

Photopolymerization Synthesis of Poly(*N*-isopropylacrylamide) Hydrogels

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ABSTRACT: Poly(*N*-isopropylacrylamide) (NIPAAm) gels were formed by photopolymerization of NIPAAm in the absence of a crosslinker using a water solvent at 25°C. Factors affecting formation were the wavelength region of irradiated light, the type of photoinitiators, and the concentrations of the photoinitiator and monomer. A high-pressure mercury lamp (400 W) was used as a light source. An NIPAAm concentration of 10 wt % and irradiation time of 15 h was used for the photopolymerization. The gel (68% yield) was formed when the quartz glass system was used, but no gelation was observed for the Pyrex glass system that transmits light with $\lambda > 290$ nm. The gel (100% yield) was easily formed, even in the latter system, when 30 mmol/L of hydrogen peroxide and potassium persulfate were used as the photoinitiator. Water soluble photoinitiators such as ferric chloride and sodium anthraquinone-2,7-disulfonate were not effective for the gel formation. Yield of the gel increased with increasing the potassium persulfate concentration (1–30 mmol/L), but it decreased when a high concentration of hydrogen peroxide (60 mmol/L) was used. The gel yield increased with the NIPAAm concentration (5–20 wt %). The degree of swelling of the resultant poly(NIPAAm) gels, which was measured by immersing the gels in water at various temperatures (0–50°C) for 24 h, steeply decreased at about 30°C with increasing temperature, exhibiting a temperature-responsive character. The gels swelled and shrank in water below and above the temperature, respectively. The extent of the character depended on the concentrations of hydrogen peroxide and monomer. The formation mechanism of the gel in the photopolymerization of NIPAAm using hydrogen peroxide photoinitiator was discussed. © 1997 John Wiley & Sons, Inc. *J Appl Polym Sci* **65**: 1313–1318, 1997

Key words: poly(*N*-isopropylacrylamide); hydrogel; photopolymerization; photoinitiator

INTRODUCTION

Poly(*N*-isopropylacrylamide) (NIPAAm) is well known to exhibit a lower critical solution temperature (LCST) at around 32°C in aqueous solution; that is, it dissolves in water below and precipitates from solution above the LCST. Poly(NIPAAm) hydrogels^{1,2} with a crosslinked structure are characterized by a temperature-responsive nature in which they swell in water below and

shrink above the LCST. The hydrogel is usually synthesized by solution polymerization^{1–5} of NIPAAm using a redox initiator such as persulfates/diamines in the presence of a crosslinker, *N,N'*-methylenebisacrylamide, at temperatures below the LCST.

In a previous article⁶ we applied a radiation-induced polymerization method for the synthesis of poly(NIPAAm) hydrogels. The method was characterized by a simple and additive-free process because no initiator and crosslinker existed in the polymerization system. Moreover, the degree of crosslinking of the gel could be controlled

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easily by irradiation conditions. This method is especially attractive for the synthesis of hydrogels in the field of controlled drug delivery^{4,7-9} because the hydrogels do not contain any residual chemical initiators. This article deals with synthesis of poly(NIPAAm) hydrogels by photopolymerization and their temperature-responsive characteristics. The gels could be synthesized by photopolymerization of NIPAAm using a photoinitiator such as hydrogen peroxide (H₂O₂) in the absence of a crosslinker. Factors affecting formation of the poly(NIPAAm) gels by photopolymerization were investigated in terms of the wavelength region of the irradiated light, the type of photoinitiators, and the concentrations of the photoinitiator and monomer.

EXPERIMENTAL

Materials

NIPAAm, acrylamide, and methacrylamide were commercial products and were purified by recrystallization. H₂O₂, potassium persulfate (K₂S₂O₈), ferric chloride, and sodium anthraquinone-2,7-disulfonate were used as the photoinitiator, all of which were reagent grade and were used without further purification.

Photopolymerization

Photopolymerization was carried out in a 3-mm i.d. Pyrex glass tube containing an aqueous solution of NIPAAm, in which known concentrations of photoinitiator were dissolved under a nitrogen atmosphere. Irradiation with a high-pressure mercury lamp (400 W) was performed at 25°C using a Riko rotary photochemical reactor (RH400-10W), around which the glass tubes were rotated. After the polymerization the gels were removed from the tubes and washed in deionized water for 1 week. The gel fraction was measured after Soxhlet-type extraction in ethanol for 24 h and drying the extracted gel under reduced pressure to constant weight. Crosslinked polymer was defined as follows:

$$\begin{aligned} & \text{crosslinked polymer (\%)} \\ &= \frac{\text{weight of ethanol-insoluble fraction}}{\text{weight of feed monomer}} \times 100 \end{aligned}$$

Measurement of Swelling

The gel (10-mm length) was immersed in deionized water at given temperatures for 24 h. After

Table I Effect of Wavelength Region of Irradiated Light on Formation of Poly(NIPAAm) Gels

Irradiation System	H ₂ O ₂ Concentration (mmol/L)	Crosslinked Polymer (%)	
		Irradiation Time: 7 h	Irradiation Time: 15 h
Quartz system	0	66.8	67.9
Pyrex system	0	0	0
Pyrex system	30	96.2	98.4

[NIPAAm] = 10 wt %, 25°C.

the treatment, excess water on the gel was wiped off by filter paper and then the gel was weighed. The swelling was calculated according to the following equation:

$$\text{swelling (g/g)} = \frac{W_s - W_o}{W_o}$$

where W_o and W_s denote weights of dried and swollen samples, respectively.

RESULTS

Formation of Poly(NIPAAm) Gels

The effect of the wavelength region of the irradiated light on the formation of the poly(NIPAAm) gel was examined using Pyrex and quartz glass tubes (Pyrex and quartz systems, respectively), and the results are shown in Table I. The Pyrex glass tube used in this study transmits light with $\lambda > 290$ nm. Photopolymerization of NIPAAm in the quartz system was initiated even in the absence of photoinitiator to form poly(NIPAAm) gel. On the other hand, no formation of the gel was observed for the Pyrex system. It was found accordingly that the light wavelength shorter than about 290 nm was responsible for the formation of the poly(NIPAAm) gel. However, the mechanical strength of the gel was insufficient for the swelling experiment. When H₂O₂ was used as a photoinitiator, the gel was formed in the Pyrex system, showing a higher yield than the quartz system. The resultant gel exhibited mechanical strength sufficient for the swelling measurement. H₂O₂ is known to be decomposed by ultraviolet light,¹⁰⁻¹²

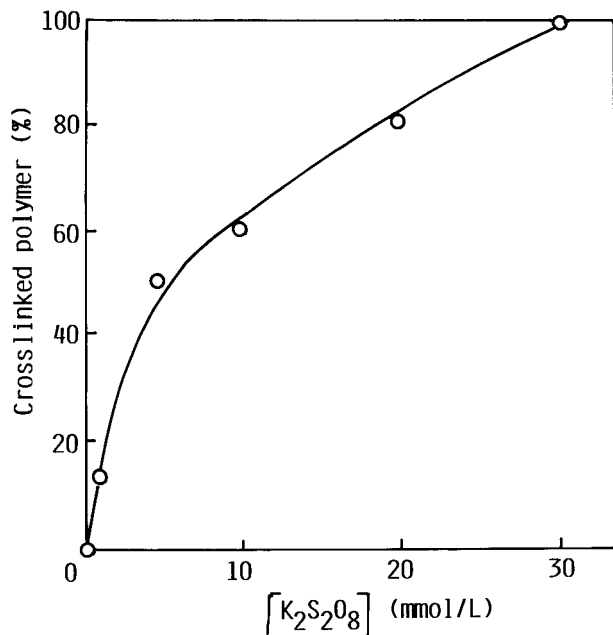


Figure 1 Effect of $K_2S_2O_8$ concentration on photoinduced formation of poly(NIPAAm) gels. [NIPAAm] = 10 wt %; irradiation at 25°C and 15 h.

and the resulting hydroxyl radicals initiate the polymerization of vinyl monomers.

The type of photoinitiators was examined in the Pyrex system using polymerization conditions, such as the NIPAAm concentration of 10 wt % and irradiation time of 15 h at 25°C. Poly(NIPAAm) gel was formed in the system sensitized with $K_2S_2O_8$ rather than the H_2O_2 . Ferric chloride^{13,14} and sodium anthraquinone-2,7-disulfonate,^{15,16} which are water soluble photoinitiators for photopolymerization of vinyl monomers, were not effective for the gel formation when concentration ranges of 0.01–30 mmol/L were examined, although polymerization of NIPAAm proceeded. Figure 1 presents the effect of the $K_2S_2O_8$ concentration on the gel formation. Gel yield increased with increasing $K_2S_2O_8$ concentration, and 100% yield was observed when a 30 mmol/L $K_2S_2O_8$ concentration was used. With an H_2O_2 -sensitized system (Fig. 2), on the other hand, an approximate 100% yield of the gel was recorded for the system of lower H_2O_2 concentrations compared to the $K_2S_2O_8$ -sensitized system. The phenomenon may have originated from a different decomposition efficiency between the two photoinitiators under the present irradiation conditions. Moreover, the gel yield was greatly reduced in the 60 mmol/L H_2O_2 concentration system. The supposition is that the hydroxyl radicals derived from the photodecompo-

sition of H_2O_2 according to eq. (1) participate in the termination of growing polymer radicals produced through eqs. (2) and (4); and the reaction as well as the combination of primary radicals is emphasized in the system of higher H_2O_2 concentrations, resulting in a decreased yield. The yield increased with increasing monomer concentration (Fig. 3), and a high yield of more than 95% was obtained for the system of the monomer concentrations beyond about 10 wt %.

Temperature-Responsive Character of Poly(NIPAAm) Gels

Figures 4 and 5 show the effects of H_2O_2 and monomer concentrations, respectively, on swelling of poly(NIPAAm) gels. The swelling steeply decreased at about 30°C with increasing temperature, exhibiting the temperature-responsive character of the poly(NIPAAm) gels. The gel swelled and shrank in water below and above the temperature, respectively. The swelling at temperatures below about 30°C (Fig. 4) depended on the H_2O_2 concentration, decreasing in the following order: 30 mmol/L > 10 mmol/L > 5 mmol/L \approx 1 mmol/L, although the level at higher temperatures was nearly equal among the gels. This suggests that the degree of crosslinking is higher for the gels prepared in the lower H_2O_2 concentration system.

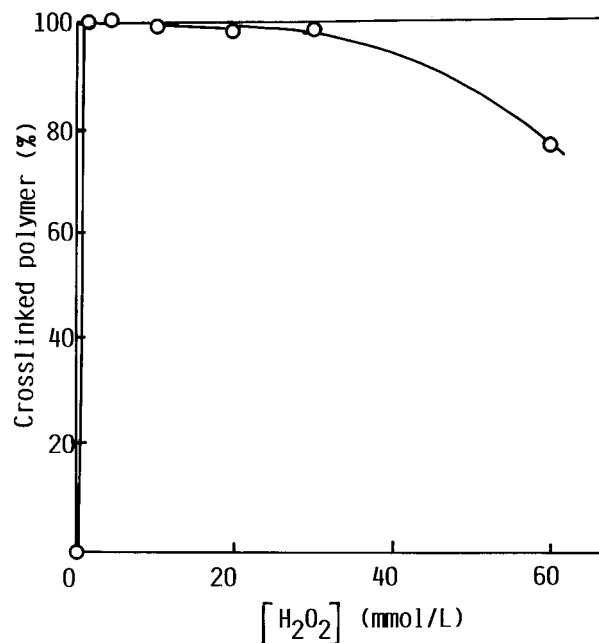


Figure 2 Effect of H_2O_2 concentration on photoinduced formation of poly(NIPAAm) gels. [NIPAAm] = 10 wt %; irradiation at 25°C and 15 h.

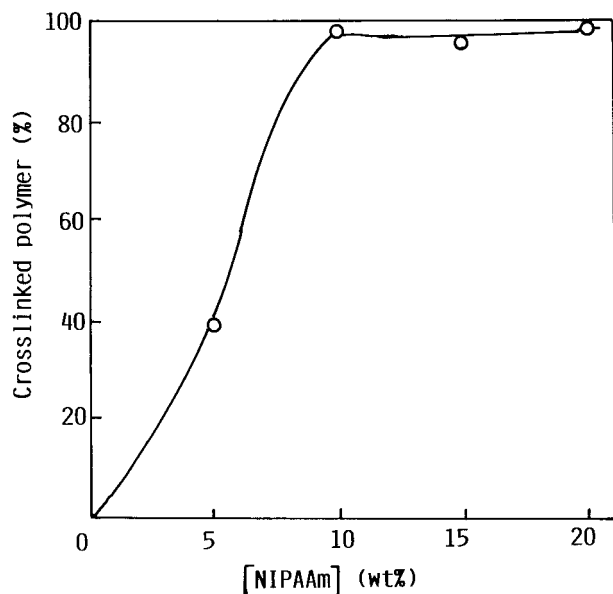


Figure 3 Effect of monomer concentration on photo-induced formation of poly(NIPAAm) gels. $[\text{H}_2\text{O}_2] = 10$ mmol/L; irradiation at 25°C and 15 h.

The gel synthesized in the 60 mmol/L H_2O_2 concentration had insufficient mechanical strength that was required for the swelling measurement. Inomata et al.¹⁷ examined the effect of a crosslinking point on the swelling behaviors of poly(NIPAAm) gels prepared by radical polymerization

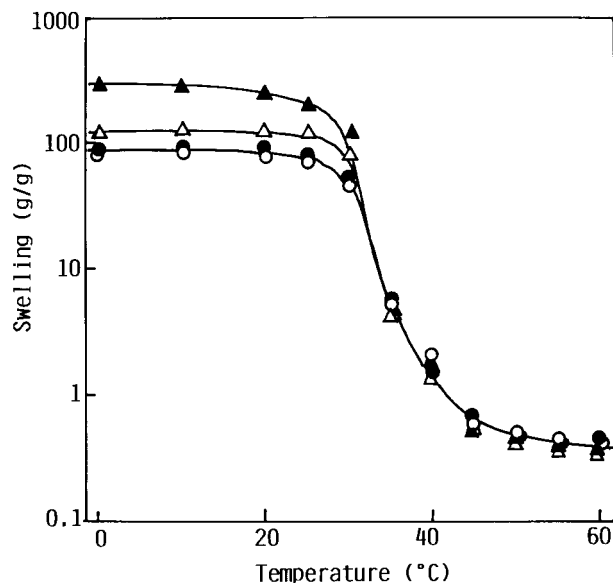


Figure 4 Effect of H_2O_2 concentration on swelling of poly(NIPAAm) gels. H_2O_2 concentration (mmol/L): (○) 1, (●) 5, (△) 10, (▲) 30; $[\text{NIPAAm}] = 10$ wt %; irradiation at 25°C and 15 h.

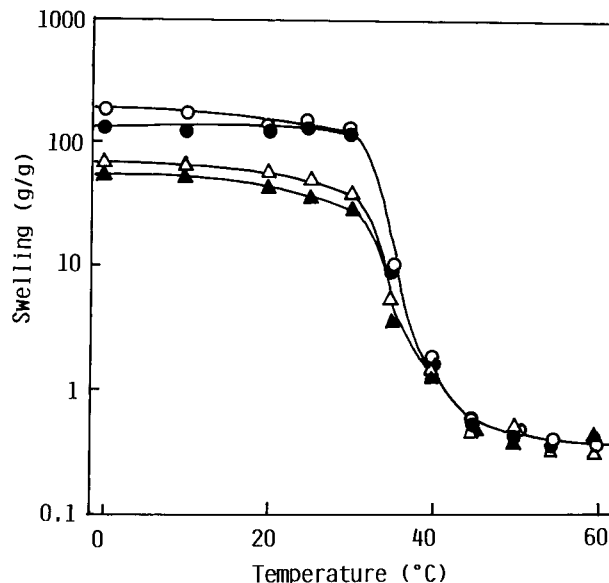
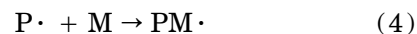
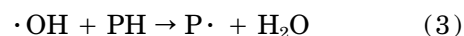


Figure 5 Effect of monomer concentration on swelling of poly(NIPAAm) gels. Monomer concentration (wt %): (○) 5, (●) 10, (△) 15, (▲) 20; $[\text{H}_2\text{O}_2] = 10$ mmol/L; irradiation at 25°C and 15 h.

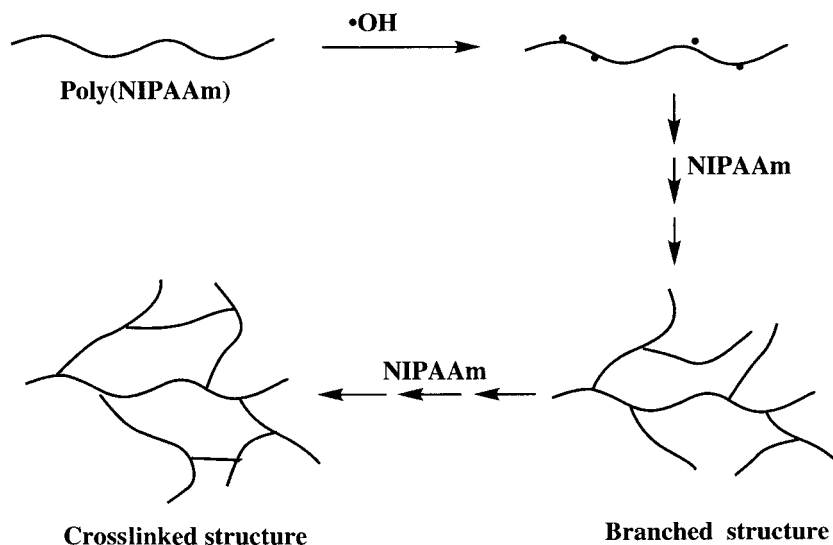
using various concentrations of *N,N'*-methylenebisacrylamide crosslinker. They observed that the swelling ratio of the gel in the swollen region decreases as the degree of crosslinking of the gel increases. As seen in Figure 5, the lower swelling level at temperatures below about 30°C was afforded for the gels prepared with the higher monomer concentrations, suggesting that higher monomer concentration is required for the formation of a gel with a higher degree of crosslinking.

DISCUSSION

It is conceivable that photopolymerization of NIPAAm in the presence of H_2O_2 photoinitiator proceeds according to eqs. (1)–(4), where M, PH, and $\text{P}\cdot$ denote NIPAAm monomer, poly(NIPAAm), and its radicals, respectively.



Equation (1) is the formation of hydroxyl radicals



Scheme 1 The formation mechanism of the poly(NIPAAm) gel.

by photodecomposition of H_2O_2 . Equation (2) leads to the formation of poly(NIPAAm). The hydroxyl radicals may also contribute to abstraction of the hydrogen atom from the poly(NIPAAm) substrate produced in the polymerization system according to eq. (3). The resultant poly(NIPAAm) radicals initiate polymerization of NIPAAm, that is, initiation of the grafting reaction, which is indicated by eq. (4). The reaction is supposed to lead to poly(NIPAAm) with a branched structure. The polymerization proceeds through repetition of such reactions, resulting in gels with a crosslinked structure. With the system of high H_2O_2 concentration, it is conceivable that the termination reaction of growing polymer radicals produced according to eq. (4) by hydroxyl radicals may be emphasized to reduce gel yield and degree of crosslinking. H_2O_2 can act as a photoinitiator for grafting^{18,19} of vinyl monomers on cellulose, where hydroxyl radicals produced by photodecomposition of H_2O_2 abstract a hydrogen atom from the substrate to yield cellulose radicals capable of initiating the grafting. However, the maximum grafting was observed at an optimum concentration of H_2O_2 and the formation of grafted polymer was restricted by the use of H_2O_2 beyond the concentration. The formation mechanism of poly(NIPAAm) gel is schematically shown in Scheme 1.

To understand the radical formation on poly(NIPAAm) leading to the crosslinked structure, the effect of the nature of the monomers was examined using acrylamide and methacrylamide; the results are shown in Figure 6. Gel formation was observed for acrylamide but not for methacryl-

amide. Accordingly, abstraction of a tertiary hydrogen atom at following structure (a) position on the poly(NIPAAm) substrate is important for the gel formation. Moreover, the abstraction reaction of another tertiary hydrogen atom at the (b) position may also participate in the gel formation. However, we found in electronic spin resonance measurements on γ -ray irradiated poly(NI-

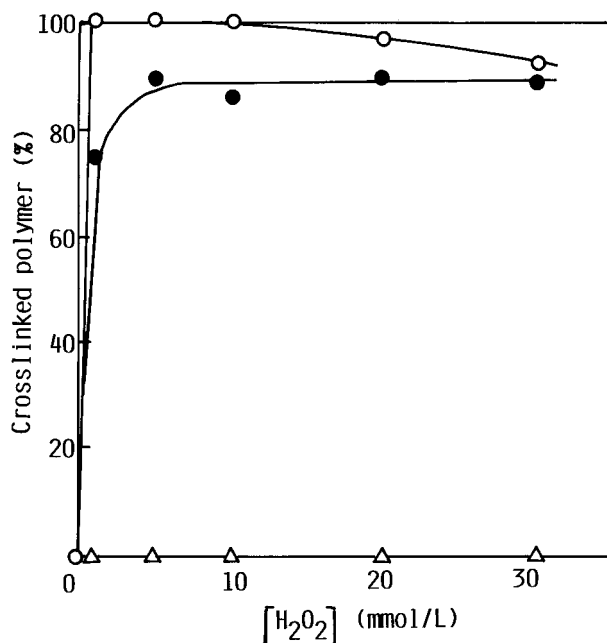
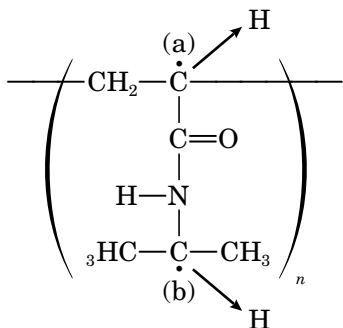


Figure 6 Formation of gels in photopolymerization of acrylamide and its derivatives. (○) NIPAAm, (●) acrylamide, (△) methacrylamide; [monomer] = 10 wt %; irradiation at 25°C and 15 h.

PAAm)²⁰ that isopropyl radicals produced at the (b) position are stable and less likely to participate in the polymerization and crosslinking reaction.



We examined the gel formation by photoirradiation of the poly(NIPAAm); that is, poly(NIPAAm) was synthesized by photopolymerization using H_2O_2 and ethanol as the photoinitiator and solvent, respectively. Poly(NIPAAm) film (200- μ m thickness) prepared by the synthesized polymer was immersed in a 0.5 wt % acetone solution of xanthone photoinitiator to yield xanthone-coated film.²¹ The sensitized film was then exposed to a high-pressure mercury lamp (the Pyrex system) at 25°C for 15 h in a nitrogen atmosphere, but no gel fraction was observed. Moreover, the same photoirradiation was examined for a 10 wt % aqueous solution of poly(NIPAAm) containing 5 mmol/L H_2O_2 , but no gelation occurred. These facts suggest that NIPAAm monomer is required for the gel formation in the course of photopolymerization; that is, the grafting reaction of NIPAAm on poly(NIPAAm) leading to a branched structure, which is shown in Scheme 1, is important for the gel formation.

Based on the above investigations, we concluded that poly(NIPAAm) gels can be synthesized by photopolymerization of NIPAAm using H_2O_2 photoinitiator, and the degree of crosslinking is controlled by the proper choice of H_2O_2 and monomer concentrations.

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