

Radiation-Induced GMA/DMAA Graft Copolymerization onto Porous PE Hollow-Fiber Membrane

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ABSTRACT: Radiation-induced graft copolymerization is a powerful technique to prepare a grafted chain with the desired properties pending onto the trunk material. In this work, a polyethylene hollow-fiber membrane was modified by this technique. The monomers glycidyl methacrylate (GMA) and *N,N*-dimethylacrylamide (DMAA) were cografted onto macroporous polyethylene hollow fiber with a grafting degree in the order of 200%. DMAA/GMA cografted membranes were compared to GMA grafted ones for the introduction of an amino acid as a specific ligand. Grafted membranes with a copolymer composition between 0 and 2 DMAA/GMA were prepared by soaking them in solutions of different mixtures of monomers. Copolymers were char-

acterized by FTIR and their composition was estimated by the analysis of the ratio of carbonyl signals. Copolymers with a higher proportion of DMAA showed improved hydrophilic properties and higher conversion rates of epoxy groups on phenylalanine ligands than those of the GMA grafted ones. However, copolymers with a DMAA/GMA ratio higher than 1 showed a detrimental effect on the pure water flux. © 2002 Wiley Periodicals, Inc. *J Appl Polym Sci* 87: 1646–1653, 2003

Key words: electron beam irradiation; graft copolymers; membranes; polyethylene (PE)

INTRODUCTION

In conventional chromatographic matrices, the highly porous particles traditionally used were designed to maximize the surface area and therefore the binding capacity even though their internal morphology limits the mass transport in the chromatographic support. An important challenge is to find a way to expose the mobile phase and target molecules to the entire surface area of the chromatographic material quickly and efficiently, including the area inside the pores.

In this way, the synthesis of functionalized macroporous membranes is able to capture ions and molecules by a convection-aided mechanism, thus allowing a fast adsorption and elution process.¹ Different ion-exchange groups, chelate-forming groups, and small molecules such as amino acids and hydrophobic ligands have been attached onto the pores of hollow-fiber membranes.^{2–7} L-Amino acids have been used as pseudobiospecific affinity ligands for proteins of clinical interest. In this way, phenylalanine (Phe) and tryptophan can be used as ligands in the treatment of

immune diseases such as rheumatism and myasthenia gravis.⁸

Radiation-induced graft polymerization (RIGP) is a powerful technique for appending a polymer chain (grafted chain) uniformly onto a porous polymeric membrane (trunk polymer).⁵ Up to 14 mmol of glycidyl methacrylate (GMA) per gram of the trunk polymer can be added without important flux reduction.⁵ Potentially, a very high concentration of reactive epoxy groups is available for ligand immobilization. However, a different degree of success was found to turn all epoxy groups into the desired ligands. High epoxy conversion has only been successfully obtained by attaching charged and small groups (i.e., diethylamine, iminodiacetic) to GMA-grafted chains onto polyethylene (PE) hollow-fiber membrane.⁹ These ligands give them a hydrophilic environment in addition to electrostatic repulsion, which turns them into a partially opened graft polymer structure (tentacle or comb-type arrangement), thus increasing their binding capacity to target macromolecules.³ Amino acids as well as hydrophobic ligands have not shown a behavior similar to the one described above when they were attached to the same modified polymer matrix.^{6,7} In the same way, peptides and proteins have not been successfully attached to a GMA-grafted chain arranged as a comb-type structure.

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N,N-Dimethylacrylamide (DMAA) has been grafted onto polypropylene membranes by glow discharge-initiated grafted copolymerization.¹⁰ This membrane exhibited excellent plasma-separation capability and hemocompatibility. Nevertheless, a low grafting degree is necessary to maintain the flux through the membrane.¹⁰ Besides, DMAA does not have reactive groups necessary to attach ligands onto this grafted polymer.

The objective of this work was to obtain a grafted copolymer onto PE hollow-fiber membranes that can share the desired properties of the GMA and DMAA monomers: chemical reactivity and high permeation flux properties of the GMA-grafted membrane and hydrophilicity and swelling behavior of the DMAA-grafted ones. We chose Phe to be immobilized as a ligand onto the grafted polymeric chains.

EXPERIMENTAL

Materials

Porous PE hollow-fiber membranes were used as a trunk polymer for grafting. The inner and outer diameters were 0.7 and 1.2 mm, respectively, with a pore diameter of 0.1 μm and porosity of 71%. GMA and DMAA were purchased from the Tokyo Kasei Co. (Tokyo, Japan) and used without further purification. L-Phe and other reagents were of analytical grade or higher.

Grafting of GMA and coupling of Phe

As shown in Figure 1(Scheme I), GMA was first grafted onto the porous PE hollow fiber by radiation-induced graft polymerization: Hollow fibers of 10 cm were irradiated by an electron beam from a cascade-type accelerator (Dynamitron, Model IEA 3000-25-2, Radiation Dynamics, Inc.) at room temperature in a nitrogen atmosphere. The accelerator was operated at the beam energy of 1 MeV and a current of 1 mA. Immediately after irradiation with a total dose of 200 kGy, the hollow fibers were immersed at 313 K into a reaction ampule containing 10% (v/v) of GMA in ethanol. After a preset time, fibers were removed from the ampule and washed several times with DMF and methanol and dried. The add-on-grafted monomer onto the PE hollow fibers was determined by weight. The resultant modified hollow fiber is referred to as the GMA membrane.

Second, Phe was coupled to the epoxy group by soaking the grafted hollow fibers at 353 K in 0.08M Phe (pH 13 adjusted using 1M NaOH). The reaction was developed up to 24 h, and after various preset times, the fibers were washed with water repeatedly, dried, and weighed. The add-on of the ligand onto the

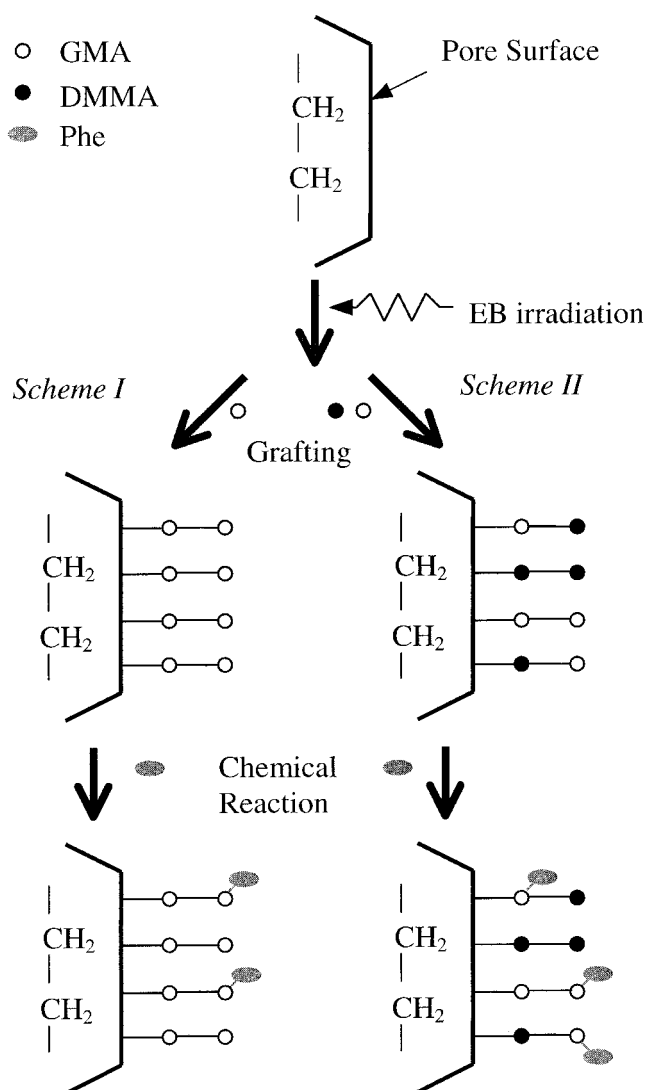


Figure 1 Preparation schemes for the addition of Phe onto PE hollow-fiber membrane: (Scheme I) GMA-grafted polymer; (Scheme II) GMA/DMAA-grafted copolymer.

grafted hollow fibers was determined by an increment of weight. The resultant modified hollow fiber is referred to as the Phe-GMA membrane.

Grafting copolymerization of GMA-DMAA and coupling of Phe

GMA and DMAA were copolymerized onto the porous PE hollow fiber by the same preirradiation technique as for GMA: Hollow fibers, 10 cm, were irradiated as previously described. Immediately after irradiation [Fig. 1(Scheme II)], the hollow fibers were soaked at 313 K into a reaction ampule containing a solution of 10% (v/v) of GMA and a variable volume of DMAA in ethanol. Final concentrations of 3.5, 7, 15, and 30% (v/v) of DMAA were used to prepare the different monomer solutions. Polymerization reac-

tions were stopped and the washing step was carried out in a way similar to that described in the previous section. Add-on grafted monomers onto the PE hollow fiber were determined by weight. The difference of a grafted copolymer in a monomer composition, represented as the DMAA/GMA (D/G) ratio, was determined by IR spectroscopy (see below). The resultant modified hollow fiber is referred to as the *X* D/G membrane, where *X* is the molar ratio.

In the second step, the chemical reaction procedure is similar to that described in the section Grafting of GMA and Coupling of Phe. Briefly, Phe was coupled to the epoxy groups by soaking the grafted hollow fibers at 353 K in 0.08M Phe (pH 13). After various preset times, the fibers were washed with water repeatedly, dried, and weighed. The add-on of the ligand onto the grafted hollow fibers was determined by an increment of the weight. The resultant modified hollow fiber is referred to as the Phe-*X* D/G membrane.

Determination of the D/G ratio

The grafted copolymer composition was estimated from the carbonyl IR signal area through a ratio of carbonyl peak areas corresponding to GMA and DMAA. A calibration curve of the ratio of carbonyl IR signal areas was previously performed using monomer mixtures. Transmission IR spectra (absorbance mode) were recorded for GMA, DMAA, and seven different mixtures of both monomers on KBr pills (0.2–7 D/G molar ratio) by an FTIR Shimadzu 8100A spectrometer. The area ratio was calculated from the carbonyl stretching vibration signals (very strong intensity, 1720 and 1649 cm^{-1} corresponding to GMA and DMAA, respectively). A previous subtracting procedure on the DMAA carbonyl signal area was performed to a spectra of mixture samples. This procedure was followed to avoid the contribution of the GMA vinyl stretching vibration signal area (1637 cm^{-1}) to the spectra of the monomer mixtures. The signal ratio against the monomer molar ratio composition was fit and linear regression was performed. This procedure gives a straight calibration line with a correlation coefficient of 0.993. To estimate the relative monomer composition of the grafted copolymer materials, we assumed that the carbonyl IR signal ratio of the monomer mixture samples and the carbonyl IR signal ratio of the grafted copolymer samples are similar.

Grafting and conversion degree determinations

Degree of grafting (dg) was defined as

$$\text{dg} (\%) = 100 [(W_1 - W_0)/W_0] \quad (1)$$

where W_0 and W_1 are the weights of the original and grafted hollow fibers, respectively.

The weight increment ratio was defined as

$$\text{WR} (\%) = 100 [(W_2 - W_1)/(W_1 - W_0)] \quad (2)$$

where W_2 is the weight after the Phe add-on reaction onto the GMA hollow fiber.

Degree of epoxy conversion (*X*) in the Phe reaction for GMA-membrane was defined as

$$X (\%) = 100 \{[(W_2 - W_1)/165]/(W_1 - W_0)/142\} \quad (3)$$

where 165 and 142 are the Phe and GMA molecular weights, respectively.

To calculate the *X*% in the Phe add-on reaction for the *X* D/G membranes, we took into account the following two assumptions: (a) All the epoxy groups were converted and (b) two chemical conversion reactions on this group are possible: Phe addition or epoxy hydrolysis. Hence, the following formula can be derived:

$$X (\%) = 100 \{[(W_2 - W_1) - 18 \times mG / (165 - 18)] / mG\} \quad (4)$$

where *mG* corresponds to the GMA molar quantity in the copolymer and can be defined as

$$mG (\text{mol}) = (W_1 - W_0) / (142 + 99 \times D/G) \quad (5)$$

where 99 is the DMAA molecular weight and *D/G* is the molar ratio of DMAA to GMA on the grafted membrane according to the IR measurements.

Photos of the GMA and D/G membranes were taken by scanning electron microscopy (SEM). Hollow-fiber membranes were fractured under liquid nitrogen to observe the internal pore structure.

Determination of pure water-flux permeation

The permeation flux of pure water through the fiber membrane was measured by a constant pressure method working at 0.1 MPa using a home-made apparatus like the one described by Yamagishi et al.⁵ After membranes were soaked in methanol, water was forced to permeate radially outward across the hollow fiber. Permeation flux was obtained by dividing the permeation flux rate by the inside surface membrane area.

Determination of swelling parameter

The swelling ratio is defined as the relative outer diameter ratio of hollow-fiber membranes in wet and

dry states. The outer diameter of the grafted hollow fibers were measured with a scale using an optical microscope before and after 20-min hydration at room temperature. A 10-min methanol treatment of the dried membranes was necessary to fill the pores before water treatment. The swelling parameter ratio (*SW* %) was defined as follows:

$$SW \% = (D_w - D_d)/D_d \times 100 \quad (6)$$

where D_d and D_w are the outer diameter of the membrane in the dry and wet states, respectively.

RESULTS AND DISCUSSION

Grafting copolymerization is used to modify membranes using a procedure which involves their activation by an electron-beam accelerator. GMA and DMAA were the selected monomers to be cogenerated onto macroporous PE hollow-fiber membranes. The characteristics of the procedure to be described are the grafting rates, chemical reactivity to the Phe addition reaction, swelling properties, and water permeability performance. Also, spectroscopic IR measurements were used to characterize the grafted copolymers and to analyze their composition.

Comparison of grafting rates

Radicals formed on the trunk polymer (PE) by electron-beam irradiation were the initial step in the polymerization reaction to grow a grafted chain from a vinyl monomer solution. Grafting rates of GMA, DMAA, and a mixture of both in an equimolar ratio onto the porous PE hollow fiber are shown in Figure 2. PE membranes soaked in a GMA monomer solution exhibited a very high grafting rate as a consequence of a large internal area exposed; in contrast, membranes soaked in a monomer solution containing the same concentration of DMAA instead of GMA showed only a negligible amount of grafting under the same reaction conditions (trunk polymer, temperature, and solvent). Other authors have also obtained negligible DMAA grafting quantities using ethanol and methanol as the solvent onto fluoropolymers by the mutual grafting technique.¹¹

The occurrence of the grafted polymer and the rate of its growth is in correspondence with the relative amount of GMA in the monomer mixture. As shown in Figure 3, the increasing amount of the DMAA monomer added to a constant GMA volume (10% v/v) in ethanol has a deleterious effect on the PE membrane grafting degree after 2 h of the grafting reaction.

D/G ratios onto the grafted polymer structures were estimated by FTIR spectroscopy. Carbonyl IR

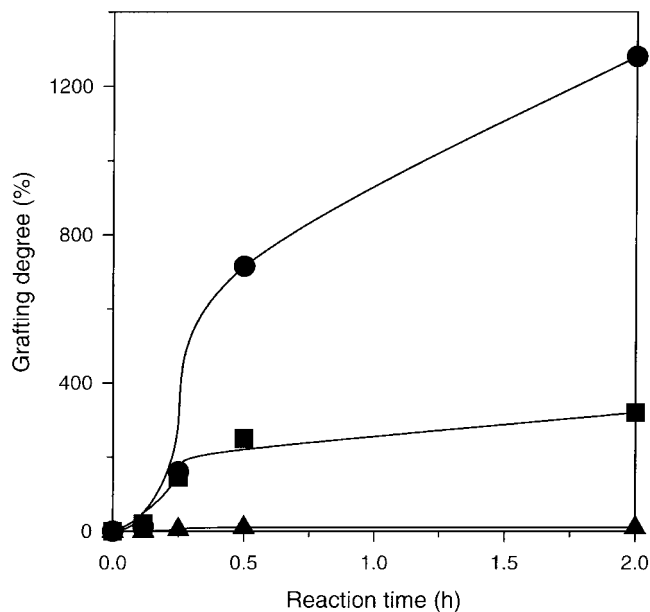


Figure 2 Effect of grafting reaction time of pure monomer solutions and monomer mixture on grafting degree onto PE hollow-fiber membranes: (▲) DMAA; (■) DMAA/GMA 1/1; (●) GMA.

signals area ratios were used to calculate the monomer constitution on the grafted copolymers. This ratio was calculated from a calibration curve determined using different monomer mixtures. D/G ratios in the polymer constitution showed a linear relation between a 1 and 4 D/G monomer ratio (Fig. 3). Nevertheless, this polymer composition ratio is not proportional; the GMA ratio in the grafted polymer increases in respect to the monomer ratio in the initial reaction vessel.

To perform the following comparative study, GMA membranes and four different D/G membranes with a grafting degree from 170 to 220% were synthesized. It was reported that the internal pore structure and constant water permeability of hydrolyzed GMA membranes are constant in a range up to 320% of the grafting degree.¹² Moreover, a grafting degree in the order of 200% was selected to obtain diverse adsorptive membranes from them.^{13,14}

Phe add-on chemical reaction

GMA membranes and four D/G membranes were used as reactive materials to attach Phe as a ligand. The reaction was carried out on alkaline medium (pH 13) at 353 K. To quantify the ligand immobilized by the chemical reaction, a weight increment ratio (*WR*) was defined. *WR*, defined by eq. (2), describes the addition of material (phenylalanine and hydroxyl groups, see below) relative to the mass added as the grafted polymer constituted by GMA and DMAA.

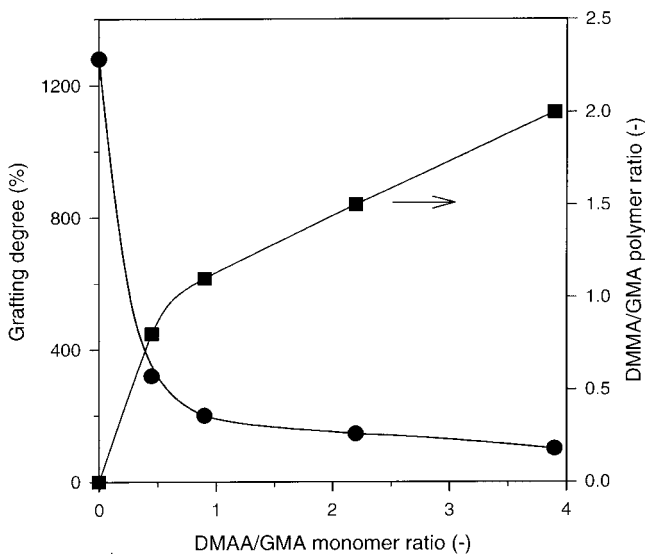


Figure 3 Effect of DMAA/GMA monomer ratio in the reaction vessel on the grafting degree at 2-h reaction time and the copolymer composition ratio: (●) grafting degree; (■) grafted copolymer composition.

Figure 4 shows the *WR* through the chemical reaction time.

Under this reaction condition, a low hydrolysis side reaction was described for the GMA membranes.^{6,15} Unreacted epoxy groups remain in the polymer structure even after a 24-h addition-reaction as was measured by FTIR (data not shown). Hence, Phe addition

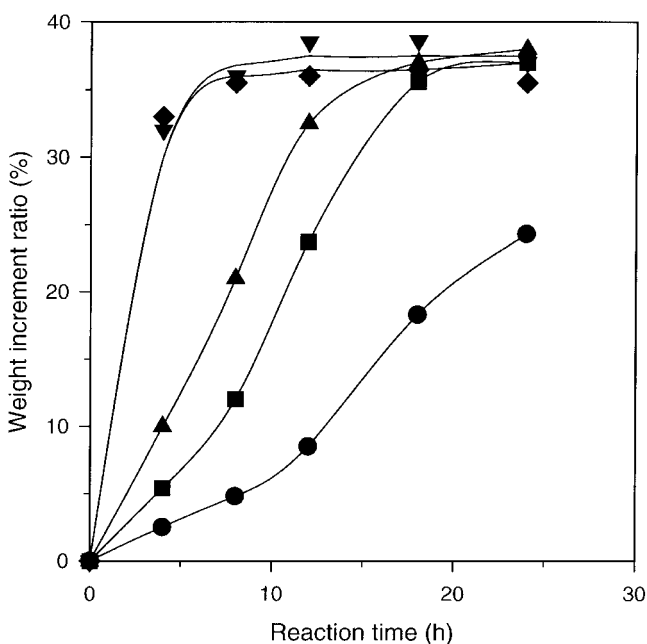


Figure 4 Effect of Phe add-on reaction time on the weight increment ratio (*WR*) for GMA and GMA/DMAA membranes: (●) GMA; (■) D/G = 0.9; (▲) D/G = 1.1; (▼) D/G = 1.5; (◆) D/G = 2.

and molar conversion can be calculated, without a significant error, by weight-difference calculations. The GMA membrane showed an epoxy conversion ratio of 20% (on total weight base) in accordance with Kiyohara et al.⁶

All the D/G membranes showed a higher weight increment ratio than that of the GMA membrane, although similar final weight increase ratios were found for all cografted ones, which were around 35% (Fig. 4). The rate to reach the maximum conversion, however, was different for D/G membranes, showing higher rates as the DMAA proportion in the grafted copolymer composition increased.

Based on the FTIR measurements and in contrast to the GMA membranes, all D/G-grafted ones showed a full epoxy group reaction after 24 h (data not shown). We have already reported that D/G-grafted membranes are sensitive to alkaline hydrolysis as a differential behavior to GMA membranes.¹⁵ Taking this fact into account, we can consider two main reactions: Phe addition and epoxy hydrolysis. Therefore, it is possible to estimate the Phe addition and the conversion ratio using eqs. (4) and (5) defined in the section Grafting and Conversion Degree Determinations.

Figure 5 shows the epoxy conversion of the GMA fraction of the grafted copolymer in the Phe add-on reaction. The GMA membrane shows only 20% epoxy conversion as was previously reported.^{6,16} The efficiency of Phe addition against the hydrolysis reaction increased as the proportion of the DMAA monomer in the copolymer structures was higher. There are at least

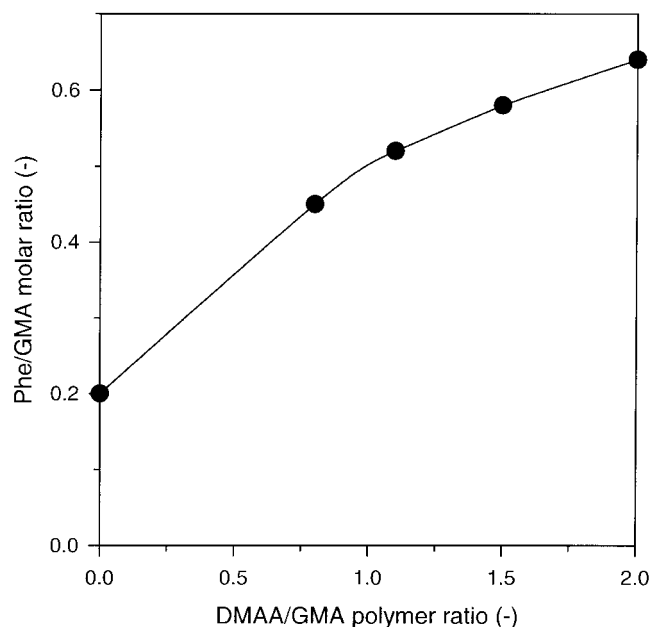


Figure 5 Effect of copolymer composition on the Phe add-on reaction after 24-h reaction. Phe/GMA molar conversion ratio is plotted against D/G polymer ratio.

TABLE I
Swelling Parameter Ratio for GMA/Membrane and Different D/G Cografterd Membranes Before and After 24 h Phe Add-on Reaction

Membrane type	SW (%) before chemical reaction	SW (%) after chemical reaction
GMA membrane	1.4	3
0.9 D/G membrane	1	7.2
1.1 D/G membrane	1.1	7.7
1.5 D/G membrane	2.5	10
2 D/G membrane	5	25

two possible explanations for the increased efficiency of the add-on reaction: First, there is a better reactant diffusion since copolymers are more water-soluble. Second, there is less steric hindrance. Therefore, it is possible to increase the add-on epoxy conversion up to 64% for a 2 D/G-grafted copolymer after 24 h of reaction. This high conversion degree was only previously achieved onto GMA membranes using diethylamine (80% conversion⁹) and iminodiacetate (60% conversion⁹).

Comparison of swelling parameter and pure water flux

The measurement of the relative fiber diameters in wet and dry states gives a parameter to compare the hydrophilicity of the grafted materials. Thus, a swelling ratio (SW) is defined by eq. (6) in the section Determination of the Swelling Parameter, and the results of the effect of the monomer composition of the grafted copolymers are tabulated in Table I. For the SW of the membranes, 0.9 D/G and 1.1 D/G membranes kept the outer diameter constant before the chemical reaction and higher ratios (1.1–2 D/G) showed a small increase in the swelling parameter. A significant increase in SW is shown for all membranes during and after the chemical reaction (Table I and Fig. 6). Phe-GMA hollow fibers showed a low increase on the outer diameter, mainly as a consequence of the PE matrix swelling induced by the alkaline medium of the Phe add-on reaction.⁶ However, the progressively higher increase on the SW achieved on the D/G membranes is assigned to the hydrophilicity of DMAA.

A swelling ratio trend (Fig. 6) for every copolymer shows a close similarity to the WR % trend shapes (Fig. 4). In spite of this similarity to the WR % plots of all the D/G membranes, the SW of each copolymer shows different end values at long conversion times (SW % between 5 and 25).

The permeation flux measured at 0.1 MPa was determined for the GMA and Phe-GMA membranes and the D/G and Phe-D/G membranes (24-h reaction time). Figure 7 shows the pure water permeation flux relative to the permeation flux of the GMA membrane.

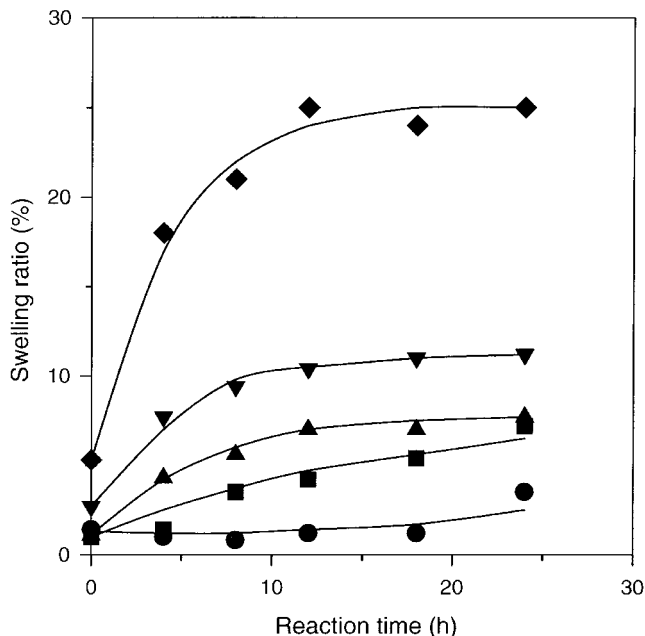


Figure 6 Effect of Phe add-on reaction time on swelling parameter ratio (SW) for GMA membrane and DMAA/GMA membranes: (●) GMA; (■) D/G = 0.9; (▲) D/G = 1.1; (▼) D/G = 1.5; (◆) D/G = 2.

Up to a 0.9 D/G ratio, the permeation flux kept to a similar flux performance. However, higher D/G ratios showed a progressive flux reduction up to a negligible permeation flux for the 2 D/G-cografterd membrane. A similar tendency was achieved for the Phe-GMA

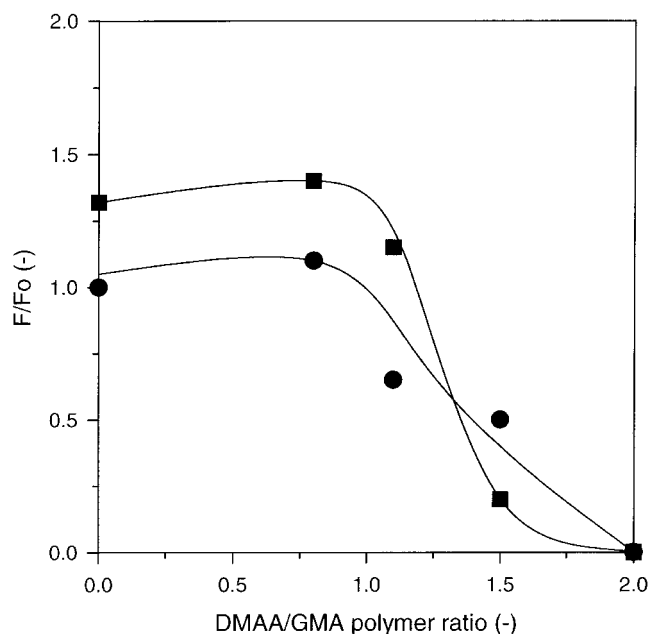


Figure 7 Effect of DMAA/GMA polymer composition on permeation flux properties, measured as relative flux in respect to GMA membrane pure water flux at 0.1 MPa pressure: (●) epoxy membranes; (■) Phe membranes.

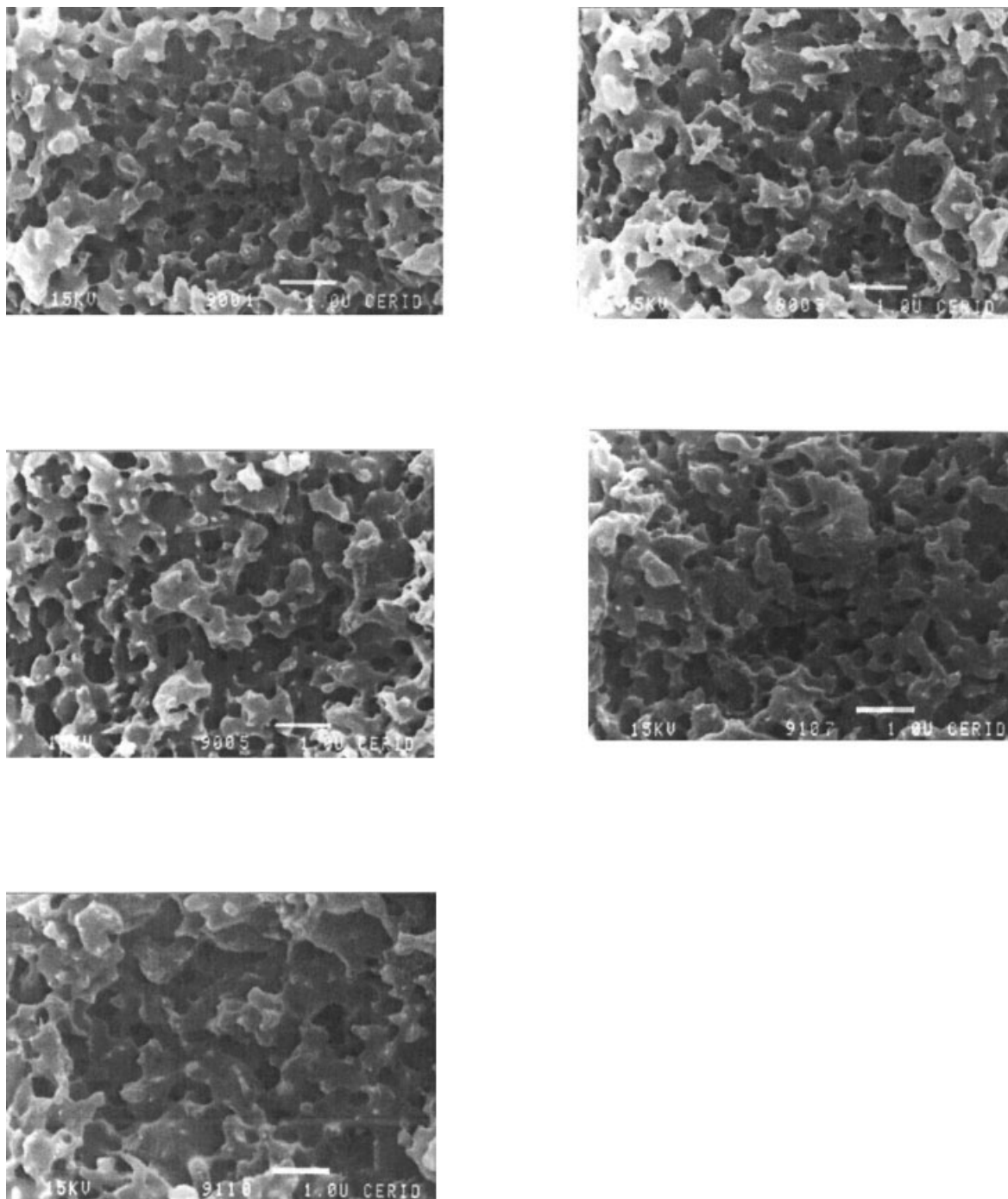


Figure 8 SEM photos of (top left) GMA membrane and D/G cografted membrane: (top right) 0.9 D/G, (middle left) 1.1 D/G, (middle right) 1.5 D/G, and (bottom). 2 D/G.

membrane and the Phe-D/G membranes with two main differences: First, a higher permeation flux was shown for the Phe-GMA and low ratio Phe-D/G membranes than for the epoxy membranes. This behavior was due to the swelling effect of the alkaline solution onto the PE matrix during the Phe addition reaction.⁶ Second, the Phe-1.5 D/G membrane showed a lower permeation flux than that of the epoxy

cografted one. This behavior could be due to partial stretching of the grafted structure as a consequence of the more hydrophilic structure of the Phe membrane than that of the GMA membrane. Finally, the negligible permeation flux measured for the 2 D/G membranes (epoxy and Phe) could be explained by the stretching behavior of the copolymer reached in the DMAA monomer. The permeation flux reduction be-

havior is in accordance with the swelling properties displayed by the D/G membranes.

Porous internal structure

Modified membranes were dried under reduced pressure and fractured in liquid nitrogen. The cross section, perpendicular to the main membrane axis, was observed by SEM. Figure 8 shows SEM photos of the GMA and D/G membranes where the internal porous structure of all of them is maintained.

CONCLUSIONS

A porous PE hollow-fiber membrane was modified by radiation-induced grafting copolymerization. Membranes in which DMAA and GMA were cogenerated [Fig. 1(Scheme II)] and GMA-grafted ones [Fig. 1(Scheme I)] were compared for the introduction of an amino acid as a ligand. The addition of DMAA in the composition of the copolymer material reduces the grafting and the rate to generate it. However, copolymers with a composition up to two DMAA units per GMA were achieved with a grafting degree of 200%.

GMA can be replaced by DMAA up to approximately 50 mol % without changing permeation fluxes. Afterward, a higher proportion of DMAA, a more hydrophilic monomer, reduces the permeability to negligible values. The total epoxy reaction was achieved for all D/G copolymers at a 24-h reaction time. Ligand addition on epoxy groups as high as 64% can be performed for the most hydrophilic copolymer. Additionally, a 1.5-fold increase in the ligand concentration per grafted polymer was achieved in all the DMAA/GMA-cogenerated membranes compared to the GMA grafted ones.

We expect that the maximum binding capacity to specific target molecules could be improved by using these cogenerated membranes, based on the following observations: (a) a higher ligand density; (b) a more hydrophilic environment of the DMAA/GMA copolymer; and (c) a more homogeneous distribution of the ligand onto the grafted copolymer structure compared to the GMA grafted membranes.

The characterization of grafted polymer branches prepared by radiation-induced cogenerated on PE is very difficult. However, a first approach to determine the copolymer composition and its useful range in pseudobiospecific ligand immobilization onto PE membranes was attempted.

NOMENCLATURE

D_d	outer diameter membrane in dry state
D_w	outer diameter membrane in wet state
DMAA	<i>N,N</i> -dimethylacrylamide
D/G	DMAA/GMA molar ratio
GMA	glycidyl methacrylate
IR	infrared spectroscopy
SW	swelling parameter ratio (%)
SEM	scanning electron microscopy
WR	weight increment ratio (%)
W_0	weight of original hollow fiber (g)
W_1	weight of grafted hollow fiber (g)
W_2	weight of Phe hollow fiber (g)
X	molar conversion due to Phe addition to the epoxy group

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