# Surface Modification of Polypropylene Film by Radiation-Induced Grafting and Its Blood Compatibility

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**ABSTRACT:** To endow blood-compatible properties onto polypropylene (PP) film, we grafted 2,3-epoxypropyl methacrylate (EPMA) to PP film with a preirradiation grafting technique and then introduced various functional groups onto the grafted PP film. The EPMA grafting extent was dependent on the absorbed dose, reaction time, and temperature. The reactions of hydroxylation, iminodiacetation, sulfonation, phosphonation, and amination were performed under various conditions to introduce functional groups into the epoxy group of EPMA-grafted PP films, respectively. We also immobilized heparin on aminated PP film to compare blood compatibility with various functionalized samples. The grafting, functionalization, and heparinization reaction were confirmed by Fourier transform infrared spectroscopy in the attenuated total reflectance mode and electron spectroscopy for chemical analysis. The blood compatibility of various functional groups and heparin-introduced samples as well as control samples was examined by the determination of platelet adsorption and thrombus formation. For the examination of the blood compatibility of functionalized PP samples, acid citrate dextrose human whole blood and platelet-rich plasma were used. The amount of the formed thrombus and the adherent platelets on functionalized PP sample surfaces were evaluated by an *in vitro* method following Imai and Nose's technique and by scanning electron microscopy, respectively. The blood compatibility of various functional-group-introduced PP films after grafting was better than that of the PP control. Phosphoric-acid-group- and heparin-introduced PP films had especially good blood compatibility.  J Appl Polym Sci 88: 1726–1736, 2003

**Key words:** surfaces; modification; functionalization of polymers; poly(propylene) (PP)

## INTRODUCTION

As medical technology has become more advanced, various polymer materials have been used for medical applications or for materials such as artificial internal organs (e.g., hearts, lungs, blood vessels, kidneys,[1–6] knee and hip joints[7]). They are also used for catheters,[8–10] blood bags,[11] disposable syringes, blood or protein storage applications,[12] and so forth. However, the antithrombogenicity of polymer materials needs to be improved for greater biomedical application, although it has been improved before. There have been various efforts to minimize or eliminate thrombogenicity. To design nonthrombogenic polymers, there have been many approaches including (1) the grafting of hydrophilic groups to the bulk polymer or polymer surface, which prevents platelet adhesion by giving nonthrombogenicity to the polymer;[13] (2) suppression of platelet adhesion and morphologic change of the adhered platelets by microphase-separated structures of polymers such as 2-hydroxy ethyl methacrylate/styrene block copolymer;[14–16] and (3) the immobilization of pharmaceutical reagents such as urokinase or heparin to the polymer.[17–20] Urokinase decomposes fibrin to dissolve the thrombus. Heparin prevents the activation of coagulation factors and platelets to give thrombogenicity to the polymer. The use of graft copolymers as nonthrombogenic material is very practical because it is not difficult to modify a conventional polymer. In such a way, the trunk of the graft copolymer provides mechanical support, and the side chains provide nonthrombogenicity.[21] Among the synthetic polymers, polypropylene (PP) has superior chemical and electrical properties as well as physical properties such as tensile strength, hardness, impact strength, and so on. Therefore, PP is widely used for fiber,[22] rope, household goods, and packing film. Also, recently, PP has been used for medical applications such as disposable syringes and oxygenators[23] because of its excellent transparency, processing, and nontoxicity. Particularly, the surface of complex oxygenator circuits has made it possible to maintain extracorporeal circulation in patients for extended periods of time with little, if any, requirement for anticoagulation.[24] Although the blood compatibility of

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oxygenators has been improved, it needs to be improved more to further extend the use time of oxygenators. Grafting is known to be a useful means for the functionalization of polymeric substrate[25] because the technique has many merits including the following: (1) the monomer with a desired function is directly grafted on the substrate, and (2) the monomer with a reactive group is first grafted, and the resultant reactive group is used as a reactive site for further functionalization. It is conceivable that the latter method is useful from the viewpoint of the introduction of wide varieties of function into polymeric materials. In the case of the latter, in general the epoxy group is chosen as the reactive group because the reactivity of the epoxy group can be utilized in the introduction of some desirable functions into polymeric materials.[26,27] The grafting method needs free radicals or peroxides to modify the surface of polymers.[25] They can be formed by ionization radiation[28–30] or ultraviolet,[31,32] plasma,[33,34] electron beam,[35] or chemical initiators.[36] Among these techniques, ionization radiation is known to be one of the more useful methods because active radicals are created on the polymer uniformly.

In these experiments, to develop medically applicable plastic for artificial internal organs, the grafting of 2,3-epoxypropyl methacrylate (EPMA) monomer onto PP film was carried out by an ionization radiation technique. Various kinds of functional groups were introduced onto the grafted PP films. The blood compatibility of modified PP films with functional groups is discussed.

## EXPERIMENTAL

### Materials

Commercial-additive-free PP film with a thickness of 200 $\mu$m (Honam Petrochemical Corp., Taejon, Korea) was used as a substrate for graft polymerization. EPMA (Aldrich Chemical Co., Milwaukee, WI), sulfuric acid (Merck, Darmstadt, Germany), iminodiacetic acid (Aldrich Chemical Co.), sodium sulfite (Junsei Chemical Co., Tokyo, Japan), sodium hydrogen sulfite (Showa Chemicals Inc., Tokyo, Japan), phosphoric acid (Aldrich Chemical Co.), and trimethyl amine (Merck) were used as received without any further treatment. All other chemicals were reagent grade. The acid citrate dextrose (ACD) whole blood and platelet-rich plasma (PRP) were supplied by the Blood Bank of Korea Red Cross (Daejon Branch), and heparin sodium salt (25,000 units, 185 USP units/mg, Sigma Chemical Co., St. Louis, MO) was used without further treatment. The PP film was cut into 3.0 $\times$ 5.0 cm pieces, ultrasonically cleaned twice in methanol for 10 min each time, and dried in a vacuum oven to a constant weight at 60°C for 24 h. The film was stored in a desiccator until irradiation. The cleanliness of the surface was verified by electron spectroscopy for chemical analysis (ESCA).

### Irradiation

PP film was irradiated with the $\gamma$ rays from a Co-60 source at an exposure rate of 4.61 kGy/h in the presence of air to a total dose of 10–30 kGy. After irradiation, PP films were stored in the refrigerator and kept at $-130$°C until the grafting experiments.

### Grafting procedure

The grafting reactions were performed in a glass ampule with a cock. The methanol was added first, followed by the monomer to make a total volume of 50 mL. The preirradiated PP was immersed in the monomer solution, purged by bubbling nitrogen gas for degassing, and then sealed in a glass ampule. The grafting reaction was carried out by placement of the ampules in a water bath set at a relevant temperature. After the grafting reaction, the EPMA homopolymer adhering to the PP surface was removed by extraction with tetrahydrofuran. Finally, the PP film was dried in a vacuum oven and weighed. The grafting yield was determined by the weight difference of the PP film before and after the grafting reaction. A detailed explanation was given in our previous articles.[26,28,30] The degree of grafting was determined by the following equation:

$$\text{Degree of grafting (\%)} = \frac{W_g - W_o}{W_o} \times 100 \quad (1)$$

where $W_g$ and $W_o$ are the weights of the grafted and ungrafted PP films, respectively. The grafting efficiency was obtained as follows:

$$\text{Grafting efficiency (\%)} = \frac{W_g}{W_g + W_h} \quad (2)$$

where $W_h$ is the weight of the EPMA homopolymer. The grafting was verified by Fourier transform infrared spectroscopy (FTIR) in the attenuated total reflectance (ATR) mode (FTIR–ATR) and ESCA. For FTIR–ATR, we used a Nicolet model 205 FTIR spectrometer (Wisconsin, USA) with a nominal 45° ATR. ESCA (Thermo VG Scientific, West Sussex, England) was carried out with a spectrometer with monochromatic AIK$\alpha$ X-ray radiation at 1486.6 eV operating at $10^{-9}$ mbar and a photoelectron takeoff angle of 60°. To consider some shift caused by the charging of the sample surface, all spectra were adjusted with the C1s peak at 284.6 eV as a reference for adventitious carbon contamination.[37]

### Functionalization of EPMA-grafted PP film

The hydroxylation, iminodiacetation, sulfonation, phosphonation, and amination reactions were performed under various conditions to introduce functional groups into the epoxy group of EPMA-grafted PP films, respectively, as described next. Heparinization was performed at optimum conditions to immobilize heparin into the amine group of the aminated PP film. The identification of the functionalized PP films was verified by the characteristic peaks of FTIR–ATR and/or ESCA. All functionalization reactions were performed under optimal conditions, respectively.

#### Hydroxylation

The epoxy group of the EPMA-grafted PP film was converted into a diol group by immersion of the grafted sample in 0.5*M* $H_2SO_4$ at 80°C for 2 h.[38]

#### Iminodiacetation

The EPMA-grafted PP was immersed in 0.4*M* iminodiacetic acid dissolved by dimethyl sulfoxide (DMSO)/water (the volume ratio of DMSO to water was 1). The reaction was performed at 80°C for 48 h as described elsewhere.[39]

#### Sulfonation

To convert the epoxy group of the EPMA-grafted PP film into a —$SO_3H$ group, the sulfonation reaction was performed in sodium hydrogen sulfite ($NaHSO_3$, 1 wt %)/sodium sulfite ($Na_2S0_3$, 9 wt %) aqueous solution at 80°C for 24 h. After sulfonation, the sodium form of the PP sample with a —$SO_3Na$ group was converted into H form by treatment with 1.0*M* HCl.[39]

#### Phosphonation

The epoxy group of the EPMA-grafted PP film was converted into a —$PO_3H$ group by immersion of the grafted sample in 85% phosphoric acid aqueous solution at 80°C for 24 h.[40]

#### Amination

To introduce heparin onto the PP film, the resultant epoxy group after the grafting reaction was aminated by immersion of the EPMA-grafted PP film in trimethyl amine solution at 70°C for 24 h.[26]

#### Heparinization

To obtain heparin-immobilized PP film, the previously mentioned aminated PP was heparinized in different heparin concentrations of aqueous sodium citrate buffer solution at 4°C for 24 h. After the heparinization reaction, the samples were washed with 5% (w/v) citric acid aqueous solution and 0.1% (v/v) Triton X-l00 aqueous solution and was subsequently rinsed with pure water in an ultrasonic cleaner for 10 min.[33] The absence of heparin in the washing water was confirmed with the toluidine blue method.[41]

### Water contact angle

The functionalized PP film surface after grafting was characterized by water contact angle measurement with an optical contact angle goniometer (Erma Optical Ltd., Tokyo, Japan). The contact angle measurement was performed at room temperature by the sessile drop method.[42] A more detailed explanation was given in a previous article.[43]

### Thrombus formation

The amount of thrombus formed on the functionalized PP film surface after EPMA grafting was calculated for each sample by an *in vitro* method following Imai and Nose's technique with ACD human whole blood.[44] Before the clot test, the samples (1.5 × 1.5 cm) were hydrated to constant weight in saline water (0.9% NaCl aqueous solution), and kept in watch glasses in a water bath at 37°C. ACD human whole blood (0.05 mL) was added to each sample. The reaction was then started by adding 0.1*M* calcium chloride aqueous solution (0.005 mL) on each sample of blood, and the blood with calcium chloride solution was mixed at once with a Teflon stick. After 30 min, distilled water (1 mL) was added to stop the reaction, and separate thrombus formed on various samples. After 5 min, the water was removed from the sample, and then the thrombus formed on the sample was taken out with a spatula. The separated thrombus was soaked in 37% formaldehyde (1 mL) solution for 5 min at room temperature to fix the formed thrombus and was then soaked in water for 5 min. The fixed thrombus obtained was blotted between pieces of cellulose-based filter papers and weighed on a chemical balance. To obtain the exact data, we measured the amount of thrombus formed on sample with the same conditions five times for each sample. The percentage of thrombus on the PP film was calculated on the base of the equilibrated thrombus on glass, which was supposed as 100% at the same conditions.

### Platelet adhesion

The functionalized samples after grafting were hydrated by placement in phosphate-buffered solution (PBS; pH = 7.4)-filled polystyrene 24-wall vials for 10 min. Each rehydrated film was transferred into PRP

prewarmed to 37°C for 30 min. After incubation at 37°C. the samples were washed carefully with PBS to remove weakly adhered platelets. Platelets that remained adhered to the PP surfaces were fixed with 2.5% glutaraldehyde in PBS for 10 min at room temperature. The platelets fixed on the surfaces were dehydrated in an aqueous ethanol-grade series for 10 min after each was washed with PBS and were then allowed to dry on a clean hood at room temperature. The platelets attached to the PP samples were examined by scanning electron microscopy (SEM; JSM-840A, Jeol, Japan) with a tilt angle of 45°. In a previous article,[43] a detailed explanation was provided.

## RESULTS AND DISCUSSION

### Grafting polymerization

PP has an important place among the synthetic polymers because of its growing commercial applications. One of the main problems of using biomaterials has been surface-induced thrombus formation, which is initiated by the adsorption of certain plasma proteins and the adhesion of platelets. Appropriate surface modification of existing polymers possessing the desired physical properties is beneficial for the improvement of biocompatibility without the alteration of the bulk properties of the biomaterials. PP can acquire some additional properties needed for a biomedical application with no change to the original desirable properties. The removal of the tertiary hydrogen atom from the PP backbone by graft polymerization with a variety of monomers provides a powerful method for the partial modification of PP and the improvement of its properties.[25] Efforts have been made to modify PP by the graft copolymerization of an appropriate monomer to introduce reactive or polar sites into the PP structure that may be used as the desirable functional groups.[22,25,26,29,30,45]

Ionization radiation grafting has proven to be a very effective technique to impart desirable properties into polymers without any consideration of the shape of the material. The attractive feature of radiation grafting is that the size of the grafted component can be easily controlled by the proper selection of the irradiation dose and its intensity.[46] Methods for the achievement of a grafting reaction with ionization radiation include (1) simultaneous irradiation of a backbone polymer in the presence of a monomer,[47–49] (2) preirradiation of a backbone polymer in a vacuum or nitrogen gas and subsequent monomer grafting by trapped radicals,[50] and (3) preirradiation of the backbone polymer in the presence of air or oxygen and subsequent monomer grafting by trapped radicals and polymeric peroxides.[51] The preirradiation methods are suitable for polymer substrates having crystallinity. PP is a highly crystalline polymer; the crystallinity

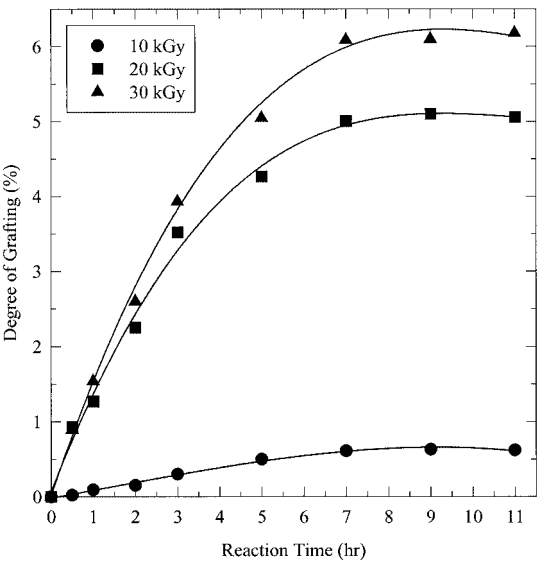


**Figure 1** Effect of reaction time on the grafting of EPMA onto irradiated PP films in 10 vol % EPMA methanol solution at 50°C.

of PP used in this experiment was found to be 63% on the basis of 147 J/mol of PP having 100% crystallinity. EPMA monomer was grafted onto PP film by a preirradiation method.

If crystalline polymers are subjected to radiation in air, a number of free radicals formed during irradiation are trapped in the rigid crystalline area of the polymer substrate, and at the same time, the trapped radicals may be gradually transformed into peroxides such as diperoxides (POOP) and hydroperoxides (POOH). Therefore, the trapped radicals and peroxides are presented in the irradiated polymer. The trapping of radicals in the polymer after irradiation is influenced by the physical state of the polymer substrate, that is, crystallinity and main chain mobility. In a previous study,[26] we found that the lifetime of the trapped free radical depends on the temperature of storage, and the concentration of trapped radicals is constant for up to 30 days in storage at −130°C in air. This can be attributed to the stoppage in the combination of free radicals, as described in eqs. (3), (4), and (5), which comes from the high crystallinity of PP film and the restriction of chain segmental motion at such a low temperature:

$$P\cdot + P\cdot \rightarrow P\text{—}P \tag{3}$$

$$POO\cdot + P\cdot \rightarrow POOP \tag{4}$$

$$POO\cdot + \cdot OOP \rightarrow POOP + O_2 \tag{5}$$

Figure 1 shows the effect of reaction time on the grafting of EPMA onto PP film that was preirradiated at 10, 20, and 30 kGy. The grafting yield, as shown, in-

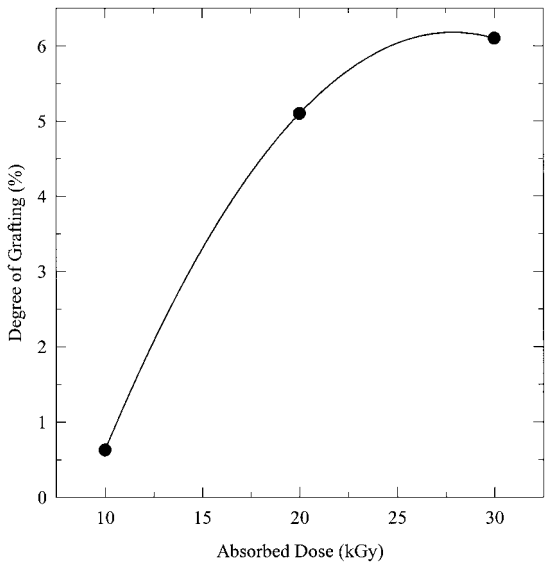


**Figure 2** Variation of the final grafting yield with preirradiation dose. The grafting conditions are the same as in Figure 1. The grafting reaction time was 9 h.

creased in proportion to reaction time up to 7 h and leveled off. For all three preirradiation doses, saturation in the grafting was achieved at around 9 h of grafting time.

Figure 2 shows the variation in the degree of grafting with preirradiation dose after grafting for 9 h. As shown in Figure 2, the higher the preirradiation dose was, the higher the grafting yield was. We interpret this to mean that such a high grafting yield in a high absorbed dose was due to the generation of a higher number of radicals on the PP film that were available for the grafting reaction with the EPMA monomer.

Figure 3 shows the effect of reaction time and temperature on the grafting polymerization. Regardless of reaction temperature, the grafting yield increased with increased grafting reaction time. When PP is irradiated in the presence of air, trapped and peroxy radicals capable of initiating the grafting reaction can be formed. If a monomer is allowed to diffuse into trapped or peroxy radicals, grafting takes place during the diffusion process. At higher grafting temperatures, the diffusion of monomer in the PP sample should be enhanced. As a result, the availability of the monomer to the grafting sites is increased, leading to a higher rate of propagation. The schematic mechanism is as follows:

$$P\cdot + M \rightarrow P\text{—}M\cdot \quad (6)$$

$$P\text{—}M\cdot + {}_nM \rightarrow P\text{—}M_{n+1} \quad (7)$$

Although the termination of primary radicals (P · ) by mutual recombination would also increase at a higher temperature , it seems that this deactivation is negligible as compared to the propagation reaction , leading to higher grafting yields. Also, the higher temperature results in the higher reactivity of radicals toward the monomer. Additionally, most of the grafting reaction, at particularly low reaction temperatures is caused by the only trapped radicals. In the case of high temperatures, however, it is possible that the reactive sites on the polymeric substrate can also be generated by the decomposition of peroxides such as diperoxides or hydroperoxides, leading to a higher grafting reaction.

When polymeric peroxides are used to initiate a graft polymerization reaction, diperoxides generate only a graft copolymerization, whereas hydroperoxides lead to an equivalent amount of graft polymers and homopolymers. The thermal decomposition of the diperoxide produces PO · radicals, whereas hydroperoxide produces PO · and OH · radicals. The OH · radicals produce homopolymers, which influence the grafting efficiency:

$$POOP \rightarrow PO\cdot + \cdot OP \quad (8)$$

$$POOH \rightarrow PO\cdot + \cdot OH \quad (9)$$

In a previous study,[45] we measured the formed peroxides by a 1,1-diphenyl-2-picrylhydrazyl (DPPH) technique when PP was irradiated at a dose of 30 kGy (exposure dose rate = 0.729 kGy/h). In that study, the DPPH technique was utilized to evaluate the concentration of peroxide formed in the irradiated polymeric substrate by counting of the quantity of DPPH consumed from the reaction of peroxide radicals with DPPH. Table I shows the amount of peroxide formed on PP film surfaces after irradiation (exposure dose

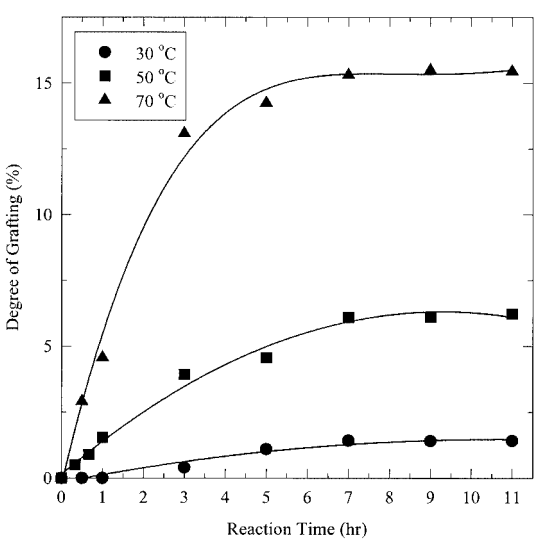


**Figure 3** Effect of reaction time on the grafting of EPMA onto 30 kGy irradiated PP film in 10 vol % EPMA methanol solution.

**TABLE I**
**Amount of Peroxide Formed on PP Films After Irradiation in Air**

| Irradiation dose (kGy) | Decomposed peroxide ($\times 10^{-6}$ mol/cm$^2$) |
|---|---|
| | — |
| 10 | 1.65 |
| 20 | 3.10 |
| 30 | 3.95 |

**TABLE II**
**Graft Polymerization of EPMA onto PP Films at 50°C for 7 h**

| Irradiation dose (kGy) | Grafting yield (%) | Amount of homopolymer (%) | Grafting efficiency (%) |
|---|---|---|---|
| 10 | 0.6 | 0.06 | 90.9 |
| 20 | 5.0 | 0.06 | 98.8 |
| 30 | 6.1 | 0.05 | 99.2 |
| 40 | 21.5 | 0.05 | 99.8 |

rate = 4.61 kGy/h) by the DPPH technique. The peroxide amount formed on the PP film after irradiation increased with increased absorbed dose.

Figure 4 shows the correlation of grafting efficiency and the grafting reaction time. Grafting efficiency decreased with increased grafting reaction time, as shown in Figure 4. We interpreted that the decrease in the grafting efficiency was due to a higher rate of homopolymerization as compared to the rate of grafting reaction. This is a feature that is evident in diffusion controlled grafting systems. In such grafting systems, the monomer availability to the grafting sites in the PP sample is considerably reduced, which eventually leads to a quick growing graft chain termination.

Table II shows the correlation of the grafting efficiency and the extent of homopolymer in the grafting reaction (EPMA concentration = 10 vol %). As shown, the amount of homopolymer formation was very low and almost similar regardless of the irradiation dose, and grafting efficiency was high in the high irradiation dose.

## Characterization of EPMA-grafted PP

FTIR–ATR and ESCA are generally regarded as important and key techniques for surface characterization and analysis. Particularly, ESCA provides total elemental analysis, except for hydrogen and helium, of any solid surface that is vacuum stable or can be made vacuum stable by cooling. Chemical bonding information is also provided. Of all the presently available instrumental techniques for surface analysis, ESCA is generally regarded the most quantitative, the most readily interpretable, and the most informative with regard to chemical information.[41] The chemical structure of the EPMA-grafted PP film was verified by FTIR–ATR and ESCA. Figure 5 shows the FTIR–ATR spectra of the control and grafted PP films. As shown, the new peak of carbonyl stretching (>C═O, at 1730 cm$^{-1}$) after grafting is presented. This peak increased with increased grafting yield. Figure 6 shows the absorbance ratios of C═O stretching to C—H bending bands from the spectra in Figure 5. The absorbance ratio increased gradually with the increased grafting yield, as shown in Figure 6. Figure 7(a,b) shows the ESCA spectra of the survey scan and its C1s core level, respectively. As shown in Figure 7(a), the EPMA-

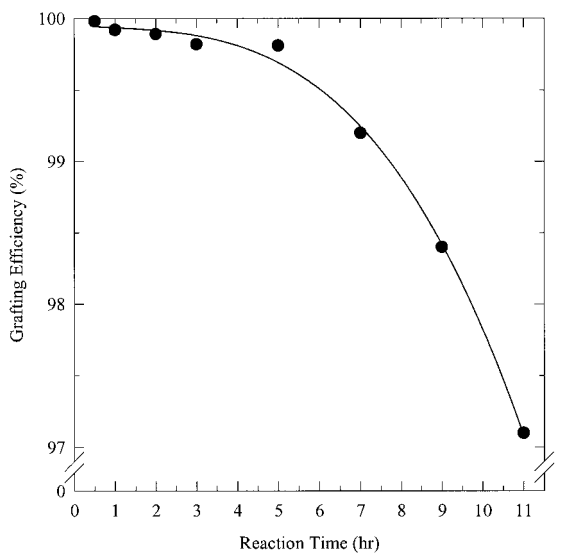


**Figure 4** Variation of the grafting efficiency with the grafting reaction time in 10 vol % EPMA methanol solution at 50°C. The absorbed dose was 30 kGy.

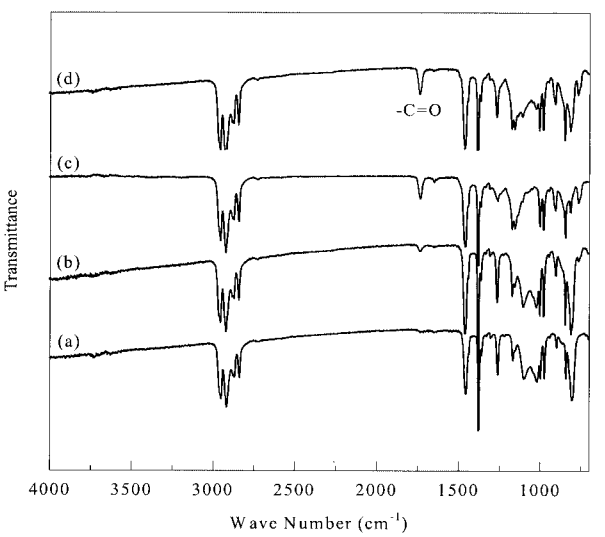


**Figure 5** FTIR–ATR spectra of (a) the control and (b) 3, (c) 7, and (d) 15% EPMA-grafted PP samples.

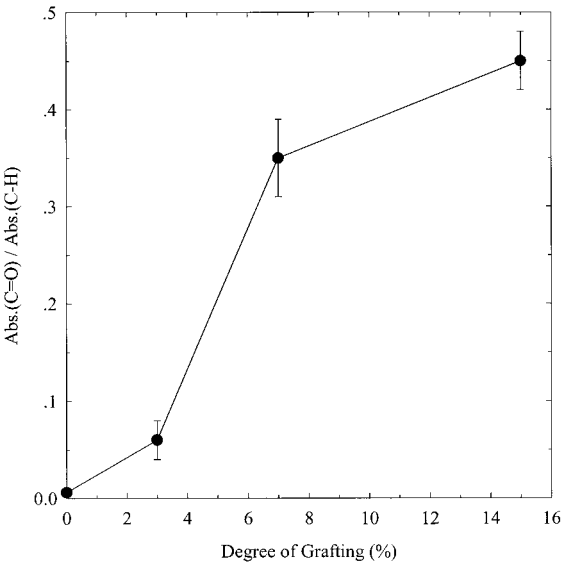


**Figure 6** Absorbance ratios calculated from the FTIR–ATR spectra in Figure 5.

grafted PP surface showed two peaks corresponding to a C1s and an O1s. The C1s core-level spectrum of Figure 7(a) is shown in Figure 7(b). The C1s spectrum was resolved into four characteristic peaks. The peaks at 288.6, 287.3, 286.3, and 284.6 eV on the PP surfaces indicate the functional groups of O—C═O, C═O, C—O, and C—C, respectively. Figure 8 shows the ESCA C1s core-level spectra of the control and grafted PP samples with the different grafting yields. With

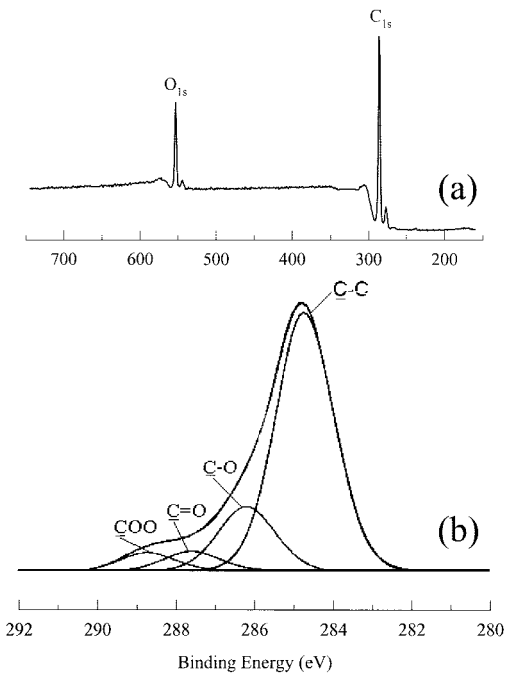


**Figure 7** ESCA spectra of (a) EPMA-grafted PP survey scan and (b) its C1s core level. The degree of grafting was 7%.

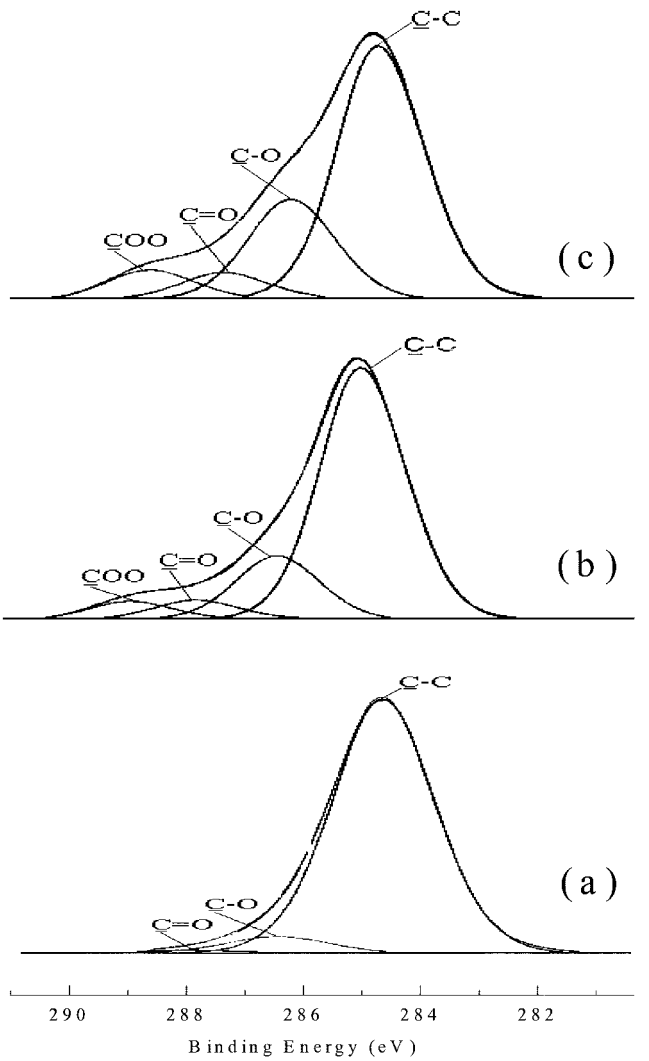


**Figure 8** ESCA c1s core-level spectra of (a) the control and (b) 7 and (c) 15% EPMA-grafted PP samples.

increased grafting yield, three characteristic peaks, functional groups O—C═O, C═O, and C—O, increased, whereas the C—C peak at 284.6 eV decreased. The PP sample without grafting had no peak for the O—C═O functional group. The atomic percentage calculated from the ESCA analysis and its ratio are shown in Table III.

**TABLE III**
**ESCA Analysis of PP Film and Grafted PP Film Surfaces**

| Grafting yield (%) | Atomic % | | | | O/C ratio |
|---|---|---|---|---|---|
| | —C—C— | —C—O— | —C═O | O═C—O— | |
| Control | 93 | 6 | 1 | — | — |
| 3 | 86 | 7 | 2 | 5 | 0.21 |
| 7 | 78 | 12 | 5 | 5 | 0.25 |
| 15 | 69 | 19 | 5 | 7 | 0.29 |

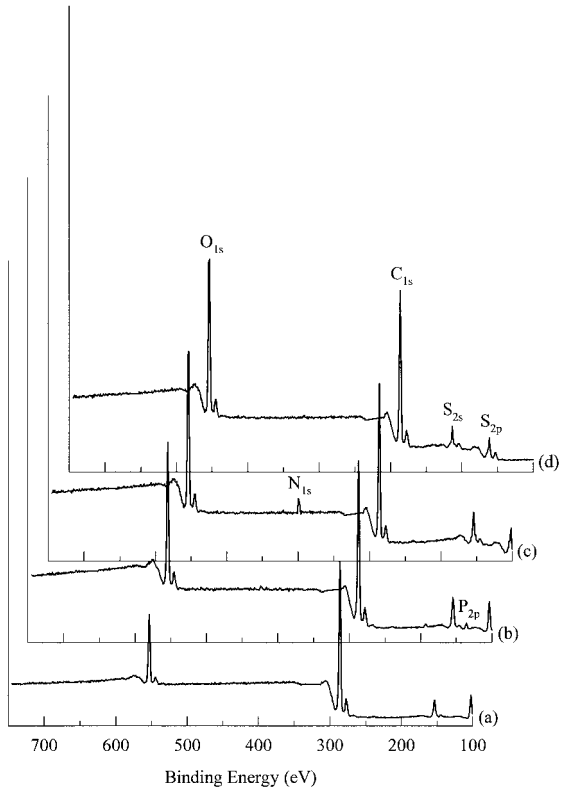


**Figure 9** ESCA survey scan spectra of (a) EPMA-grafted PP and (b) phosphonated, (c) aminated, and (d) sulfonated PP samples after grafting. The degree of grafting was 7%.

### Introduction of functional groups in EPMA-grafted PP

Knowledge of the interfacial interaction of polymers with blood is important in establishing polymer blood compatibility. Two important aspects of the interaction of foreign materials, polymeric substrates, with blood are platelet adhesion and blood coagulation, which leads thrombus formation on materials. These processes are dependent on the surface properties of the materials. When a material is exposed to blood, the first event that takes place is the adsorption of proteins from the blood onto the material surface. On adsorption of these proteins, the surface of the material is altered, and the subsequent events are determined by the modified material surface properties. Therefore, various kinds of functional groups were introduced onto the EPMA-grafted PP films at optimal reaction conditions, respectively, to compare the blood compatibilities of PP films with different functional groups.

Figure 9 shows the ESCA survey scan spectra of functionalized PP samples after grafting. From characteristic peaks of the introduced functional groups, it was found that functionalization reaction was preceded successfully.

Heparin is a hetropolysaccharide whose chains consist of alternating derivatives of 2-amino-2-desoxy-D-glucose and uronic acid linked together via 1→4 glycoside bonds.[41] The activity of heparin is, to a large extent, determined by the amount and the mode of distribution of the functional groups along the carbohydrate chain. The anticoagulant activity of heparin is endowed by its ability to form strong complexes with a variety of blood clotting factors and, thus, to neutralize their actions. Nowadays, the use of heparin for the thromboresistant-enhancing surface modification of polymeric materials seems quite obvious. To immobilize the heparin within the polymer, many methods have been reported, including physical adsorption, blending or dispersion, ionic bonding, and covalent bonding. Of the four methods, the ionic and covalent bonding methods were mainly used because they were fixed within the polymer or on the polymer surface and were not released from the polymer. Wilson[20] reported on heparinized polymers as thromboresistant biomaterials after the surface modification of various polymeric substrates was performed by physical adsorption, grafting coupling, and graft polymerization techniques. Han et al.[18] studied the surface modifications of polyurethanes by poly(ethylene oxide) grafting and/or heparin immobilization for long-term biomedical applications. Kang et al.[33] studied the blood compatibilities of heparin-immobilized polyurethane after modification by oxygen plasma glow discharge, and they reported that heparin was coupled to the carboxylic acid or amine groups grafted on the substrate surface. The aminated PP films after grafting were heparinized to obtain heparin-immobilized PP samples and identified by FTIR–ATR and ESCA, respectively, as shown in Figures 10 and 11. Figure 10 shows the FTIR–ATR spectra of grafted and heparinized samples, respectively. As shown in Figure

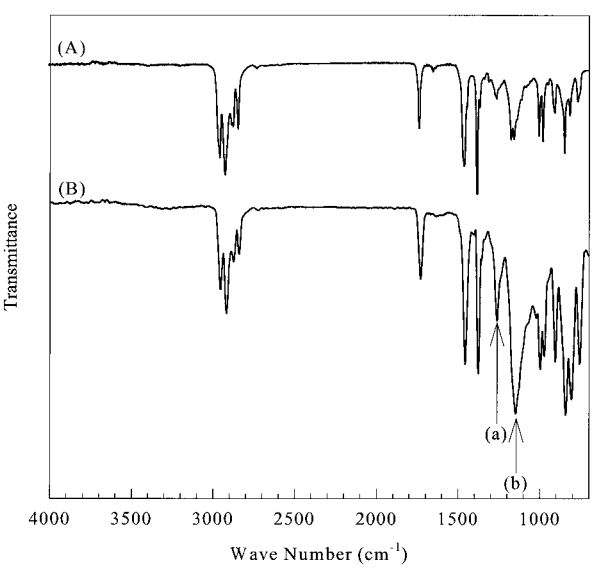


**Figure 10** FTIR–ATR spectra of (A) EPMA-grafted PP and (B) heparinized PP samples. The degree of grafting was 7%.

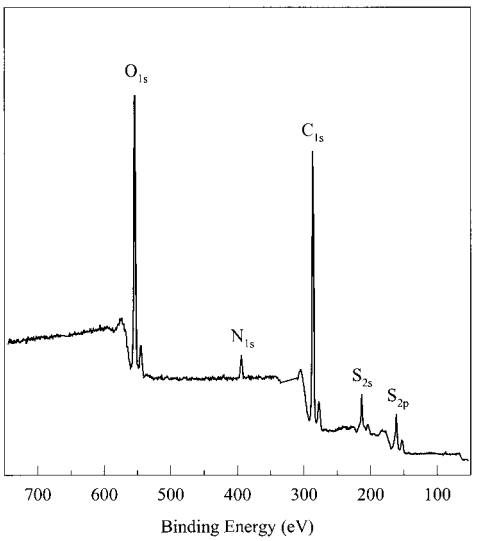


**Figure 11** ESCA survey scan spectrum of the heparinized PP sample. The degree of grafting was 7%.

10(B), the absorption around 1230 $cm^{-1}$, caused by S═O asymmetric stretching in heparin, probably overlapped the broad band at 1225–1230 $cm^{-1}$ by the C—O— linkage in the grafted sample [see peak (a)]. Symmetric stretching of S═O in the heparin may have overlapped the strong absorption at 1150 $cm^{-1}$ by the —C—O—C— of EPMA linkage [see peak (b)]. The ESCA survey scan spectrum of heparinized sample was shown in Figure 11. The ESCA spectrum showed five characteristic peaks corresponding to $C_{1s}$, $O_{1s}$, $N_{1s}$, and $S_{2s}$ or $S_{2p}$, as expected. This result was due to the significantly immobilized heparin to the PP sample.

## Blood compatibility

The wettability of a surface-modified material is one of the important factors affecting its blood compatibility. Hydrophilic polymeric surfaces reduce interfacial free energy between the polymeric material and blood, which increases the surface wettability of polymer. When a drop of liquid is placed in contact with a solid surface, it will either form a drop or spread to the sample. If a drop is formed, the angle that the drop makes with the surface will vary depending on the nature of the liquid and the surface. The angle is called the contact angle.

Experimental concerns in contact angle studies include contamination and the proper choice of solvents. Commonly used liquids are simple organics and, particularly for biomaterials, pure water. The contact angles of water droplets in air on various PP samples functionalized after grafting were examined to establish the relationship between the different functional groups and the hydrophilicity, as shown in Figure 12. As shown, the water contact angle for samples functionalized by different hydrophilic functional groups decreased with respect to the control or EPMA-grafted samples. For the phosphonated PP sample, the water contact angle was lower than that of the others. The phosphonated PP could be attributable to the hydrophilicity of the PP surface due to the minimum interfacial free energy with water.

When a foreign surface comes in contact with blood, the initial response is the adsorption of blood proteins, followed by platelet adhesion and activation of the coagulation pathways, leading to thrombus formation. A particularly effective polymer for the prevention of protein adsorption and platelet adhesion appears to be a hydrophilic polymer, probably because of its minimum interfacial free energy and high hydrophilicity.[13] Figure 12 shows the amount of thrombus formed on the control and the PP samples functionalized with various functional groups after grafting. The figure shows that the amount of thrombus formed on the functionalized PP film decreased with respect to the control; particularly, the amount of thrombus formed on the PP sample with the phosphoric acid group was lower than that of those with other functional groups except heparin immobilization. Such behavior was probably due to the minimum interfacial free energy in between the sample surface and the blood, as described previously. Figure 13 shows the SEM photographs of platelet adhesion on the PP surfaces after contact with PRP. As can be seen in figure, the PP sample with the phosphoric acid group had the low platelet adhesion. The phosphoric-acid-group-intro-

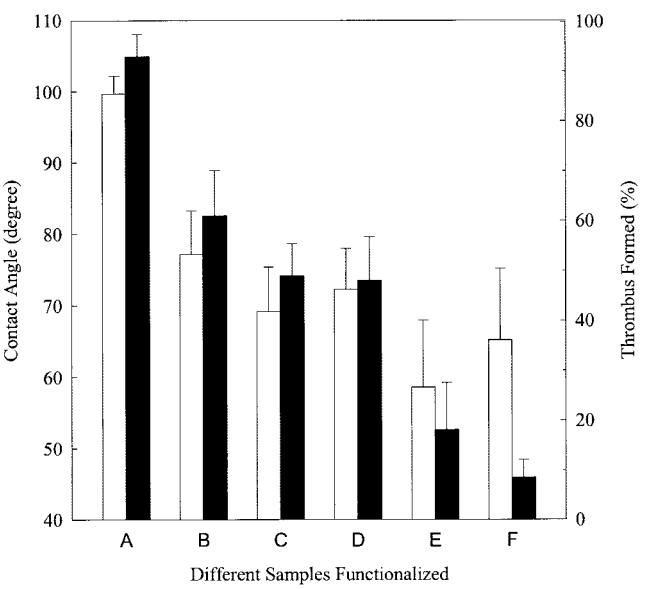


**Figure 12** Differences in the surface properties of (a) the PP control and PP samples introduced with (b) hydroxyl, (c) iminodiacetic acid, (d) sulfonic acid, and (e) phosphoric acid groups and (f) heparin after grafting. The degree of grafting was 7%. Unfilled bars represent the contact angle; filled bars represent the thrombus formed.

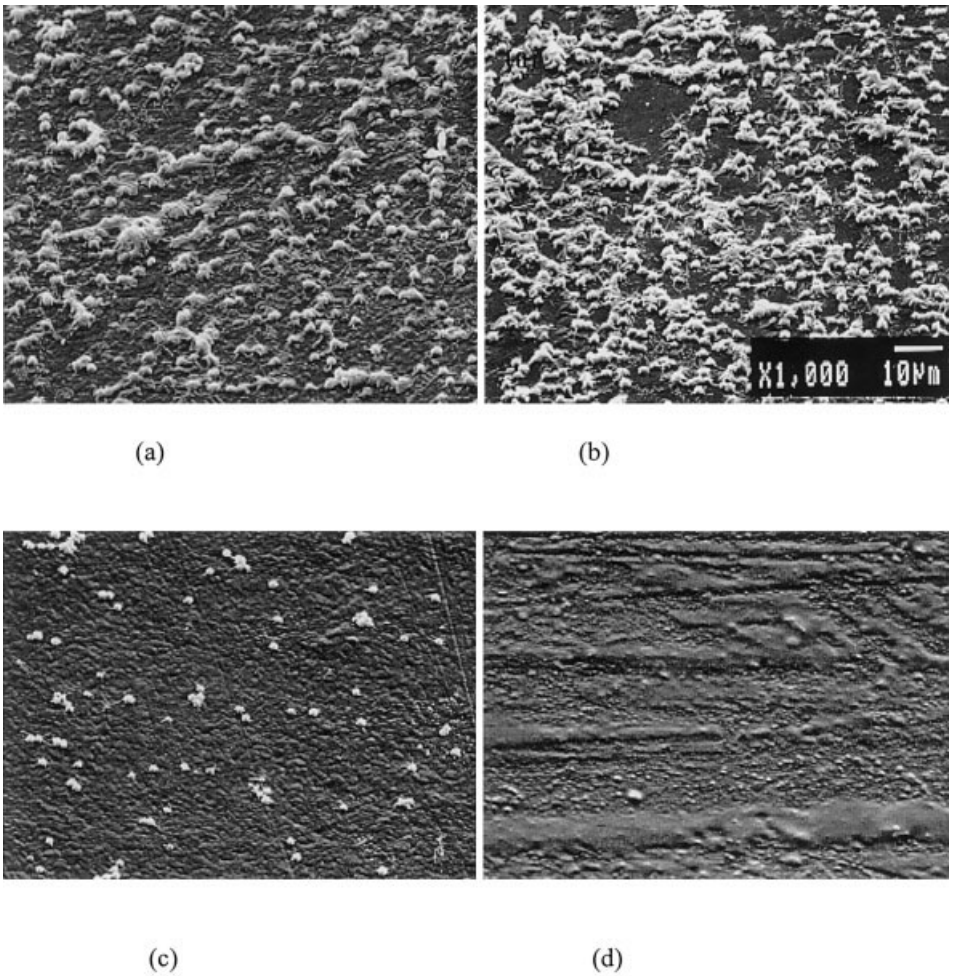


**Figure 13** SEM photographs of platelets adhered on (a) the PP control, (b) EPMA-grafted PP, and PP samples introduced with (c) phosphoric acid groups and (d) heparin after grafting. The degree of grafting was 7%.

duced and heparin-immobilized PP films had good blood compatibility properties.

## CONCLUSIONS

To endow blood-compatible properties onto PP film, EPMA was grafted to PP film with a preirradiation grafting technique, and then various functional groups were introduced onto the grafted PP film. The EPMA grafting extent was dependent on the absorbed dose, reaction time, and temperature. It was shown that the adhered platelet and amount of thrombus formed on the functionalized PP films decreased with respect to the control; particularly, the amount of thrombus formed on the PP sample with a phosphoric acid group was lower than that of those with the other functional groups except heparin immobilization. Phosphoric-acid-group-introduced and heparin-immobilized PP films had good blood compatibility properties.

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