

Synthesis and Phase Separation of Poly(*N*-isopropyl acrylamide-*co*-methoxy polyethyleneglycol monomethacrylate)

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Received 30 August 2005; accepted 1 December 2005

DOI 10.1002/app.23884

Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The poly(*N*-isopropyl acrylamide-*co*-methoxy polyethyleneglycol monomethacrylate, NIPAM-*co*-MPEG) with different length of ethylene oxide (EO) were synthesized from their monomers, NIPAM and MPEGs. The numbers of repeating units of EO were 6, 10, 24, and 46. The chemical structure and mole ratio of the monomers was determined by Fourier transform infrared (FTIR), ¹H-NMR, and ¹³C-NMR spectroscopy. The *d*-spacing increased with the number of EO and the values of the copolymers were in the range of 0.437–0.452 nm. The lower critical solution temperature of the poly(NIPAM-*co*-MPEG) shifted to higher temperature as the number of EO and the amount of MPEG

increased. The change of chemical shift for methoxy proton in MPEG exhibited a larger than those of the other protons of the poly(NIPAM-*co*10–2MPEG). Activation energy (E_a) for methoxy proton in MPEG showed a larger value than that of the methyl proton in NIPAM. These NMR results indicate the fact that more significant conformational transformations occur in the methoxy group through the phase separation than in the methyl group in NIPAM. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 101: 1833–1841, 2006

Key words: synthesis; *N*-isopropyl acrylamide; ethylene oxide; phase separation; NMR

INTRODUCTION

Poly(*N*-isopropyl acrylamide, NIPAM) and its copolymers have been used in biotechnology, drug delivery system, agriculture, food industry, and other fields because they exhibit a volume phase transition phenomenon with temperature, electric current, pH, ions, chemical species, or solvents.^{1–6} Poly(NIPAM) exhibits the phase transition at about 32–34°C in aqueous solution.^{7–9} The temperature is defined as the lower critical solution temperature (LCST) in water. Below that temperature, the polymer solution is swollen, hydrated, and hydrophilic, and above the LCST, the solution becomes collapsed, dehydrated, and hydrophobic. The LCST can be controlled by incorporating more hydrophilic or hydrophobic monomer in the composition.^{10–28}

To control LCST of the poly(NIPAM), many studies have been devoted to the copolymers of poly(NIPAM) with acrylic acid,^{10–17} methacrylic acid,^{18,19} hydroxyethyl methacrylate,²⁰ acrylamide,²⁰ alternating copol-

ymers of maleic anhydride,^{21,22} and polyethyleneglycol (PEG) derivatives.^{23–28}

Many methods including cloud point measurement,²⁹ light scattering,^{7,27} differential scanning calorimetry,³⁰ fluorescence,^{28,31} and spectrometer^{32–34} have been used to reveal the essential mechanism of the phase separation of the poly(NIPAM) aqueous solution. Zeng et al.³² investigated the phase separation in poly(NIPAM)/water solutions by NMR technique and reported that above LCST, all the resonance peaks became broad and the spectra lost their fine structure. The integral intensity of the water proton relative to that of the lone proton in the isopropyl group increases with increasing temperature, suggesting that some water molecules appear to be released out of the hydrated shells around the polymer chains.

Besides the control of LCST, the PEG grafted copolymers have attracted considerable attention in controlled release technology owing to their good biocompatibility and excellent physicochemical properties.^{35–39} Studies on light scattering, fluorescence, and electron paramagnetic resonance of the poly(NIPAM) with PEG derivatives have attracted much attention because of their scientific interest and technological significance.^{27,28,31} Virtanen et al.²⁷ reported that the factors determining the shrinking and collapse of poly(NIPAM) with PEO derivatives include hydrophobic interactions, intrachain and interchain interac-

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Contract grant sponsor: Korea Research Foundation; contract grant number: KRF-2003–003-D00076.

TABLE I
Basic Properties of MPEGs and Feed Composition of Poly(NIPAM-co-MPEG)

Sample	M _n ^a /N ^b	MPEG (g/mol %)	Theoretical mole ratio	Calculated mole ratio ^c
Poly(NIPAM-co-6 ^d MPEG)	300/6	0.08/1.0	0.0101	0.0105
Poly(NIPAM-co-10MPEG)		0.127/1.0	0.0101	0.0105
Poly(NIPAM-co-10-2MPEG)		0.323/2.5	0.0256	0.0263
Poly(NIPAM-co-10-5MPEG)	475/10	0.663/5.0	0.0526	0.0536
Poly(NIPAM-co-10-7MPEG)		1.020/7.5	0.0811	0.0795
Poly(NIPAM-co-10-10MPEG)		1.399/10.0	0.1111	0.0943
Poly(NIPAM-co-24MPEG)	1100/24	0.295/1	0.0101	0.0098
Poly(NIPAM-co-46MPEG)	2080/46	0.557/1	0.0101	0.0096

^a M_n is number average molecular weight of MPEG.

^b N is number of repeating unit of MPEG.

^c Calculated by ¹H-NMR data.

^d The number means the number of repeating unit of EO in MPEG.

tions, and the solubilizing effect of PEO on the shrinking backbone. They also suggested^{27,28} that the collapsed aggregates resided either in the outer PEO shell close to the aqueous phase or in a less polar phase close to the poly(NIPAM) core of the copolymer. These results indicate that upon the collapse of the poly(NIPAM)-g-PEO aggregates, the most dramatic changes are detectable in the hydrophobic core of the copolymer and in the outermost part of the hydrophilic shell. Therefore, NMR studies on the chain conformation and the dynamic behavior of the protons of the poly(NIPAM) copolymer are very important to reveal the essential mechanism of the phase separation of the copolymer aqueous solution.

Although there have been a few light scattering and fluorescence studies on the phase separation of the poly(NIPAM) copolymers with PEG derivatives, little progress has been made on the NMR studies related to phase separation of the copolymer.

The present study was carried out to determine the phase separation behavior of the copolymer with PEG derivatives using NMR techniques and the effects of the chain length and the content of the PEG derivatives on the LCST. This article also describes the syntheses of linear graft copolymers, for which poly(NIPAM) was chosen as a hydrophobic core, and for a hydrophilic shell, poly(methoxy polyethyleneglycol monomethacrylate, MPEG) was chosen as a new PEG derivative because of its high solubility in water in a wide temperature range.

EXPERIMENTAL

Materials

α,α' -Azobisisobutyronitrile (AIBN, Fluka, Buchs, Switzerland) was recrystallized twice from methanol. 1,4-dioxane (Aldrich, St. Louis, MO) was purified by distillation. *N*-isopropyl acrylamide (NIPAM, Aldrich) and four methoxy polyethyleneglycol monomethacry-

late (MPEG, Aldrich) were used without further purification. Basic properties of the MPEGs are summarized in Table I. All solvents were analytical grade and used as received.

Copolymerization procedure

The copolymers composed of NIPAM and MPEG were prepared by a radical solution polymerization. Copolymerization of NIPAM with 1, 2.5, 5, 7.5, and 10 mol % of MPEG were carried out in 1,4-dioxane at 70°C with AIBN radical initiator. Feed composition is given in Table I. Appropriate quantities of NIPAM, MPEG, and 1,4-dioxane were placed in 250 mL three neck flask with magnetic stirrer. Dried nitrogen was bubbled into the monomer/solvent mixtures for 10 min to remove the oxygen dissolved in the reaction mixture. AIBN dissolved in 6 mL 1,4-dioxane was added to the mixture for 2 min using dropping funnel. After copolymerization at 70°C for 3 h, the copolymers were isolated from reacted mixture by precipitation with diethyl ether, then washed several time with diethyl ether. The precipitate was filtered and dried under vacuum at 30°C for 24 h. The copolymer compositions were found by ¹H-NMR spectroscopy using integral area of chemical shift of functional groups.

Measurements

Fourier transform infrared (FTIR) spectra were recorded on a Bomen-MB-100 FTIR spectrometer in the 400–4000 cm⁻¹, where 16 scans were taken at a 4 cm⁻¹ resolution. ¹H and ¹³C-NMR spectra were obtained on a Bruker ARX-500, 500 MHz high performance FT-NMR spectrometer with concentration of 30 mg/mL in D₂O as solvent at various temperatures. The spin-lattice relaxation time (*T*₁) was determined by means of the inversion recovery method with a pulse of about 5 *T*₁. The temperature of a polymer solution was

in the range of 30–40°C controlled to $\pm 0.1^\circ\text{C}$. The weight average molecular weights (M_w) and polydispersity index (PI) of the copolymers were determined by gel permeation chromatography with Waters-150C with tetrahydrofuran as the solvent. M_w of the poly(*N*-isopropyl acrylamide-*co*-methoxy polyethyleneglycol monomethacrylate, NIPAM-*co*-MPEG) were in the range of 12,000–18,000, when polystyrene was taken as the standard. The PI values of the copolymers were in the range of 1.82–2.15. X-ray diffraction (XRD) was carried out by using Rigaku X-ray generator (Cu $K\alpha$ radiation with $\lambda = 0.15406\text{ nm}$) at room temperature. The powder dried under vacuum at 30°C for 24 h was used as XRD samples. The diffractograms were scanned in 2θ ranges from 4 to 60° at a rate of 5° min^{-1} . The LCSTs of poly(NIPAM-*co*-MPEG) in aqueous solution were determined by observing the percentage of light blockage through polymer solution in phosphate buffer solution (pH, 7.0). The concentration of the copolymer solutions was 30 mg/mL in distilled water as solvent. The copolymer solutions were put into a cell consisting of two parallel cover glasses spaced by 2 mm thick O-ring. The cell was mounted on a hot stage (Mettler, FP 82), and the hot stage was placed on an optical microscope (Leica) so that the light beam of the microscope could go through the cell. And then the cell was heated from 25 to 70°C at rate 0.4°C/min using a temperature controller (Mettler, FP 80 HT). The intensity of light transmitted through the cell was recorded with temperature and the percentage of light blockage was determined as follows.

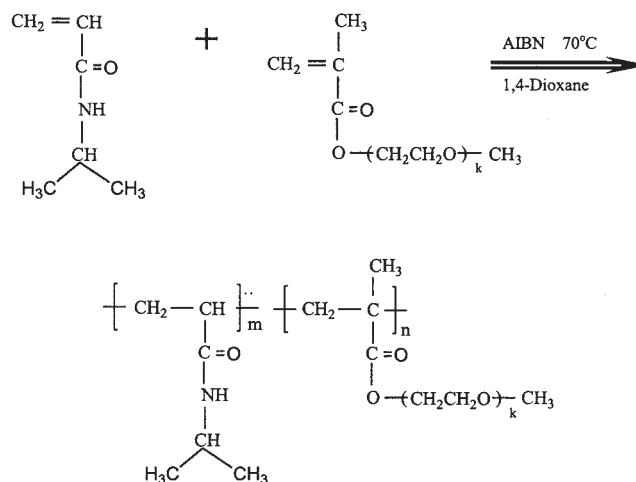
$$\% \text{ Blocking of light} = \frac{I_B - I_T}{I_B - I_F} \times 100$$

where I_B is the intensity of light when an empty cell was placed, I_F is the intensity when light beam was completely blocked by placing an opaque plate in the light path, and I_T is the intensity of light when the cell containing polymer solution was monitored at a given temperature.

RESULTS AND DISCUSSION

Chemical structure and basic properties of the synthesized copolymers

As schematically shown in Scheme 1, the poly(NIPAM-*co*-MPEG) were synthesized from their respective monomers, NIPAM and MPEGs, by a radical copolymerization. The chemical structure and composition of the copolymers was obtained with FTIR and ^1H , ^{13}C -NMR spectra. Figure 1 gives the FTIR spectra of the poly(NIPAM), poly(NIPAM-*co*-MPEG), and their monomers. The amide and ester peaks can be identified in the FTIR spectra, which are specific to the



Scheme 1 Synthesis of the poly(NIPAM-*co*-MPEG) copolymers.

NIPAM and MPEG components, respectively. The amide peaks of the NIPAM units appeared at 1651 cm^{-1} (C=O stretching), 1544 cm^{-1} (N—H bending), and 3438 cm^{-1} (N—H stretching). These FTIR peaks of poly(NIPAM) are similar to the other studies.^{14,33,40} In the spectra of poly(NIPAM-*co*-MPEG), in addition to the characteristic peaks of NIPAM component, the characteristic C=O and C—O stretching bands of the ester group of the MPEG component appeared at 1725 and 1254 cm^{-1} , respectively. As shown in Figure 1(b), the presence of C=O peak at 1725 cm^{-1} with increasing in mol % of 10MPEG indicates the incorporation of MPEG unit to poly(NIPAM).

Figures 2 and 3 show the ^1H -NMR spectra of the poly(NIPAM) and the poly(NIPAM-*co*-MPEG), respectively. The NMR results of poly(NIPAM) are in reasonable agreement with previous results.^{21,32,34} ^1H -NMR peaks of the poly(NIPAM) appeared at 1.1 ppm (CH_3), 1.5 ppm (CH_2), 1.9 ppm (CH in main chain), 3.8 ppm (CH in side chain), and 7.5–8.0 ppm (NH). ^{13}C -NMR peaks of the poly(NIPAM) also appeared at 22 ppm (CH_3), 35 ppm (CH_2), 42 ppm (CH in side chain), 70 ppm (CH in main chain), and 175 ppm (C=O) as shown in previous result.³² In the spectra of poly(NIPAM-*co*-MPEG), in addition to the characteristic peaks of the poly(NIPAM), the carbon peaks of O— CH_3 (methoxy) and O— CH_2CH_2 — (ethylene oxide [EO]) of the MPEG component appeared at 58 ppm and 73 ppm, respectively. The presence of the methoxy and EO carbon in ^{13}C -NMR spectrum indicates the incorporation of MPEG unit to PNIPAM.

^1H -NMR peaks of the O— CH_2CH_2 — and O— CH_3 of the copolymer appeared at 3.6 ppm and 3.3 ppm, respectively, as shown in Figure 2. Copolymer compositions were calculated from the ratio of ^1H -NMR peak area of the homopolymer and copolymers. Two ^1H -NMR peaks at 3.8 ppm (CH in NIPAM unit) and

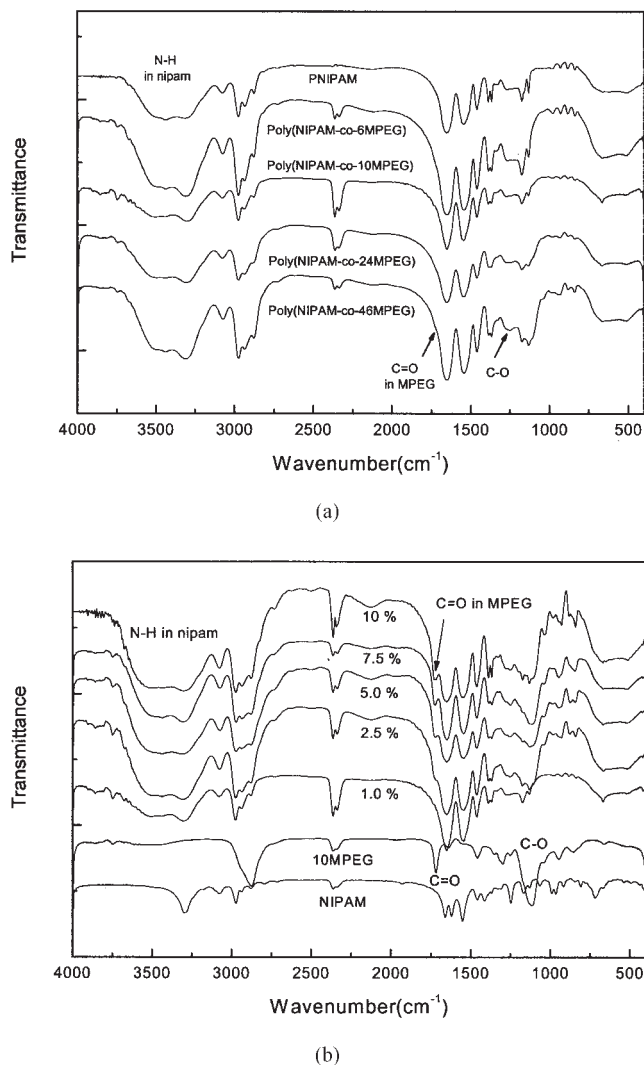


Figure 1 FTIR spectra of the poly(NIPAM-co-MPEG) with different MPEG (a) and mol % of 10MPEG (b).

3.3 ppm (O—CH₃ in MPEG unit) are characteristics for poly(NIPAM-co-MPEG) and can be used as analytical signals for quantitative analysis of the copolymer composition. Figure 4 shows ¹H-NMR spectra of the poly(NIPAM) and poly(NIPAM-co-MPEG) in the ppm range of 3.0–4.0. Calculated mole ratios are summarized in Table I. Copolymer mole ratios calculated using ¹H-NMR data were in reasonable agreement with initial feed ratios. A good agreement between feed ratio and mole ratio calculated using ¹H-NMR data indicates the proper incorporation of MPEG unit to poly(NIPAM).

Figure 5 shows the XRD patterns of the poly(NIPAM) and poly(NIPAM-co-MPEG). No significant difference in diffraction patterns was observed between the poly(NIPAM) and the poly(NIPAM-co-MPEG). There are two strong peaks at 7.74° and 20.33°, with a weak peak at 39.20° for the poly(NIPAM). For the poly(NIPAM-co-MPEG), the angle in 20.33° of poly-

(NIPAM) decreased with increasing of the number of EO. The decrease in 2θ means the increase in d -spacing of crystal structure of the polymers. The d -spacing is determined by the diffraction position in the X-ray method, using the Bragg equation: $2d \sin\theta = \lambda$, where d is d -spacing, θ is the diffraction position, and λ is the wavelength. The d -spacings and 2θ of the poly(NIPAM) and the poly(NIPAM-co-MPEG) are given in Table II. The d -spacing of poly(NIPAM), poly(NIPAM-co-6MPEG), poly(NIPAM-co-10MPEG), poly(NIPAM-co-24MPEG), and poly(NIPAM-co-46MPEG) are 0.437 nm, 0.445 nm, 0.448 nm, 0.453 nm, and 0.452 nm, respectively. The increase in the d -spacing with the number of EO is an indication of the increase in the interlayer spacing of the copolymers. Increase in d -spacing also means increase in amorphous state of the copolymer structure because of MPEG units. The increase in interlayer spacing may be an indirect evidence of the synthesized copolymer. The increase in the interlayer spacing might be caused from the increase in the size of side chain of the poly(NIPAM-co-MPEG).

Investigation of phase separation of the synthesized copolymers

The LCSTs of poly(NIPAM-co-MPEG) in aqueous solution are determined by observing the percentage of

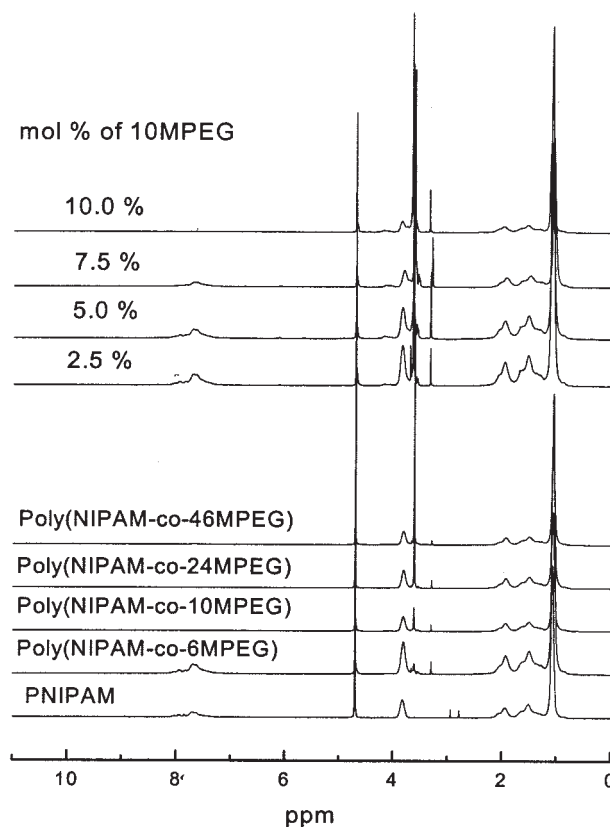


Figure 2 ¹H-NMR spectra of the poly(NIPAM-co-MPEG) with different MPEG (a) and mol % of 10MPEG (b).

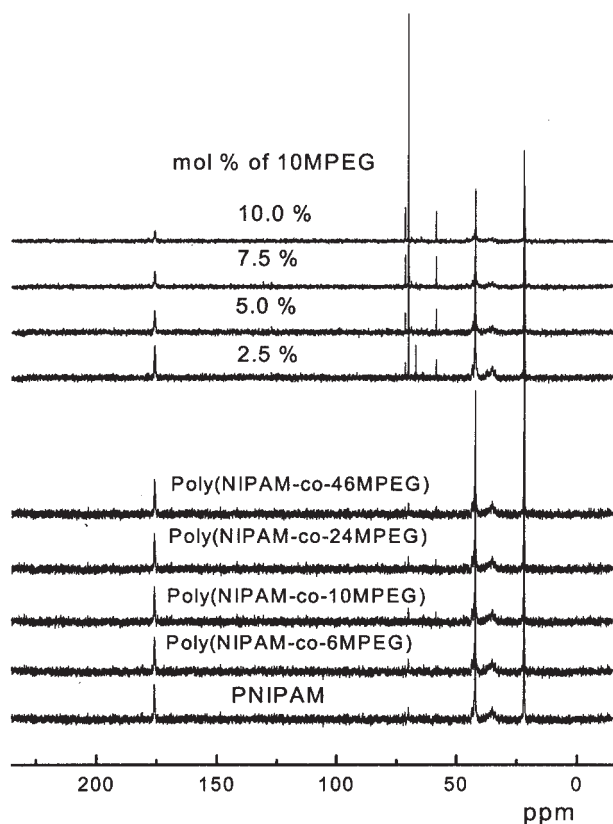


Figure 3 ^{13}C -NMR spectra of the poly(NIPAM-co-MPEG) with different MPEG (a) and mol % of 10MPEG (b).

light blockage through polymer solution. Figure 6 shows the change of light blockage of the poly(NIPAM) and the poly(NIPAM-co-MPEG) aqueous solution with temperature. Each experiment was conducted at $\text{pH} = 7.0$. The LCSTs of the poly(NIPAM-co-MPEG) shifted to higher temperature as the length of EO increased. The phase separation temperature at which light blockage of poly(NIPAM) start to increase was 32°C . The phase transition temperatures of the copolymer were 33°C for poly(NIPAM-co-6MPEG), 34°C for poly(NIPAM-co-10MPEG), and 58°C for poly(NIPAM-co-24MPEG). However, there was no change in light blockage with temperature for poly(NIPAM-co-46MPEG). The LCST of the NIPAM copolymers with MPEG depends on the number of repeating unit of EO in poly(NIPAM-co-MPEG) when the value is below 24. Similar relationship between the grafting degree of PEG and LCST was observed for the NIPAM copolymers with PEG derivatives.^{22,27} The hydrophobic interactions of NIPAM compete with solubilizing effect and the surface stabilizing of MPEG. The stabilizing effect is more pronounced with increasing the length of EO. An increase in the number of repeating unit of EO increases the LCST of the NIPAM copolymers. At high number of EO such as 46MPEG, the collapse of poly(NIPAM) copolymer is almost totally prevented because the solubilizing effect and surface

stabilizing of MPEG is more effective in the experimental temperature range. So the phase separation of poly(NIPAM-co-46MPEG) was not observed in the range of 30 – 70°C .

The amount of PEG derivatives also affects the LCST of the copolymers. Figure 7 shows the light blockage of the poly(NIPAM-co-MPEG) with various mole percent of 10MPEG in aqueous solution. The LCST of the copolymers increased with mole percent of 10MPEG. The separation temperatures of the copolymers were 36°C for 2.5 mol %, 39°C for 5 mol %, 44°C for 7.5 mol %, and 65°C for 10 mol %. As mentioned before, the stabilizing effect is more pronounced with increasing amount of 10MPEG. The other copolymers except 46MPEG showed similar trend in LCST with the 10MPEG copolymer.

^1H -NMR experiments of the poly(NIPAM) and poly(NIPAM-co-10-2MPEG) were carried out to investigate the chain conformation of the polymers with the temperature. Figure 8 shows ^1H -NMR spectra of the poly(NIPAM) and poly(NIPAM-co-10-2MPEG) in D_2O at three different temperatures below and above the LCST. The ^1H -NMR results of poly(NIPAM) in Figure 8(a) are in reasonable agreement with previous NMR investigation of phase separation.^{32,34} So the

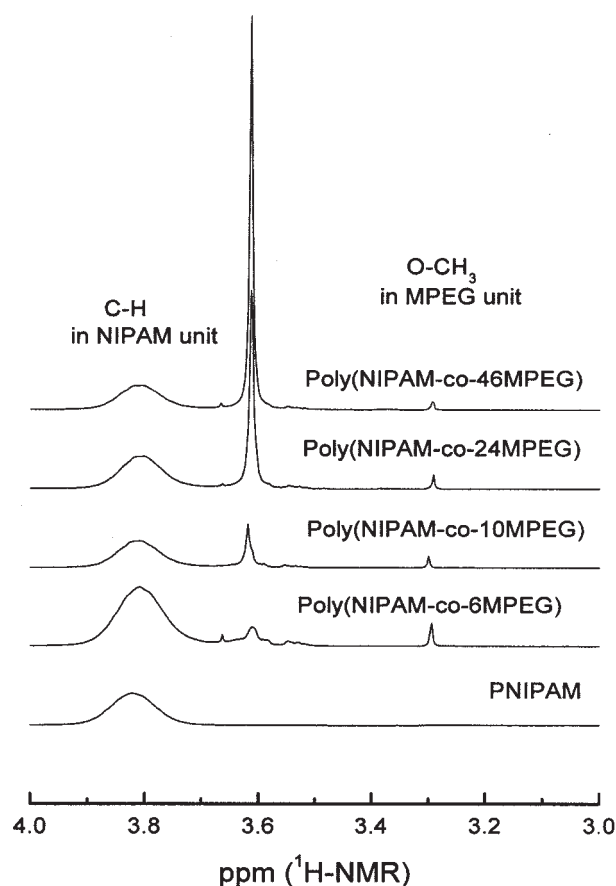


Figure 4 ^1H -NMR spectra of the poly(NIPAM) and the poly(NIPAM-co-MPEG) in the range of 4.0–3.0 ppm.

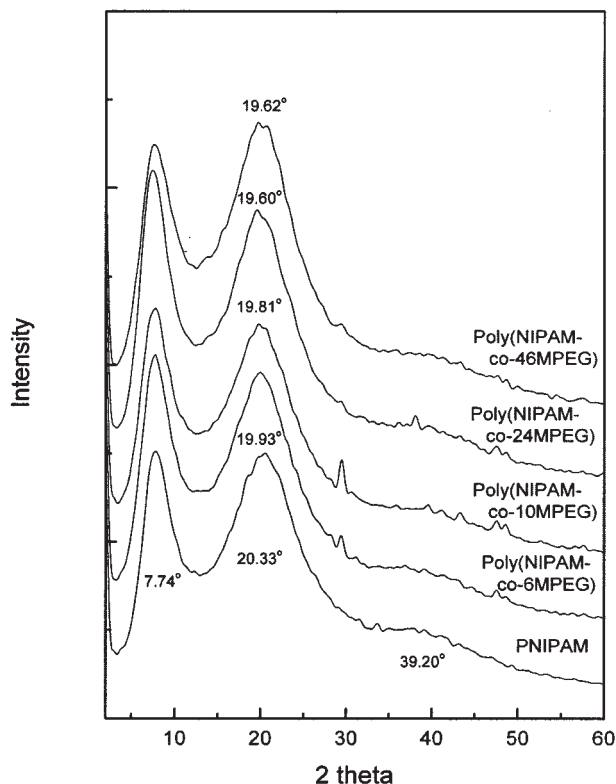


Figure 5 XRD patterns of the poly(NIPAM) and the poly(NIPAM-co-MPEG).

NMR results of poly(NIPAM) were not discussed further here.

Figure 8(b) shows $^1\text{H-NMR}$ spectra of the poly(NIPAM-co-10-2MPEG) in D_2O at three temperatures indicated. As the temperature is increased from 30 to 34°C, so that it is still below the LCST of the copolymer, there are no significant changes in $^1\text{H-NMR}$ spectra. As the temperature is 37°C (above the LCST), all proton resonance peaks shift slightly toward lower field but peaks do not disappear in the spectra. According to Zeng et al., peaks that belong to meth-

TABLE II
 2θ and d -spacing of the Poly(NIPAM-co-MPEG)

Sample	2θ (°)		
	d -spacing (nm)		
PNIPAM	7.74	20.33	39.20
	1.141	0.437	0.230
	7.70	19.93	39.39
Poly(NIPAM-co-6MPEG)	1.147	0.445	0.229
	7.75	19.81	39.74
	1.140	0.448	0.227
Poly(NIPAM-co-10MPEG)	7.42	19.60	39.75
	1.191	0.453	0.227
	7.60	19.62	40.53
Poly(NIPAM-co-46MPEG)	1.162	0.452	0.222

^a Calculated by $2d \sin \theta = \lambda$ ($\lambda = 0.15406$ nm).

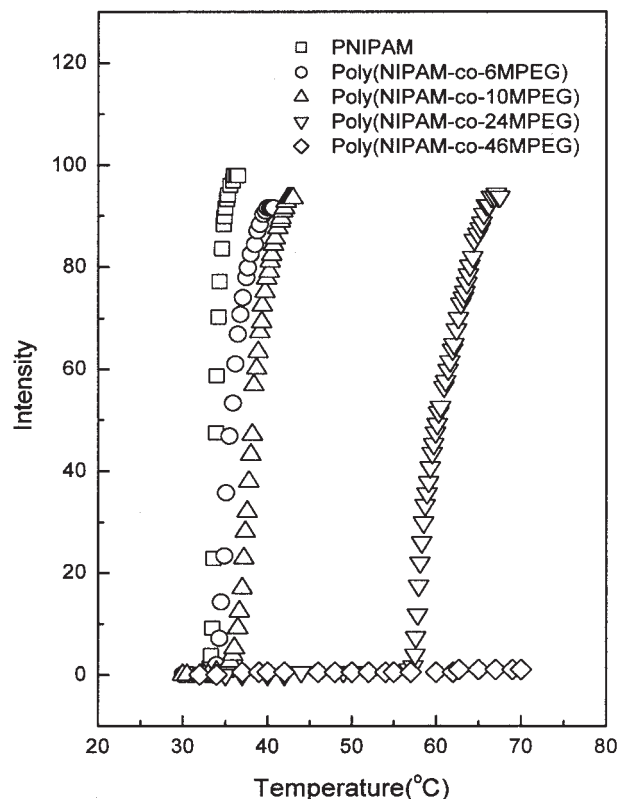


Figure 6 The change of light blockage of the poly(NIPAM) and the poly(NIPAM-co-MPEG) with the number of repeating unit of EO.

ylene and methyl protons almost disappeared above LCST because of a masking effect of methyl groups. Peaks remaining of the copolymer above LCST might be caused by more significant conformational change of MPEG group than methyl group. Among them, the change of chemical shift for $-\text{OCH}_3$ proton exhibits a larger than those of the other protons as shown in Figure 9. As pointed by Tokuhiko et al.,³⁴ the larger change in the chemical shift of the $-\text{OCH}_3$ proton implies that conformational change of methoxy group in MPEG is more significant than in isopropyl groups of poly(NIPAM) during the phase separation.

At below LCST, the poly(NIPAM) chains gradually shrink when solution temperature approaches the critical, and flexible MPEG chains with high hydrophilicity turn outward pointing out to the water phase and sustain the polymer aggregates soluble. The aggregates may be concluded to consist of a poly(NIPAM) core sterically stabilized by a MPEG shell. At LCST and higher, some of the water molecules are released out of the hydrated MPEG shell as a result of hydrogen bond breaking, so the structure of the hydrated shell is partially destroyed. Evidence for water release could be obtained by measuring the change of the integral intensity for water protons at 4.8 ppm relative to the integral intensity for CH at 3.8 ppm as shown in Figure 9.

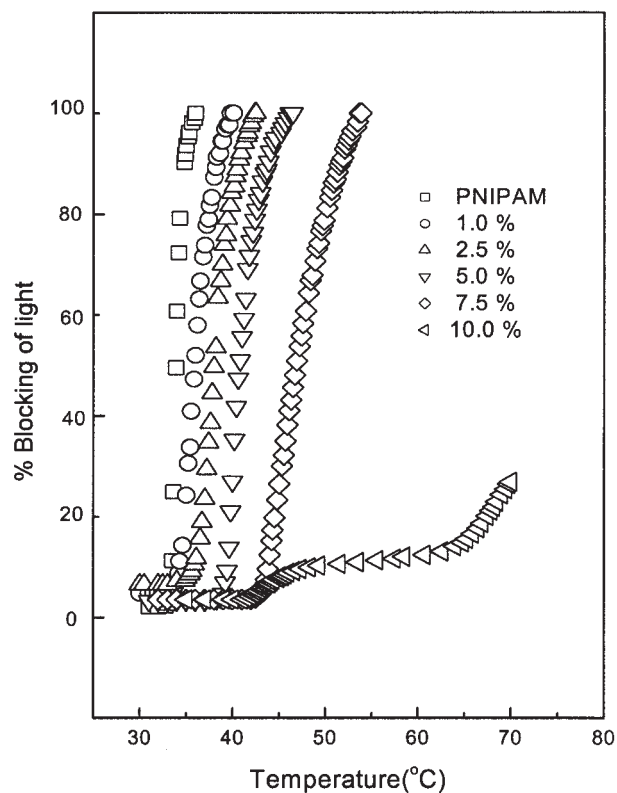


Figure 7 The change of light blockage of the poly(NIPAM-co-MPEG) with different mol % of 10MPEG.

The temperature dependence of T_1 was studied to determine the dynamic behavior of the poly(NIPAM).^{32,34} For a specific proton, there is a minimum in its curve of T_1 against temperature dividing the curve into high- and low-temperature sides.^{41,42} With increasing temperature, the relaxation for the methyl proton in the isopropyl group follows the T_1 curve on the high-temperature side of the T_1 minimum, whereas the T_1 behavior of the backbone protons follows the curve on the low-temperature side. The T_1 behavior of poly(NIPAM) are in reasonable agreement with previous T_1 investigation.^{32,34} So the T_1 behavior of poly(NIPAM) did not present here.

To investigate the dynamic behavior of the copolymer, the plot of the T_1 against the temperature was made for the poly(NIPAM-co10-2MPEG) as shown in Figure 10. The temperature dependences exhibited distinct differences between chemical groups. The T_1 values for the methyl protons in the *N*-isopropyl group increased with rising temperature. The temperature dependence of T_1 for the lone proton in the *N*-isopropyl group, the methoxy proton and EO proton of the MPEG group appears to follow a curve that is convex upwards. The T_1 behaviors of both methylene and methyne protons in the backbone were completely opposite to the side chain protons. A rudimentary theory⁴¹ can be sufficiently adopted to relate T_1

with correlation time (τ) and the temperature dependence of τ is described by the Arrhenius expression. In the observed temperature range, the experimental T_1 versus temperature curve usually locates on either side depending on the product of the Larmor frequency and correlation time. The proton relaxation behavior of the side chain protons in *N*-isopropyl and MPEG groups follows the T_1 curve on the high-temperature side of the T_1 minimum, whereas the T_1 behavior of the backbone protons follows the curve on the low-temperature side as reported in T_1 behavior of the poly(NIPAM).^{28,34} The temperature dependences of T_1 suggest that the relaxations of side groups are slow down while those of the backbone groups are speed up.³² A simple technique has been described to quantify approximate activation energies (E_a).³⁴ Because the accuracy of T_1 is low above LCST where the resolution of proton signals decreases, E_a determined from the slopes of Figure 10 in the range of 30–37°C

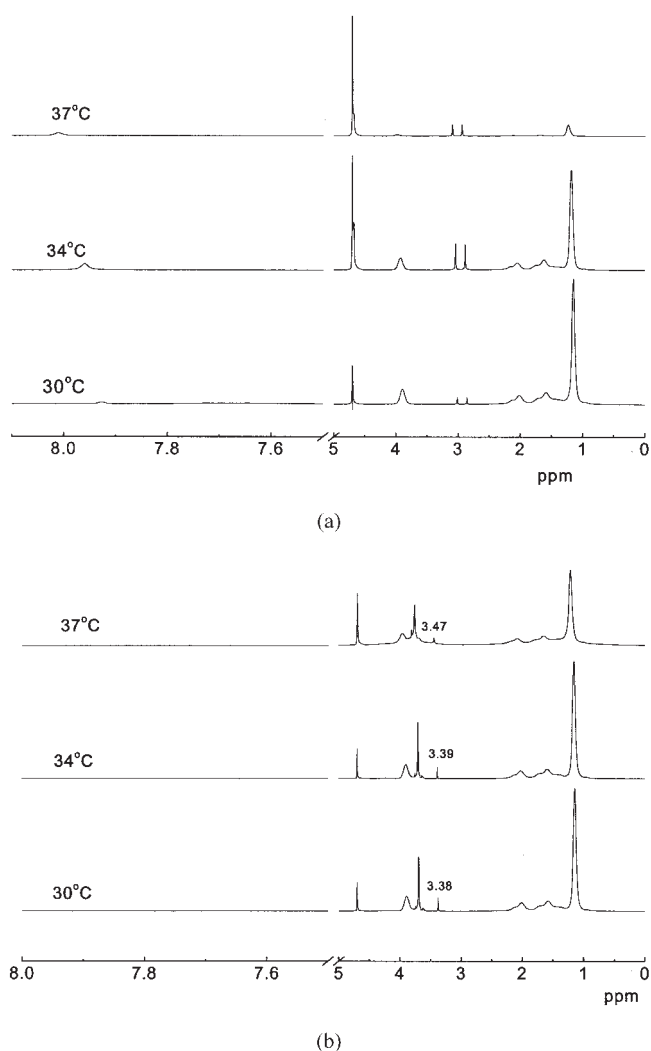


Figure 8 $^1\text{H-NMR}$ spectra of the poly(NIPAM) (a) and poly(NIPAM-co-10-2MPEG) (b) at three temperatures indicated.

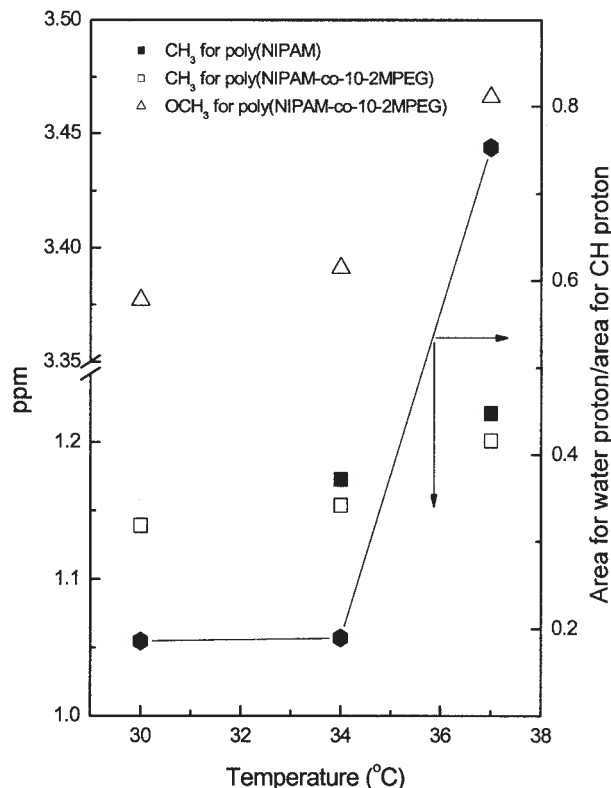


Figure 9 Plot of the chemical shifts for CH_3/OCH_3 and the integral intensity at 4.8 ppm (H_2O) of poly(NIPAM-co-10-2MPEG) as a function of temperature.

and Boltzmann constant. E_a values are summarized in Table III. The larger value in activation energy for the methoxy group ($E_a = 2.35$ cal/mol) suggests that more significant conformational transformations occur in the methoxy group through the phase separation than in the methyl group ($E_a = 1.19$ cal/mol).

By integrating the NMR results for the copolymer solution as shown above, a physical picture of the process involving continuous phase transition emerges as follows: The backbone of the copolymer and its isopropyl group are hydrophobic. Therefore, it is reasonable to assume that this copolymer is made water soluble by the formation of hydrogen bonds between the amide group in NIPAM, the methoxy group in MPEG, and water. The water molecules strapped by these bonds form a thin shell of ordered structure around the hydrophilic part such as methoxy group. With increasing the solution temperature, some of the water molecules are released out of the hydrated shell as a result of hydrogen bond breaking as shown in Figure 9, so the structure of the hydrated shell by MPEG is destroyed. Then, it forms hydrophobic bonding because the hydrophobic interactions of the methyl group in *N*-isopropyl are more pronounced with increasing the temperature. As hydrophobic bonding becomes stronger between the methyl groups, the microenvironment around the co-

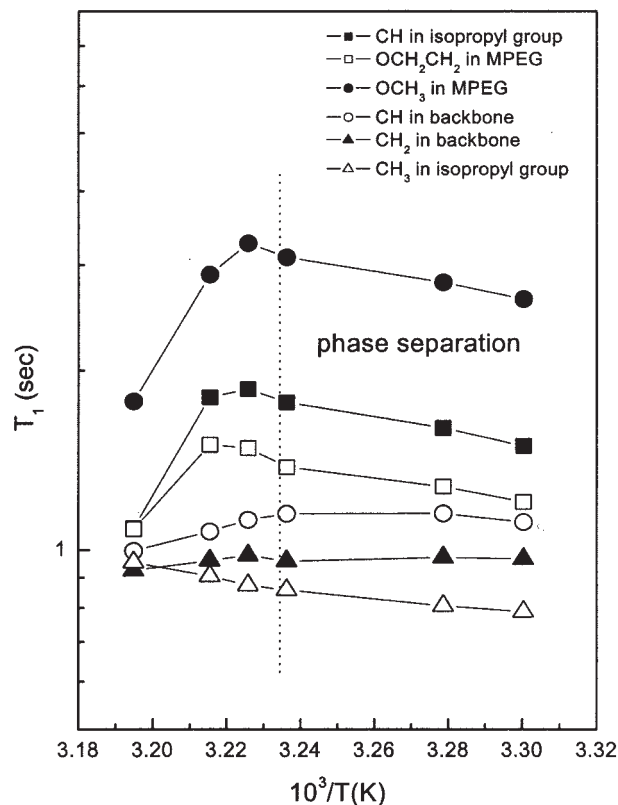


Figure 10 Proton spin-lattice relaxation time (T_1) of poly(NIPAM-co-10-2MPEG) in D_2O as a function of solution temperatures.

polymer should become less polar. Winnik et al.³¹ have shown with fluorescence techniques that the polarity of poly(NIPAM) is lowered to that of organic liquids such as methanol and tetrahydrofuran.

CONCLUSIONS

New aspects of the synthesis and phase separation of the NIPAM copolymers with MPEG were developed and discussed. The chemical structure and the composition of the poly(NIPAM-co-MPEG) was confirmed by FTIR and NMR spectra. Copolymer compositions

TABLE III
Approximate Activation Energies of the Poly(NIPAM) and Poly(NIPAM-co-10-2MPEG)

Groups	Activation energy ^a (E_a , cal/mol)
CH in isopropyl	2.39
OCH_2CH_2 in MPEG	2.15
OCH_3 in MPEG	2.35
CH in backbone	0.12
CH_2 in backbone	0.05
CH_3 in isopropyl	1.19

^a Calculated by $E_a = \text{slope} \times \text{Boltzmann constant}$.

calculated using $^1\text{H-NMR}$ data were in reasonable agreement with initial monomer ratios. The d -spacing increased with the number of EO of the poly(NIPAM-*co*-MPEG). The phase separation of the poly(NIPAM-*co*-MPEG) shifted to higher temperature as the number of EO and the amount of MPEG increased. LCSTs of the copolymer were 34°C for poly(NIPAM-*co*-6MPEG), 36°C for poly(NIPAM-*co*-10MPEG), and 58°C for poly(NIPAM-*co*-24MPEG). However, there was no change in light blockage with temperature for poly(NIPAM-*co*-46MPEG). With increasing solution temperature, the spin-lattice relaxation time (T_1) for the protons in side chain increased, while that for the protons in the backbone chain decreased. E_a for methoxy proton in MPEG group exhibited a larger than that of the methyl proton in NIPAM. These results suggest that more significant conformational transformations occur in the methoxy group in MPEG through the phase separation than in the methyl group in NIPAM

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