluble polymer; however, poly(HEMA) having OH groups is insoluble in water. Thus, the PC groups have a greater hydrophilic character than OH groups.

The value of Mf was then calculated from the values of θ_A and θ_R. Since the value of Mf increases with either an increase in hysteresis ($\theta_A - \theta_R$) or a decrease in θ_A, it reflects the mobility and the hydrophilicity of the surface [19,28]. Fig. 8 shows the Mf values of the original PE and PE/PVAc polymer blend. The PC group on the surface assumed the largest Mf value. This implies that the PC group might exhibit a greater hydrophilic surface than the hydroxyl group. This is due to the contribution of the zwitterionic structure of the PC group on the surface [29]. This increased surface mobility may contribute toward an abrupt change in the water structure due to the presence of functional groups.

Protein adsorption is recognized as the first event following the implantation of biomaterials and has been shown to play an important role in determining subsequent events, including thrombus formation, the foreign body reaction, bacterial infection, and other undesirable responses [30]. There is thus considerable interest in surfaces that might inhibit or prevent protein adsorption [31]. It is well known that the amount of plasma proteins adsorbed on a surface is one of the dominant factors in evaluating the blood compatibility of these materials. Moreover, the composition of the proteins and the conformational change in the proteins adsorbed on the surface are also important for evaluating blood compatibility. Figs. 9 and 10 show the amount of protein adsorption on the surfaces of PE and PE/PVAc polymer blend. The amount of the adsorbed protein on the surface was in good agreement with the contact angle with water, as shown in Fig. 7. That is, the amount of protein adsorbed on the PE substrate decreased with an increase in the polarity of the functional group on the surface of the PE/PVAc polymer blend. The relationship between the protein adsorption and the kind of the functional group on the surface has already been reported [32–34]. According to these reports, the amount of adsorbed protein was abundant on the hydrophobic surface. The amount of adsorbed protein decreases according to hydrophilicity of the surface.

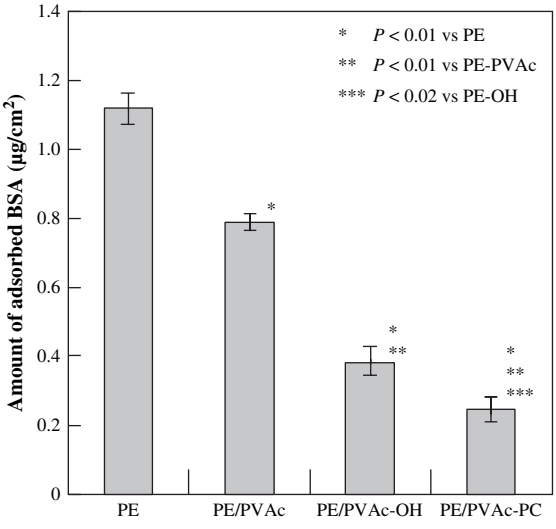

Fig. 9. Amount of BSA adsorbed on PE and PE/PVAc polymer blend with various functional groups.

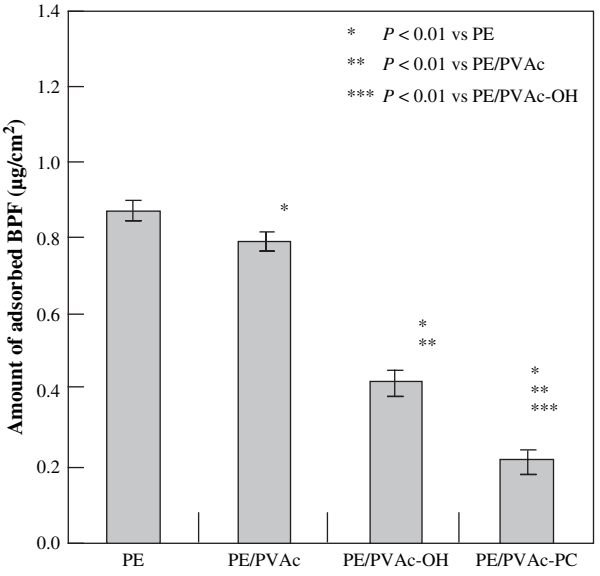

Fig. 10. Amount of BPF adsorbed on PE and PE/PVAc polymer blend with various functional groups.

This phenomenon does not depend on the kind of the protein. These facts confirm our results. Park et al. reported one possible mechanism for understanding protein adsorption on the polymer surface [35]. When a protein is adsorbed on the polymer surface, water molecules between the protein and the polymer need to be displaced such that direct contact is induced between the amino acid residues and the polymer surface. This phenomenon induces a conformational change in the proteins. Ishihara studied this phenomenon and hypothesized that if the water state at the surface is similar to that in an aqueous solution, the protein need not release the bound water molecules, even when the protein molecules are in contact with the surface [36,37]. The hydrophobic interaction between the proteins and the MPC polymer surface is weakened. Further, when contact was established with the MPC polymer surface, the conformational change during protein adsorption was suppressed. These excellent properties of protein adsorption resistivity are due to a unique water state at the surface of the MPC polymers [38,39]. We considered the relationship between the water state and protein adsorption on the PE/PVAc polymer blend. From the dynamic contact angle measurement, it was confirmed that the surface of the introduced PC group easily harmonized with water. It is considered that the water state at the surface of PE/PVAc-PC is more similar to that in an aqueous solution than that at the surface of the PE/PVAc-OH. Therefore, it is thought that the PC groups on the surface suppressed the protein adsorptions most. Ishihara et al. reported that the conformational change in albumin and fibrinogen was suppressed even when they were adsorbed on the MPC polymer surface [36]. As a consequence of reduction in protein adsorption and suppression in conformational change at plasma protein, the extent of other biological response such as platelet adhesion [40], cell adhesion [41,42], and the foreign body response [43], which require protein recognition for cell attachment, may also be reduced.

4. Conclusion

We prepared a new polymer blend composed of PE and PVAc by *in situ* radical polymerization of VAc using $scCO_2$. Next, we converted the acetyl group on the surface of the PE/PVAc polymer blend to a hydroxyl group following the PC group without an adverse effect on the bulk properties.

The hydrophilicity of the PE/PVAc polymer blend depended on the surface chemical structure introduced by the surface reactions. In particular, the adsorption of plasma protein decreased with the hydrophilicity of the surface. The PC groups effectively reduced the adsorption of the protein. As a consequence of reduction in protein adsorption and suppression in conformational change at plasma protein, it is possible that other unfavorable response may also be controlled, including the cell adhesion and foreign body response. We conclude that the surface modification of PE after blending with PVAc is a promising procedure for synthesizing new polymer materials for biomaterials.

The surface modification using surface-initiated grafting method can modify only the surface [11,12,44,45]. Only the mechanical properties of the substrate material can be expected. However, necessary mechanical properties are different in accordance with the intended use of biomaterials like an artificial bone and an artificial vascular, etc. In this synthetic method of a novel polymer blend using $scCO_2$, various new materials can be created by changing the following conditions such as the change in content rate of blending polymer and the kind of polyolefin and blending polymer. Also, mechanical properties of these materials can be controlled according to the above-mentioned condition. Phosphorylcholine groups with excellent biocompatibility can be introduced onto the surface of these materials by surface reaction. The introduction of other functional groups on the surface can provide another functionality. Therefore, we think that biomaterials corresponding to various regions such as soft tissue, hard tissue, and organs can be created by the synthesis method of novel polymer blend using $scCO_2$.

Additionally, the surface initiator of graft polymerization, the photochromic compound, the pigment molecule, etc. can be introduced onto the surface if it uses the molecule with a reactive site with the hydroxyl group. Thus, the application of these new polymer materials is expected in other technical fields. The modification technology of the bulk and the surface explained with this article is a promising procedure for the creation of new polymer materials.

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References

[1] Ratner BD, Hoffman AS, Schoen FJ, Lemons JE. Biomaterials science: an introduction to materials in medicine. Academic press; 1996.

[2] Tsuruta T, Nakajima A, editors. Multiphase biomedical materials. Utrecht, The Netherlands: V.S.P.; 1989.
[3] Watkins JJ, McCarthy TJ. Macromolecules 1994;27:4845.
[4] Sawaguchi T, Muroga Y, Ishikawa H, Hoshi T, Hagiwara T, Yano S. Kobunshi Ronbunshu 2005;62:251.
[5] Ishihara K, Ueda T, Nakabayashi N. Polym J 1990;22:355.
[6] Ueda T, Oshida H, Kurita K, Ishihara K, Nakabayashi N. Polym J 1992; 24:1259.
[7] Hyatt JA. J Org Chem 1984;49:5097.
[8] Yamasaki A, Imamura Y, Kurita K, Iwasaki Y, Nakabayashi N, Ishihara K. Colloids Surf B Biointerfaces 2003;28:53.
[9] Ogawa R, Watanabe J, Ishihara K. Sci Technol Adv Mater 2003;4:539.
[10] Ishihara K, Nishiuchi D, Watanabe J, Iwasaki Y. Biomaterials 2004;25: 1115.
[11] Moro T, Takatori Y, Ishihara K, Konno T, Takigawa Y, Matsushita T. Nat Mater 2004;29:2863.
[12] Feng W, Zhu S, Ishihara K, Brash JL. Langmuir 2005;21:5980.
[13] Ito T, Iwasaki Y, Narita T, Akiyoshi K, Ishihara K. Colloids Surf B Biointerfaces 2005;41:175.
[14] Ye SH, Watanabe J, Takai M, Iwasaki Y, Ishihara K. Biomaterials 2006; 27:1955.
[15] Feng W, Zhu S, Ishihara K, Brash JL. Biointerphases 2006;1:50.
[16] Huang XJ, Xu AK, Wan LS, Wang AG, Wang JL. Langmuir 2005;21: 2941.
[17] Ishihara K, Iwasaki Y, Nakabayashi N. Polym J 1999;31:1231.
[18] Zhang J, Busby AJ, Roberts CJ, Chen X, Davies MC, Tendler SJB, et al. Macromolecules 2002;35:8869.
[19] Ishihara K, Fukumoto K, Iwasaki Y, Nakabayashi N. Biomaterials 1999; 20:1545.
[20] Busby AJ, Zhang J, Naylor A, Roberts CJ, Davies MC, Tendler SJ, et al. J Mater Chem 2003;13:2838.
[21] Shen Z, McHugh MA, Xu J, Belardi J, Kilic S, Mesiano A, et al. Polymer 2003;44:1491.
[22] Li D, Liu Z, Han B, Song L, Yang G, Jiang T. Polymer 2002;43:5363.
[23] Kirby CF, McHugh MA. Chem Rev 1999;99:565.
[24] Sato Y, Takishima S, Masuoka H. Fluid Phase Equilib 1999;162:269.
[25] Berens AR, Huvard GS, Korsmeyer RW, Kunig FW. J Appl Polym Sci 1992;46:231.
[26] Li D, Han BX, Liu Z. Macromol Chem Phys 2001;202:2187.
[27] Teraya T, Takahara A, Kajiyama T. Polymer 1990;31:1149.
[28] Kataoka K, Taira H, Kikuchi A, Tsuruta T, Hayashi H. In: Akutsu T, Koyanagi H, editors. Heart replacement – artificial heart 5. Tokyo: Springer; 1996. p. 29.
[29] Huang X-J, Xu Z-K, Huang X-D, Wang Z-G, Yao K. Polymer 2006;47: 3141.
[30] Horbett TA, Brash JL, editors. Proteins at interfaces II: fundamentals and applications. ACS symposium series no. 602. Washington, DC: ACS; 1995.
[31] Brash JL. J Biomater Sci Polym Ed 2000;11:1135.
[32] Prime KL, Whitesides GM. J Am Chem Soc 1993;115:11714.
[33] Sigal GB, Mrksich M, Whitesides GM. J Am Chem Soc 1998;120: 3464.
[34] Lestelius M, Liedberg B, Tengvall P. Langmuir 1997;13:5900.
[35] Lu DR, Lee SJ, Park K. J Biomater Sci Polym Ed 1991;3:127.
[36] Ishihara K, Nomura H, Mihara T, Kurita K, Iwasaki Y, Nakabayashi N. J Biomed Mater Res 1998;39:323.
[37] Ishihara K. Sci Technol Adv Mater 2000;1:131.
[38] Kitano H, Sudo K, Ichikawa K, Ide M, Ishihara K. J Phys Chem B 2000; 104:11425.
[39] Kitano H, Imai M, Mori T, Gemmei-Ide M, Yokoyama Y, Ishihara K. Langmuir 2003;19:10260.
[40] Ishihara K, Iwasaki Y. Polym Adv Technol 2000;11:626.
[41] Ishihara K, Ishikawa E, Iwasaki Y, Nakabayashi N. J Biomater Sci Polym Ed 1999;10:1047.
[42] Long SF, Clarke S, Davies MC, Lewis AL, Hanlon GW, Lloyd AW. Biomaterials 2003;24:4115.
[43] Yung LL, Cooper SL. Biomaterials 1998;10:31.
[44] Iwasaki Y, Saito N. Colloids Surf B Biointerfaces 2003;32:77.
[45] Ishihara K, Iwasaki Y, Ebihara S, Shindo Y, Nakabayashi N. Colloids Surf B Biointerfaces 2000;18:325.