Radiation Synthesis of Binary Hydrogels with Thermoresponsive Pores

Nobuhiro Sato*, Manabu Ueda, Tomochika Matsuyama and Masaaki Sugiyama
Research Reactor Institute, Kyoto University, 2-1010 Assahiro-nishi, Kumatori-cho, Sennan-gun, Osaka 590-0494 Japan
Fax: 81-72-451-2633, e-mail: sato-n@rri.kyoto-u.ac.jp

Two types of hydrogels composed of poly(ethylene glycol) (PEG) and poly(N-isopropyl acrylamide) (PNIPAm) were synthesized via γ-ray-induced gelation. One type gel was a solid binary hydrogel. Gelation of PEG aqueous solutions was performed by γ-irradiation and homogeneous PEG matrix gels impregnated with NIPAm was also irradiated with γ rays. The other type gel was a porous binary hydrogel. It was also synthesized by γ-irradiation to a porous PEG matrix gel impregnated with NIPAm. The porous matrix gel was made by mixing silica microparticles (ca. 1.0 μm in diameter) into a PEG aqueous solution before gelation and then chemically decomposing them after gelation. These hydrogels show different thermoresponsive behavior. The swelling ratio of both hydrogels is reduced when the temperature is raised from 12 to 40 °C. However, the swelling ratio of the porous binary hydrogels was smaller than that of the solid binary hydrogels. In the solid gel, the PNIPAm chains are uniformly distributed and therefore the contraction of PNIPAm chains causes the shrinkage of the whole gel. In contrast, the PNIPAm chains of the porous gel are more localized in the pore spaces of PEG matrix gels, and exert less influence on the volume change of the whole gel.

Key words: Radiation synthesis, Hydrogels, Porous gels, Thermoresponsive materials

1. INTRODUCTION

Poly(N-isopropyl acrylamide) (PNIPAm) is widely known for its thermoresponsive nature based on the coil-globule transition of its polymer chain at its lower critical solution temperature (LCST). PNIPAm hydrogels are also thermoresponsive and exhibit an abrupt volume change at LCST around 34 °C [1, 2]. Many attempts have been made to utilize this property for the functional materials such as actuators[3], drug delivery system[4], and separation processes[5]. Other common polymer hydrogels such as a poly(ethylene glycol) (PEG) hydrogel hardly show such clear thermoresponsive behavior, but the incorporation of PNIPAm chains into the matrix of common hydrogels is expected to render them thermoresponsive as keeping original merits of the matrix gels, such as biocompatibility, easy preparation, costs and availability.

We have been studying the γ-ray-induced modification of polymeric systems to fabricate the functionalized materials of nano molecular assembly [6-12]. The γ-ray-induced modification has a unique advantage in material preparation. Since high-energy photons can directly generate active species in the target materials, chemical reactions can be promoted without any additives like reaction initiators, promoters, and catalysts, which merit leads to fewer impurities in the final products. Moreover, hydrogels are widely used as biocompatible materials and therefore residual impurities are required to be as few as possible. Another merit lies in the gel structure. In general, polymer gels are made by cross-linking of polymers by using various cross-linking reagents. However, the cross-linker induces the structural disorder in the gel system. On the contrary, γ-ray-induced gelation requires no cross-linkers and therefore the disorder brought by the external factors can be suppressed [13, 14].

In this study we treat the binary hydrogels in which PNIPAm is incorporated into a PEG matrix gel. Preparation of the PEG matrix gel and incorporation of PNIPAm were both carried out by γ-ray-induced reaction. Two types of matrix gels were prepared before incorporating of PNIPAm: one is a nonporous solid PEG hydrogel, and the other is a porous PEG hydrogel. Here, we report the thermoresponsive property of these two types of gels in terms of swelling behavior in water, as well as the characteristics of the porous binary gel in which PNIPAm gel is localized in the pore.

2. EXPERIMENTAL

A typical method of γ-ray-induced binary gel preparation is illustrated in Figure 1. In the first step, solid (nonporous) and porous PEG matrix gels were prepared. PEG (M.W. 20,000, Wako pure chemical) was dried for 1 h under vacuum at 60 °C before use. A PEG aqueous solution (10 wt%) bubbled with nitrogen gas for 1 min was sealed in a sample tube and then irradiated with γ rays from the 60Co γ-ray source of Research Reactor Institute, Kyoto University. After the irradiation, several rectangular pieces (ca. 5 × 5 × 2 mm) were cut out from the formed gel. Unreacted PEG was removed out by the three-time washing procedure of soaking in water and then drying in vacuum at 60 °C both for several hours. Thus the solid PEG matrix gel was obtained. The porous PEG gel was synthesized as follows. Silica
microparticles (Nippon Shokubai KE-P100, mean diameter 1.02 µm) were fully mixed in a 10 wt% PEG aqueous solution with ultrasonic irradiation. The ratio of silica/PEG, which is hereafter referred to as $r_{Si}$, was 1.0 and 0.1. The silica-dispersed solution was irradiated with $\gamma$ rays, and the unreacted PEG in the formed gel was washed out as described above. Then the silica in the gel was decomposed by chemical treatment with hydrofluoric acid. In the second step, PNIPAm was incorporated into the PEG matrix gels as follows. The PEG matrix gel was first completely dried in vacuum at 30 °C for 12 h. The dry gel was immersed in an excess amount of N$_2$-bubbled aqueous solution (10 wt%) of an N-isopropyl acrylamide (NIPAm, Wako pure chemical) monomer. Thus PNIPAm are impregnated into the PEG gels. The weight ratio of impregnated PNIPAm to PEG was about 2. After taken out from the NIPAm solution, it was again irradiated with $\gamma$ rays, and the product gel was washed by the similar manner for the PEG matrix gel to remove unreacted NIPAm. Thus the PEG/PNIPAm binary hydrogels were obtained. For all $\gamma$-irradiations, the dose rate was fixed to 3.0 kGy/h.

The PNIPAm content in the binary gel defined as the weight ratio of PNIPAm to PEG was evaluated in the following manner using IR spectroscopy. First, IR spectra were measured for various compositions of PEG/PNIPAm polymer blends. The absorbance ratio of the C=O stretching peak at 1647 cm$^{-1}$ to the C−O stretching peak at 1105 cm$^{-1}$ was plotted against the weight ratio of the PEG/PNIPAm polymer blends. This plot was used as the master curve. Next, the IR spectrum of PNIPAm-incorporated gels was measured, and the height of the above two peaks was obtained. Finally, the weight ratio of the two components in the binary gel was evaluated from the absorbance ratio with reference to the master curve.

The swelling ratio of the gel was determined by the weight ratio of the fully-swollen gel to the dry gel. The swelling ratio measurement was carried out at 12 and 40 °C, which are below and above LCST of PNIPAm, respectively.

3. RESULTS AND DISCUSSION

PEG matrix gel preparation. Figure 2 shows the gel content of $\gamma$-irradiated PEG solutions as a function of absorbed dose of $\gamma$ rays. The gelation point appears at 13 kGy and the gel content reaches its saturation value of ca. 90 % above 40 kGy. In this study, therefore, we employed a dose of 60 kGy as a sufficient dose value for preparing PEG matrix gels.

The pore formation in the PEG matrix gel was indirectly confirmed from IR spectra and AFM images. IR spectra obtained after chemical decomposition of silica particles in the PEG matrix gel reveal that strong absorption from the Si-O-Si band observed before the decomposition almost diminishes after that. A more apparent result can be obtained by using AFM. Figure 3 shows the AFM images taken for the thin slices of the silica-containing PEG matrix gel and that after the HF treatment. Before the HF treatment, the shape of silica particles are clearly observed, but it becomes almost invisible after the treatment. This indicates the complete decomposition of silica particles and pore formation at the previous position of silica particles. Since the AFM observation was carried out for the dry gels, it was hard to verify the morphology of the formed pores themselves. However, these results strongly suggest that the pores are formed in the PEG matrix gels.

Incorporation of PNIPAm. Figure 4 shows the con-
tent of PNIPAm incorporated in the PEG matrix gels plotted against the dose of γ rays. The content of PNIPAm for the solid gel rapidly increases with increasing dose, and almost reaches its saturation value of 2 at 1 kGy irradiation. For the porous gels, the increase in the PNIPAm content is steeper, and the saturation value of the PNIPAm content becomes higher than the solid gel. This result evidently indicates that PEG/PNIPAm binary hydrogels are successfully synthesized by γ-irradiation. As is seen from this plot, the PNIPAm content can be controlled by the dose of γ irradiation. It is also found that the porous PEG gels contain larger amount of PNIPAm than the solid gels do. The reason for this difference will be discussed later.

Thermoresponsive swelling behavior. Figure 5 displays the temperature-dependent swelling behavior of the binary gels. The plot points along the upper solid line in Figure 5 are measured on 12 °C and those along the lower dotted line on 40 °C. As shown in this plot, the swelling ratio at 40 °C is significantly smaller than that at 12 °C, and the difference of the swelling ratio becomes larger with increasing PNIPAm content. This result proves that incorporation of PNIPAm brings thermoresponsive property to the non-thermoresponsive PEG matrix gel. Figure 5 also displays the results for the porous PEG matrix. The plot points for the porous gels are along with the line for solid gels at 12 °C, but deviate from the line at 40 °C. This fact suggests that the structure of solid and porous gels is similar at 12 °C, but dissimilar at 40 °C. As discussed later, PNIPAm chains in the porous gel are considered to be localized in the pore space. When PNIPAm expands and fills the pores at 12 °C, the whole gel appears macroscopically uniform and resembles the solid gel. On the other hand, when PNIPAm are contracted in the pores at 40 °C, the gel has many voids in itself and shows the structure dissimilar from the solid gel.

For clarity the inverse of shrink ratio is plotted against PNIPAm content as shown in Figure 6, where the shrink ratio is defined as the weight ratio of the fully swollen gel at 40 °C to that at 12 °C. The plot points for porous gels also show a monotonic increase with increasing amount of incorporated PNIPAm as those for the solid gels, but their values are smaller for almost all points. This result apparently shows that the porous gels are less shrinking than the solid gels.

Effect of the pores in the matrix. From the above results, it is found that solid and porous binary gels show different dependence of the swelling behavior on temperature. This difference is likely to be attributable to the difference of PNIPAm chain distribution in the PEG matrix. As seen in Figure 4, the porous gels contain more PNIPAm than the solid gels do. If there is no difference on the distribution of the incorporated PNIPAm chains between the solid and porous gels, the PNIPAm content should be almost the same. However, this is not the case. This fact implies that PNIPAm chains are quite localized in the pore space of the porous PEG matrix gel, whereas they are uniformly distributed in the solid PEG matrix gel.

This consideration also explains the difference of thermoresponsive behavior. In the solid matrix gel,
Solid binary hydrogel

Larger size change → Whole gel shrinks

Porous binary hydrogel

Smaller size change → PNIPAm gels shrink within the pore

Figure 7. Scheme of the volume change of PEG/PNIPAm binary hydrogels at elevated temperatures above LCST of PNIPAm.

PNIPAm chains are uniformly distributed, and therefore contraction of PNIPAm chains at a temperature above its LCST leads to the shrinkage of whole gels. In contrast, in porous gels, large amount of PNIPAm is located in the pore space. Contraction of PNIPAm chains leads to the shrinkage of PNIPAm gel that is limited in the pore space and exerts less influence on the whole gel.

The above behavior of the porous gels may have another meaning in view of the void of the pore. Below the LCST of PNIPAm, the pores in the PEG matrix gel are filled with PNIPAm gels. Above the LCST, however, the PNIPAm gel shrinks within the pore and the rest space becomes a void. This means that the volume of the void is varied with temperature. Therefore, it can be said that the porous binary hydrogel in this study behaves as a hydrogel with thermoresponsive pore. The above consideration can be schematically pictured in Figure 7.

Finally, the effect of the silica particle content should be mentioned. In our result obtained here, there is no explicit difference between \( r_{Si} = 1.0 \) and 0.1. It was expected that the higher silica content gave rise to the larger amount of PNIPAm incorporation and the less swelling ratio change on temperature change, but the results for two samples are almost the same. The reason for this may be ascribed to the aggregation of smaller silica particles. Once large aggregates of silica particles are formed even though carefully dispersed in a PEG aqueous solution, such large aggregates might precipitate during the \( \gamma \)-irradiation and they reduce the actual content of silica particles in the solution. Actually, after \( \gamma \)-irradiation experiments, we recognized slight inhomogeneity in some silica-containing samples. Therefore various contents of silica particles should be used for investigation to clarify their effect.

4. CONCLUSION

The formation of PEG matrix hydrogels and the incorporation of PNIPAm into them were both carried out by utilizing \( \gamma \) ray irradiation to obtain PEG/PNIPAm binary hydrogels. As a result, thermoresponsive property was given to the non-thermoresponsive PEG hydrogels without any other chemical additives. The porous binary hydrogels were also prepared by dispersing and decomposing silica microparticles in PEG aqueous solutions. The porous binary gels seem to be less sensitive to the ambient temperature change compared with solid binary hydrogels, because the incorporated PNIPAm is localized in the pore space. This fact also suggests the formation of thermoresponsive pores in the binary hydrogel systems. As the temperature is raised from below LCST to above LCST of PNIPAm, PNIPAm chains shrink in the pores and vacant void spaces are open. It is expected that, using this feature, novel functionalized hydrogels can be developed for new drug delivery systems, intelligent separation membranes, and capturing materials for hazardous substances.

5. REFERENCES


(Received October 31, 2011; Accepted December 18, 2011)