RAFT Polymerization of *N*-Isopropylacrylamide in the Absence and Presence of $Y(OTf)_3$: Simultaneous Control of Molecular Weight and Tacticity

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ABSTRACT: The reversible addition−fragmentation chain transfer (RAFT) polymerization of *N*-isopropylacrylamide (NIPAM) was carried out successfully in the absence and presence of Lewis acid $Y(OTf)_3$ to synthesize controlled molecular weight atactic and isotactic poly(NIPAM)s using both 1-phenylethyl phenyldithioacetate (PEPD) and cumyl phenyldithioacetate (CPDT) as the RAFT agents. The polymerization rate is about 16 times faster in the presence of the Lewis acid than that in the absence and 1.4 times faster with PEPD than with CPDT as the RAFT agent. The polymer with a higher polydispersity was obtained when prepared in the presence of the Lewis acid than that in the absence. A longer induction period was observed using CPDT than PEPD. The chain-end structure of isotactic poly(NIPAM) was determined by ^{1}H NMR and MALDI−TOF mass spectrometry. The RAFT agent derived isotactic poly(NIPAM) was the main product as expected from the well-accepted mechanism of RAFT polymerization. Moreover, a series of stereoblock [atactic(a)-*b*-isotactic(i)] poly(NIPAM) with different block lengths were synthesized via a one-pot synthesis procedure: synthesis of the atactic block in the absence of the Lewis acid followed by the addition of the Lewis acid to synthesize the isotactic block. The longer is the isotactic block length, the higher is the meso dyad value of the stereoblock polymer as expected. We also successfully synthesized the diblock copolymers, a-poly(NIPAM)-*b*-polystyrene and i-poly(NIPAM)-*b*-polystyrene, starting with the atactic and isotactic poly(NIPAM) macro-RAFT agents, respectively.

Introduction

The simultaneous control of molecular weight and stereochemistry of a polymer is one of the unattained targets in controlled radical polymerization because either is now independently achievable by some methods. For molecular weight control, living radical polymerization[1] is the most useful procedure, where metal-catalyzed living radical polymerization,[2] nitroxide-mediated polymerization,[3] and reversible addition−fragmentation chain transfer (RAFT) polymerization[4] have been widely employed. Stereocontrol in radical polymerization is difficult due to the planar configuration at the propagating radical chain-end carbon in comparison to that in ionic or coordination polymerization, where metal species can interact with the propagating chain end. However, it has become possible in the radical polymerization of special monomers bearing a bulky group[5] or a chiral auxiliary group[6] to give highly isotactic polymers. Recently, one of our groups developed a more general method for the stereocontrolled radical polymerization of methacrylates,[7] acrylamides,[8] and methacrylamides[9−14] catalyzed by Lewis acids such as rare earth metal trifluoromethanesulfonates (OTf).

Therefore, we aimed to control both molecular weights and steric structure of polymers by combining the living radical polymerization and the stereocontrolled radical polymerization. Especially, we focused on the controlled radical polymerization of *N*-isopropylacrylamide (NIPAM), which can be polymerized only by a radical mechanism to give a water-soluble polymer[15] with wide applications such as a thermoresponsive polymer gel.[16] Among various living radical polymerizations, the RAFT process is now best in controlling molecular weight of polyacrylamides[17,18] and has recently been employed for NIPAM by two research groups[19,20] to give poly(NIPAM) with controlled molecular weights and narrow molecular weight distributions. The molecular weight control in the RAFT systems is based on a dynamic equilibrium between the propagating radical and the dormant species with a dithiocarbonyl group derived from the RAFT agent (Scheme 1). The choice of RAFT agents is thus important in controlling the radical polymerization. However, none of these examples are for fine stereochemical control of polymers.

In a recent communication, we first reported the synthesis of molecular weight controlled isotactic poly(NIPAM) using 1-phenylethyl phenyldithioacetate (PEPD) as the RAFT agent in the presence of a Lewis acid such as $Y(OTf)_3$ in a methanol−toluene (1/1, v/v) mixture at 60 °C.[21] Very recently, Matyjaszewski et al. reported the streocontrolled living radical polymerization of *N*,*N*-dimethylacrylamide by using the same strategy and synthesized stereoblock poly(*N*,*N*-dimethylacrylamide).[22] Here, we will report on the overall kinetic study of the RAFT polymerization of NIPAM in the absence and presence of $Y(OTf)_3$ using two chain

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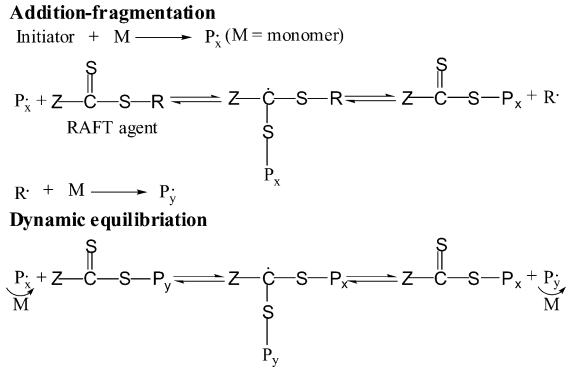
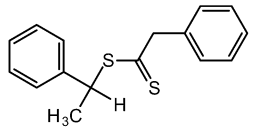
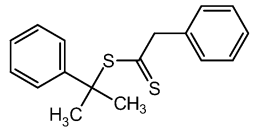
Scheme 1. Mechanism of RAFT Process



Scheme 2. Structures of RAFT Agents



1-Phenylethyl phenyldithioacetate (PEPD)



Cumyl phenyldithioacetate (CPDT)

transfer agents, PEPD and cumyl phenyldithioacetate (CPDT) (Scheme 2). NMR and MALDI−TOF mass techniques were used to determine the chain-end structure of the isotactic poly(NIPAM). We have also extended the RAFT polymerization procedure to the one-pot synthesis of stereoblock poly(NIPAM) with different block lengths and to the synthesis of diblock copolymers atactic(a)−poly(NIPAM)-*b*-polystyrene and isotactic(i)−poly(NIPAM)-*b*-polystyrene. All these block copolymers were characterized by GPC, NMR, and a solubility study.

Experimental Section

Materials. NIPAM (Wako, >98%) was recrystallized twice from hexane. Styrene (Wako, >98%) was distilled under vacuum over CaH_2 before use. AIBN (Kishida, 99%) was recrystallized from methanol. $Y(OTf)_3$ (Aldrich, 98%), $Yb(OTf)_3$ (Aldrich, 99.99%), $Sc(OTf)_3$ (Aldrich, 99%), and $Lu(OTf)_3$ (Aldrich, 98%) were dried under vacuum before use. Dehydrated methanol (Kanto, >99.8%), dehydrated toluene (Kanto, >99.5%), and dehydrated tetrahydrofuran (THF) (Kanto, >99.5%) were used as received.

1-Phenylethyl phenyldithioacetate (PEPD)[23] and cumyl phenyldithioacetate (CPDT)[24] were synthesized according to the literature (Scheme 2).

Polymerization Procedure for the Kinetic Study. The polymerization was carried out in a dry glass tube capped with a two-way glass stopper under dry nitrogen. For a typical kinetic study in the absence of a Lewis acid, NIPAM (4.52 g, 40 mmol), PEPD (38 mg, 0.138 mmol), and AIBN (7.6 mg, 0.046 mmol) were placed in a dry glass tube under dry nitrogen and dried under vacuum for 1 h. Then toluene (20 mL) and methanol (20 mL) were added using a degassed syringe. The obtained stock solution was divided into 10 dry and degassed polymerization glass tubes. The tubes were then placed in a thermostated bath at 60 °C for the desired time. The reaction was stopped by cooling at −78 °C. For a typical kinetic study in the presence of the Lewis acid, NIPAM (4.52 g, 40 mmol), PEPD (38 mg, 0.138 mmol), AIBN (7.6 mg, 0.046 mmol) and $Y(OTf)_3$ (2.5 g, 4.7 mmol) were placed in a dry glass tube under dry nitrogen and dried under vacuum for 1 h. Then toluene (20 mL) and methanol (20 mL) were added using a degassed syringe. The obtained stock solution was divided into 10 dry and degassed polymerization glass tubes. The tubes were then placed in a thermostated bath at 60 °C for the desired time. The reaction was stopped by cooling at −78 °C. The polymer yields were determined by ^{1}H NMR spectroscopy of the reaction mixtures and also gravimetrically. For the polymerization in the absence of a Lewis acid, the polymers were precipitated from hot (heated just above 40 °C) diethyl ether, isolated by centrifugation, and dried overnight at 60 °C under vacuum. For the polymerization in the presence of the Lewis acid, the reaction mixture was precipitated in a large excess of diethyl ether and isolated by centrifugation and dried at 60 °C under vacuum. The polymer was freed from the Lewis acid by dissolving the polymer−Lewis acid mixture in methanol and precipitating it from an excess amount of water at room temperature. This procedure was repeated three times to remove the Lewis acid completely from the polymer.

One-Pot Synthesis of Stereoblock Homopolymer of NIPAM. One-pot synthesis of stereoblocks of atactic-*b*-isotactic poly(NIPAM) was performed using PEPD as the chain transfer agent. At first, the atactic block was synthesized in the absence of the Lewis acid in a methanol−toluene (1:1) mixture at 60 °C for a desired time to vary the chain length of the atactic block. Then, Lewis acid $Y(OTf)_3$ as a methanol solution was added to form the isotactic block of different chain lengths. The reaction was continued at the same temperature for another few hours so that the total reaction period was around 16 h. For a typical run, NIPAM (0.452 g, 4 mmol), PEPD (3.8 mg, 0.014 mmol), and AIBN (0.76 mg, 0.005 mmol) were placed in a dry glass tube under dry nitrogen and dried under vacuum for 1 h. Then toluene (2 mL) and methanol (2 mL) were added using a degassed syringe. The tube was then placed in a thermostated bath at 60 °C for 2.5 h. After that, 0.5 mL of the raw reaction mixture was taken out through a degassed syringe in order to determine the monomer conversion (by ^{1}H NMR), molecular weight, molecular weight distribution, and tacticity. Then, the Lewis acid $Y(OTf)_3$ (0.27 g, 0.5 mmol) in methanol (2 mL) was added through a degassed syringe. The reaction was continued at the same temperature for another 14 h. The reaction was stopped by cooling at −78 °C. The final polymer yield was determined gravimetrically from diethyl ether insoluble part. For the atactic block synthesis, monomer conversion was 16%. Polymer is precipitated from hot (heated just above 40 °C) diethyl ether, isolated by centrifugation, and dried overnight at 60 °C under vacuum. The molecular weight (M_n) and polydispersity (M_w/M_n) of the obtained polymer were 0.45×10^4 and 1.26, respectively. Meso dyad value of the obtained polymer was 47%. For the stereoblock polymer synthesis, the final reaction mixture was precipitated in a large excess of diethyl ether (solvent for atactic poly(NIPAM)) and isolated by centrifugation and dried at 60 °C under vacuum. The polymer yield is 89%. The polymer was freed from the Lewis acid by dissolving the polymer−Lewis acid mixture in methanol and precipitating it from an excess amount of water at room temperature. This procedure was repeated three times to remove the Lewis acid completely from the polymer. The molecular weight (M_n) and polydispersity (M_w/M_n) of the obtained polymer were 2.21×10^4 and 2.09, respectively. The meso dyad value of the obtained polymer was 78%. ^{1}H NMR of the both polymers is shown in Figure 7.

Synthesis of Diblock Copolymers. For a typical run, atactic poly(NIPAM) ($M_n = 2.24 \times 10^4$, $M_w/M_n = 1.22$) macrochain-transfer agent (0.1 g, 0.0045 mmol) and AIBN (0.2 mg, 0.0012 mol) were taken in a dry glass tube capped with a two-way glass stopper under dry nitrogen and degassed under vacuum for 1 h. THF (2 mL) and styrene monomer (0.5 mL, 4.36 mmol) were added into the polymerization reactor through a degassed syringe. The mixture was stirred at room temperature to solubilize all ingredients in the polymerization medium. The tubes were then placed in a thermostated bath at 60 °C for 48 h. The reaction was stopped by cooling at −78

°C. The monomer conversion (26.3%) was determined by ^{1}H NMR ($CDCl_3$, 25 °C). The final reaction mixture was precipitated in a large excess of diethyl ether and isolated by centrifugation. The molecular weight (M_n) and polydispersity (M_w/M_n) of the obtained diblock copolymer were 5.73×10^4 and 1.58, respectively. The isolated polymer was redissolved in excess acetone (solvent for diblock copolymer but nonsolvent for polystyrene) and centrifused, supernatant was collected, and acetone was removed by evaporation. This procedure was repeated one more time to remove polystyrene homopolymer from the diblock copolymer. A trace amount of polystyrene homopolymer was observed. The purified diblock copolymer was finally dried under vacuum. After purification from acetone, the observed molecular weight (M_n) of the a-poly(NIPAM)-*b*-polystyrene was almost the same (5.60×10^4 with $M_w/M_n = 1.57$). NMR of the diethyl ether insoluble polymer is shown in Figure 9.

Solubility Studies of Stereoblock and Diblock Copolymers. 2 mg of polymer sample was taken in 1 mL of solvent and kept overnight—in some cases 1 week to ensure the solubility (swelling or insolubility) properties.

Polymer Characterization. The average molecular weights and polydispersities of the polymers were measured by size exclusion chromatography (SEC) against polystyrene standard in DMF containing 0.1 mol/L LiCl at a flow rate of 0.5 mL/min at 40 °C on two polystyrene gel columns, TSK gel α-M (bead size 13 μm and measurable molecular weight range $10^{2.5}-10^7$) and TSK gel α-3000 (bead size 7 μm and measurable molecular weight range $10^{2.5}-10^5$), using JASCO RI-930 and JASCO UV-970 detectors. The theoretical number-average molecular weight was calculated using the following equation

$$M_n(\text{theor}) = \frac{[\text{NIPAM}]_0}{[\text{CTA}]_0} x_m M_m + M_{CTA}$$

where x_m is the fraction conversion of monomer, M_m is the molecular weight of the monomer, and M_{CTA} is the molecular weight of the chain transfer agent.

The ^{1}H NMR spectra were recorded on a Varian Gemini 2000 spectrometer (400 MHz). For the determination of the NIPAM conversion, the ^{1}H NMR spectrum of the polymerization mixture was measured in DMSO-d_6 at room temperature, and the integration of the monomer C═C−H peak at 5.7 ppm was compared with the N−C−H peak intensity of the polymer and the monomer at 4.1 ppm. The dyad tacticity of poly(NIPAM) was determined from the methylene proton peaks of the polymer recorded in DMSO-d_6 at 170 °C.[8] For the diblock copolymer synthesis, styrene conversion was determined from ^{1}H NMR in $CDCl_3$ (for a-poly(NIPAM)-*b*-polystyrene synthesis) or in the $CDCl_3$−DMSO-d_6 (1/1, v/v) mixture (for i-poly(NIPAM)-*b*-polystyrene synthesis) at room temperature by comparing the integration of vinylic proton peak of the monomer with the aromatic proton of the monomer and the polymer.

MALDI−TOF mass spectrometry was performed on a PerSeptive Biosystems equipped with a 337 nm N_2 laser in the reflector mode and at 20 kV acceleration voltage. Dithranol (Aldrich, 97%) was used as a matrix. Sodium trifluoroacetate was added for ion formation. Samples were prepared from a THF solution by mixing the matrix (20 mg/mL), sample (10 mg/mL), and salt (10 mg/mL) in a ratio of 10:1:1.

Results and Discussion

RAFT Polymerization of NIPAM in the Absence and Presence of Y(OTf)$_3$ Using PEPD and CPDT RAFT Agents. NIPAM was polymerized in a methanol−toluene (1:1) mixture in the absence and presence of $Y(OTf)_3$ using AIBN as an initiator and PEPD and CPDT both as RAFT agents at 60 °C. Parts A and B of Figure 1 show the time vs $\ln([M]_0/[M])$ plots for PEPD and CPDT RAFT agent systems, respectively. The polymerization rates were around 16 times faster in the presence of the Lewis acid than that in the absence for the both RAFT agent systems. Initially, there were induction periods for both systems. We have roughly estimated the induction periods simply by extrapolating the linear part of the each curve to the time axis.[20] For the PEPD system, the induction periods were around 50 and 130 min for the polymerization in the presence and absence of $Y(OTf)_3$, respectively. For the CPDT system, the induction periods were around 180 and 260 min for the polymerization in the presence and absence of $Y(OTf)_3$, respectively. Therefore, a longer induction period was observed with CPDT than PEPD irrespective of the presence or absence of the Lewis acid. The induction periods observed here for the all polymerization systems were like others reported in the literature.[20,25−27] On the other hand, the polymerization rate is relatively faster (around 1.4 times) (calculated from the slope of the linear part of the pseudo-first-order kinetic curves) for the PEPD system than the CPDT system irrespective of the polymerization in the absence and presence of the Lewis acid. Moreover, the observed induction periods are relatively shorter for the polymerization of NIPAM in the presence of $Y(OTf)_3$ rather than that in the absence. This may be due to the higher reactivity of the Lewis acid-complexed both NIPAM

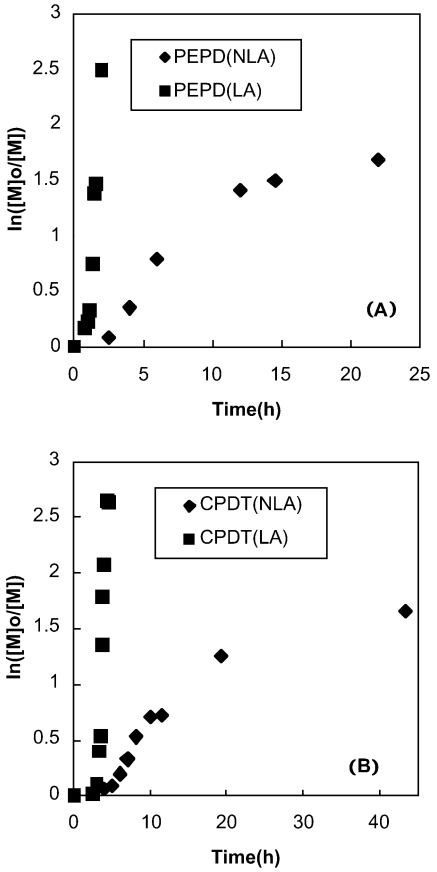


Figure 1. Plots of time (h) vs $\ln([M]_0/[M])$ (where $[M]_0$ = concentration of the monomer at $t = 0$ h and [M] = concentration of the monomer at the corresponding time) in the polymerization of *N*-isopropylacrylamide (NIPAM) using [NIPAM] = 1 M, [AIBN] = 1.2 mM in methanol/toluene (1/1, v/v) mixture at 60 °C: (A) [PEPD] = 3.47 mM, (◆) [$Y(OTf)_3$] = 0 M, (■) [$Y(OTf)_3$] = 0.12 M; (B) [CPDT] = 3.47 mM, (◆) [$Y(OTf)_3$] = 0 M, (■) [$Y(OTf)_3$] = 0.12 M (where AIBN = 2,2′-azobis(isobutyronitrile), PEPD = 1-phenylethyl phenyldithioacetate, CPDT = cumyl phenyldithioacetate, OTf = trifluoromethanesulfonate, NLA = absence of $Y(OTf)_3$ and LA = presence of $Y(OTf)_3$).

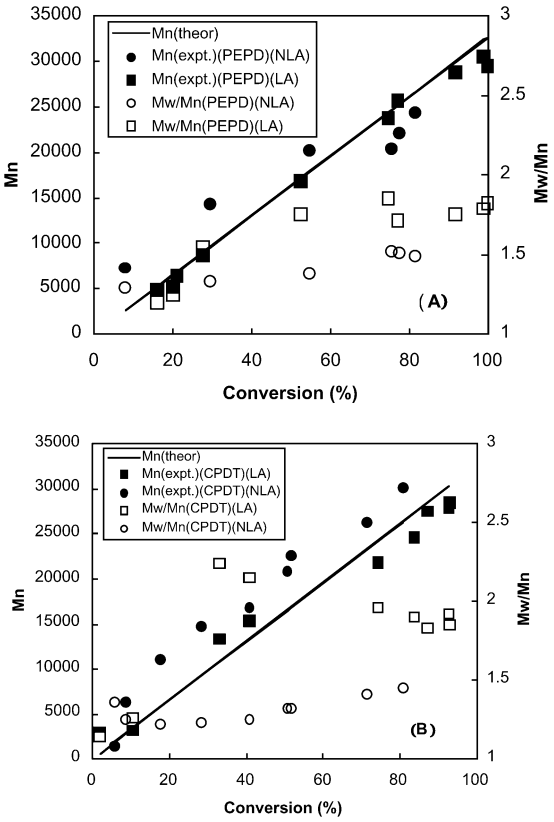


Figure 2. Plots of conversion (%) vs number-average molecular weight (M_n) and polydispersity (M_w/M_n) (where M_w = weight-average molecular weight) in the polymerization of *N*-isopropylacrylamide (NIPAM) using [NIPAM] = 1 M, [AIBN] = 1.2 mM in methanol/toluene (1/1, v/v) mixture at 60 °C: (A) [PEPD] = 3.47 mM, [$Y(OTf)_3$] = 0 M: (●) M_n(expt), (○) M_w/M_n (expt) and [$Y(OTf)_3$] = 0.12 M: (■) M_n(expt), (□) M_w/M_n (expt); (B) [CPDT] = 3.47 mM, [$Y(OTf)_3$] = 0 M: (●) M_n(expt), (○) M_w/M_n (expt) and [$Y(OTf)_3$] = 0.12 M: (■) M_n(expt), (□) M_w/M_n (expt) (where AIBN = 2,2′-azobis(isobutyronitrile), PEPD = 1-phenylethyl phenyldithioacetate, CPDT = cumyl phenyldithioacetate, OTf = trifluoromethanesulfonate, NLA = absence of $Y(OTf)_3$ and LA = presence of $Y(OTf)_3$). (—) M_n-(theor).

monomer and propagating radical than those without the complexation with the Lewis acid.[8]

Parts A and B of Figure 2 show the corresponding plots of percent conversion vs M_n(expt), M_n(theor), and M_w/M_n (polydispersity) (M_w = weight-average molecular weight) in the absence and presence of $Y(OTf)_3$ for PEPD and CPDT systems, respectively. M_n(expt) increases almost linearly with an increase in conversion. Observed M_n(expt)s are close to M_n(theor). In the absence of the Lewis acid, for the both RAFT agent systems, M_w/M_n became broader with an increase in conversion. This was also observed for the RAFT polymerization of NIPAM using the cumyl dithiobenzoate/AIBN initiation system in 1,4-dioxane and may be due to two probable reasons: (a) chain transfer to the monomer and/or (b) termination by disproportion.[19] The formation of a three-arm star chain during the RAFT polymerization of styrene reported by Kwak et al.[28] was not observed in the GPC profiles of our poly(NIPAM) samples.

However, in the presence of the Lewis acid, for the PEPD system, polydispersity increased initially with an increase in conversion and became almost leveled off around 1.8. For the CPDT system, polydispersity also increased initially with an increase in conversion and reached a maximum value of 2.24 around 35% conversion and after that decreased slightly with an increase in conversion. The observed higher polydispersity in the presence of the Lewis acid ($Y(OTf)_3$) may be due to the faster rate of polymerization owing to the complexation of the Lewis acid with the monomer and propagating radical and also due to the concomitant slower rate of exchange within the dormant intermediate radical complexed with Lewis acid through the thiocarbonylthio group and the active propagating radical. Another possibility may be due to some unknown side reactions assisted by Lewis acid. Similar observations were also reported in the literature,[8,11,22,29−31] and these might lead to the higher polydispersity in the resulting polymer.[32,33] It is to be noted that the polydispersity of the resulting poly(NIPAM) was decreased with increasing the ratio of chain transfer agent to initiator (Table 1).

Table 1. RAFT Polymerization of *N*-Isopropylacrylamide (NIPAM) at Higher Ratio of RAFT Agent to Initiator Concentration[a]

run	RAFT (mM)	yield[d] (%)	M_n(theor) $\times 10^{-4}$	M_n(expt)[e] $\times 10^{-4}$	M_w/M_n[e]
1[b]	PEPD (3.47)	93	6.05	5.54	1.84
2[b]	PEPD (9.17)	86	2.12	2.28	1.39
3[b]	PEPD (18.30)	14	0.17	0.30	1.07
4[c]	CPDT (3.47)	97	6.30	5.98	1.85
5[c]	CPDT (6.94)	93	3.05	3.44	1.65

[a] [NIPAM] = 2.0 M, [AIBN] = 1.2 mM, [$Y(OTf)_3$] = 0.2 M, methanol−toluene (1/1) mixture = 4 mL. [b] Polymerization time = 4 h. [c] Polymerization time = 6 h. [d] Diethyl ether-insoluble part. [e] Determined by SEC in DMF containing 0.1 M LiCl at 40°C (PS standard).

Therefore, the controlled polymerization of NIPAM can be attained using both PEPD and CPDT as the chain transfer agents and AIBN as the initiator in the absence and presence of the Lewis acid in a methanol−toluene mixture at 60 °C.

The tacticity of the poly(NIPAM)s prepared in methanol−toluene (1:1) using either PEPD or CPDT in the absence of the Lewis acid was m = 47%. The tacticity of the poly(NIPAM)s obtained in the kinetic study using PEPD in the presence of 0.12 M $Y(OTf)_3$ was isotactic with m = 80−84%. The propagating chain end carbon radical center has almost planar configuration in the absence of Lewis acid. This planar configuration favors both the meso and recemo type addition of the monomer with equal probability. This leads to produce the atactic poly(NIPAM) with meso diad value of 47% (which is almost close to 50%). The higher isotacticity (meso diad value) in the presence of Lewis acid may be due to the multiple coordination of the bulky Lewis acid $Y(OTf)_3$ with the last two pendant amide groups of the propagating radical and the incoming monomer unit which in turn favors the meso type addition of Lewis acid-complexed monomer. Similar types of observations are also reported by us earlier in the polymerization of acrylamides,[8] methacrylamides,[9−14] and methacrylates[7] in the presence of bulky lanthanide triflate Lewis acids. The tacticity slightly decreased with an increase in conversion (Figure 3). As the reaction progressed, the reaction mixture became viscous, and some polymer chains may trap some Lewis acid molecules through the complexation, which nominally decreases the local concentration of the Lewis acid near the propagation site. This may be a plausible reason for the slight decrease of tacticity with increasing conversion.

Chain-End Analysis of Isotactic Poly(NIPAM). Figure 4 shows the ^{1}H NMR spectrum (400 MHz,

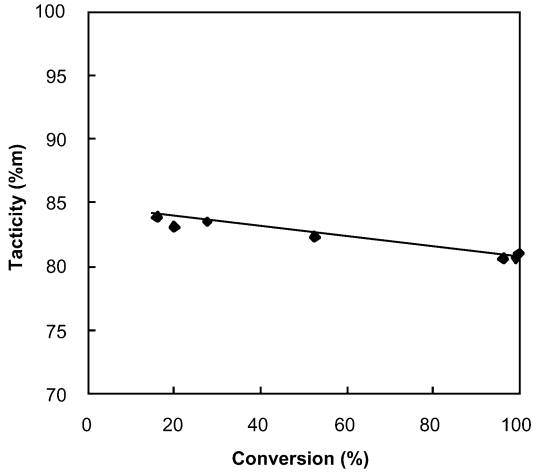


Figure 3. Plot of conversion (%) vs tacticity (% *m*) in the polymerization of *N*-isopropylacrylamide (NIPAM) using [NIPAM] = 1 M, [AIBN] = 1.2 mM, [PEPD] = 3.47 mM, [$Y(OTf)_3$] = 0.12 M in methanol/toluene (1/1, v/v) mixture at 60 °C.

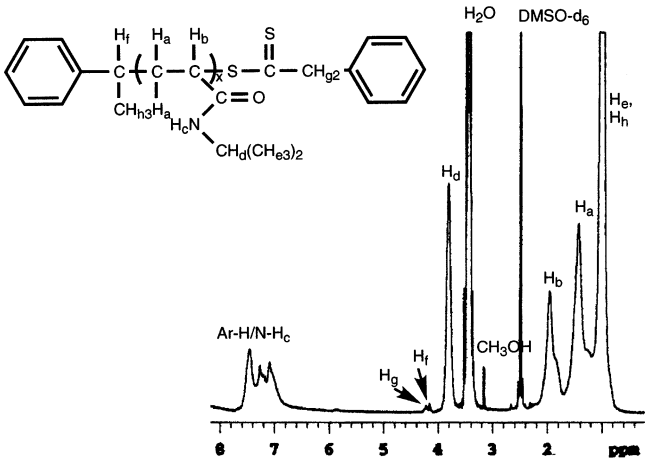


Figure 4. ^{1}H NMR (400 MHz, DMSO-d_6, room temperature) spectrum of isotactic poly(NIPAM) (having M_n = 9000, M_w/M_n = 1.55, obtained at 28% conversion) obtained in the polymerization of NIPAM (1 M) using PEPD RAFT agent (3.47 mM) in the presence of $Y(OTf)_3$ (0.12 M) in methanol/toluene (1/1, v/v) mixture at 60 °C.

DMSO-d_6, RT) of the isotactic poly(NIPAM) (M_n = 9000, M_w/M_n = 1.55) prepared with AIBN as initiator and PEPD in the presence of $Y(OTf)_3$ in a toluene−methanol (1:1, v/v) mixture at 60 °C. Apart from the characteristic peaks of the methyl (H_e) and methine (H_d) protons of the isopropyl group, and backbone methylene (H_a) and methine (H_b) protons of the main-chain repeating units of NIPAM, the methine proton (H_f) of 1-phenylethyl fragment at the α-chain end of the polymer was observed at 4.1 ppm followed by a broad triplet at 4.15 ppm, which corresponds to the methylene proton (H_g) of the benzyl fragment at the ω-chain end of the polymer. Aromatic protons of both chain-end fragments were overlapped with the amido methine (H_c) proton of the isopropyl group of the main-chain repeating units of NIPAM. Aromatic protons are observable around 7.1 ppm along with amido methine proton around 6.4 ppm, when the spectrum was taken in the same solvent at 170 °C (spectrum not shown). Therefore, the polymer chain end was capped with the RAFT agent fragment as expected according to the well-known mechanism of the RAFT process. Moreover, M_n of the polymer was calculated from the peak intensity ratios of the methine (H_d) protons of the isopropyl group to the methine proton (H_f) of the 1-phenylethyl fragments at the α-chain end of the polymer. The M_n(NMR) value is 11 200, which is slightly higher than the M_n(SEC) (9000). This discrepancy may be due to the use of standard polystyrene for the calibration in the GPC measurement.

The chain-end structure of the same isotactic poly(NIPAM) was also determined by MALDI−TOF mass spectrometry. In the literature, there were a few reports on the use of MALDI−TOF mass spectrometry for the characterization of low molecular weight atactic poly(NIPAM) obtained with the RAFT systems.[19,20] However, there was no report about the chain-end structure of the isotactic poly(NIPAM) prepared by the RAFT. Figure 5 shows the MALDI−TOF mass spectrum of the same isotactic poly(NIPAM) used for the NMR study. There was a single main series of peaks, whose interval was regular and separated by 113.13, the molar mass of the monomer, NIPAM. The absolute value of each peak is equal to the molecular weight expected for the polymer (depending on the degree of polymerization, *n*) with chain transfer agent fragments at the polymer chain ends (α-chain end with the 1-phenylethyl group and the ω-chain end with phenyldithioacetate) and sodium ion from the salt used with the matrix. The peak at 1993.44 mass (*m*/*z*) (a) corresponds to structure A with *n* = 15. This structure is expected from the proposed well-known mechanism of the RAFT polymerization. A similar series of peaks were also observed for the atactic poly(NIPAM) obtained with other RAFT agents.[19,20] However, there were three minor series of peaks (b, c, and d) besides the main series of the peaks (a) (inset, Figure 5). The same minor series of peaks are also separated by 113.13, the molar mass of the monomer, NIPAM. The absolute values of the b peaks are equal to the molecular weight expected for the polymer with the RAFT agent fragments at chain ends (structure B with *n* = 15). The absolute values of the c peaks are equal to the molecular weight expected for the polymer with phenyldithioacetate at the ω-chain end and an initiator fragment at the α-chain end and sodium ion from the matrix (structure C with *n* = 15).[20] The absolute values of the d peaks are equal to the two possible structures with the molecular weight of the polymer expected with a 1-phenylethyl group at the α-chain end and a sodium ion and the ω-chain end with either a double bond terminated disproportion product (structure D_1 with *n* = 15) or its hydrogenated product (structure D_2 with *n* = 15). These two probable structures may be formed due to the chain transfer to the monomer, the termination by disproportionation, or fragmentation of the chain-end structure in the MALDI−TOF mass spectrometer. A similar chain end structure was detected for the atactic poly(NIPAM) as reported in the literature.[19,20]

Synthesis of Stereoblocks of Atactic-*b*-Isotactic Poly(NIPAM). One-pot synthesis of stereoblocks of atactic-*b*-isotactic poly(NIPAM) was performed using PEPD as the RAFT agent. At first, the atactic block was synthesized in the absence of the Lewis acid in methanol−toluene (1:1) at 60 °C for the desired time to vary the chain length of the atactic block. Then, $Y(OTf)_3$ was added to form the isotactic block of different chain lengths. The reaction was continued at the same temperature for another few hours so that the total reaction

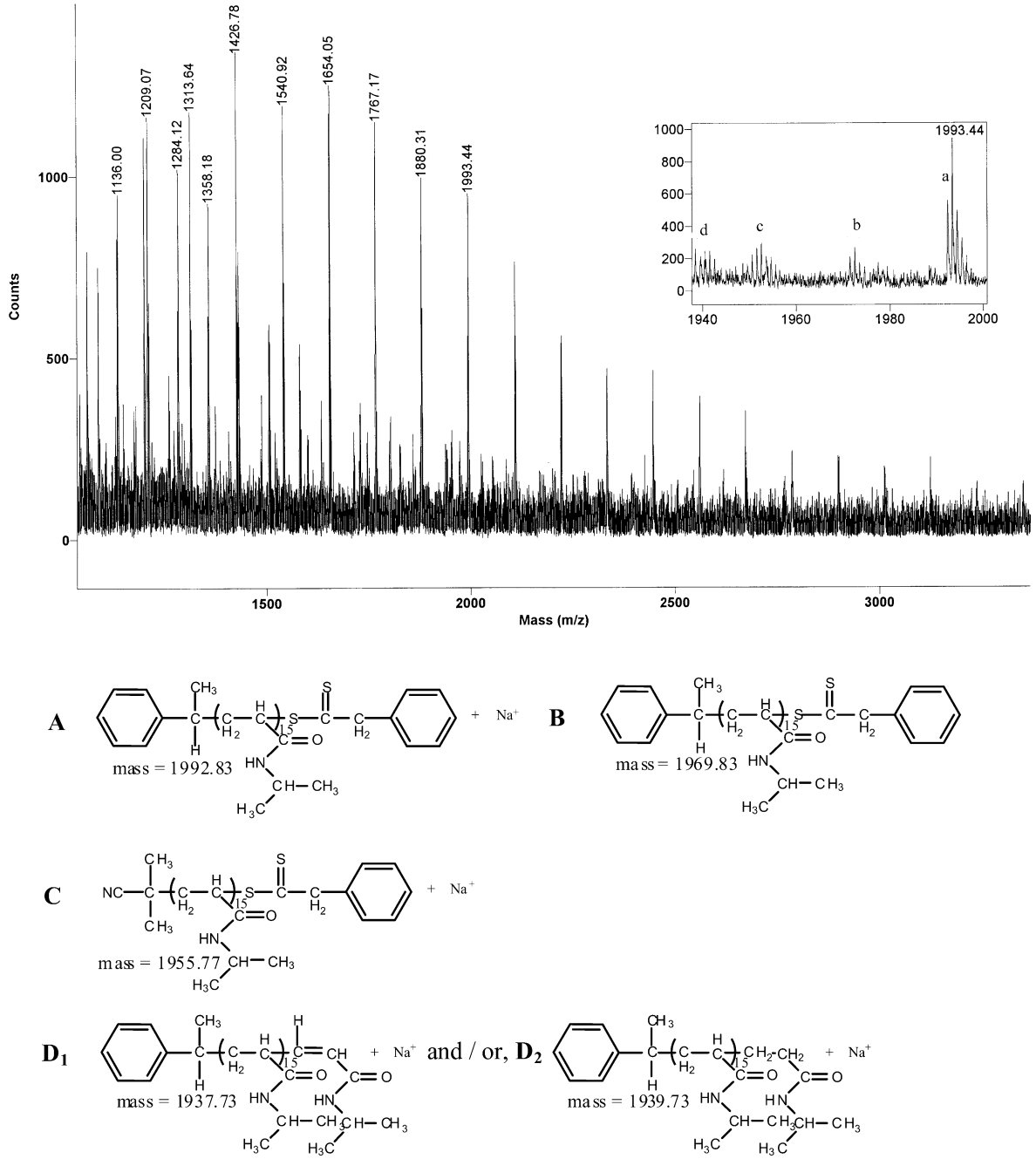


Figure 5. MALDI−TOF mass spectrum of isotactic poly(NIPAM) (M_n = 9000, M_w/M_n = 1.55, obtained at 28% conversion) used for the ^{1}H NMR study in Figure 4. Inset: enlargement of the region from 2000 to about 1935 mass (m/z) for the determination of chain-end structures. Bottom: chain-end structure determination.

period was around 16 h. The results of the synthesis of three stereoblocks with different chain lengths of atactic and isotactic blocks are shown in Table 2.

Atactic blocks with 0.45 × 10^4, 1.04 × 10^4, and 1.32 × 10^4 molecular weights are prepared first after 2.5, 4, and 6 h reactions in the absence of the Lewis acid (Table 2, runs 1a, 2a, and 3a, and Figure 6), respectively. The corresponding conversions are 16%, 40%, and 51%. The observed molecular weights were close to the theoretical values. The polydispersity of these polymers were around 1.25. The tacticities of these polymers are the same (m = 47%) as observed earlier.[21] After the addition of $Y(OTf)_3$ in methanol to each polymerization system, the polymerizations were continued to make the isotactic block for another 14, 12, and 10 h. Final conversions were around 90%. Final stereoblock copolymers had molecular weights 2.21 × 10^4, 2.55 × 10^4, and 2.39 × 10^4, respectively (Table 2, runs 1b, 2b, and 3b, and Figure 6). The observed molecular weights were slightly lower than the theoretical values. The polydispersity of the final stereoblock copolymers was higher than that of the atactic block polymers (Table 2 and Figure 6), and the polydispersity values increased with an increase in time for the synthesis of the isotactic block. This may be due to the higher propagation rate in the presence of the Lewis acid. The isotacticity of the final stereoblock copolymers was decreased with an increase of the time for the polymerization in the absence of the Lewis acid (Figure 7). These stereoblock copolymers should have a different solubility property due to their inherent structures.

Table 3 shows the solubility properties of these three stereoblock copolymers. All these are soluble in acetone, THF, methanol, DMF, DMSO, and 1,4-dioxane solvents,

Table 2. Synthesis of Stereoblocks of Atactic-*b*-Isotactic Poly(NIPAM) Using RAFT Polymerization[a]

run	time (h)	conv[b] (%)	M_n(theor)[d] $\times 10^{-4}$	M_n(expt)[e] $\times 10^{-4}$	M_w/M_n[e]	tacticity[f] (*m*/*r*)	*m*[g] (isotactic block)
1a	2.5	16[c]	0.53	0.45	1.26	47/53	
1b	14	89	2.96	2.21	2.09	78/22	85.9
2a	4	40[c]	1.33	1.04	1.22	47/53	
2b	12	90	2.99	2.55	1.84	70/30	85.8
3a	6	51[c]	1.69	1.32	1.29	47/53	
3b	10	93	3.09	2.39	1.65	63/37	82.7

[a] Initial reaction conditions (for runs 1a, 2a, and 3a): $[NIPAM]_0 = 1$ M, $[PEPD]_0 = 3.4$ mM, [AIBN] = 1.2 mM, methanol = 2 mL, toluene = 2 mL, polymerization temperature = 60 °C. 0.2685 g $Y(OTf)_3$ in 2 mL of methanol was added to each polymerization runs (1a, 2a, and 3a) after their corresponding reaction times and continued for required time mentioned in runs 1b, 2b, and 3b, respectively. [b] Diethyl ether-insoluble part. [c] Determined by ^{1}H NMR of the reaction mixture in DMSO-d_6 at RT. [d] M_n(theor) = ($[NIPAM]_0/[PEPD]_0$) × convn (%) × mol wt of NIPAM. [e] Determined by SEC in dimethylformamide containing 0.1 M LiCl at 40 °C (PS standard). [f] Determined by ^{1}H NMR in DMSO-d_6 at 170 °C. [g] Calculated on the basis of M_n(expt) and meso diad (*m*) values of atactic block and stereoblock polymer.

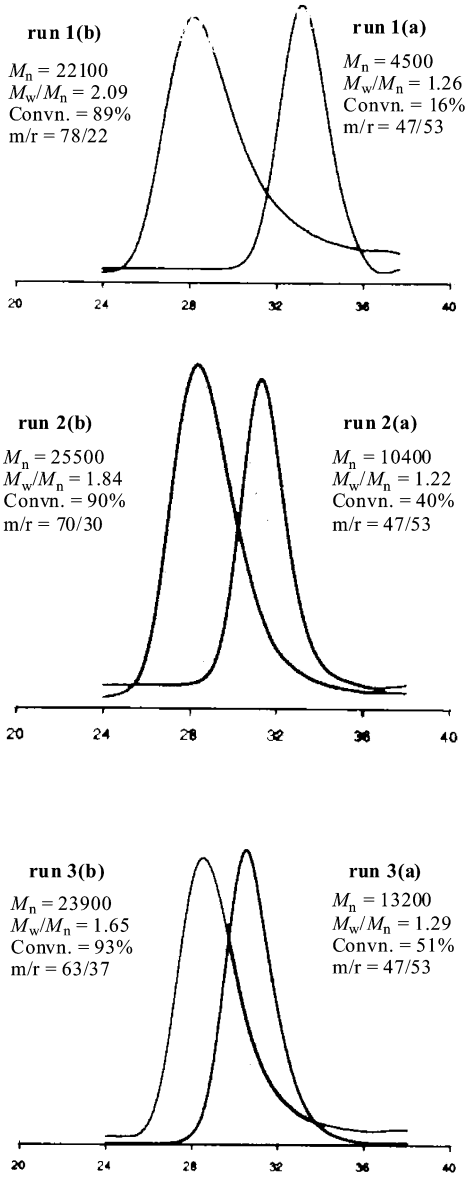


Figure 6. SECs (RI) of prepolymers and final polymers in the synthesis of stereoblock poly(NIPAM)s with different stereoblock lengths (Table 2).

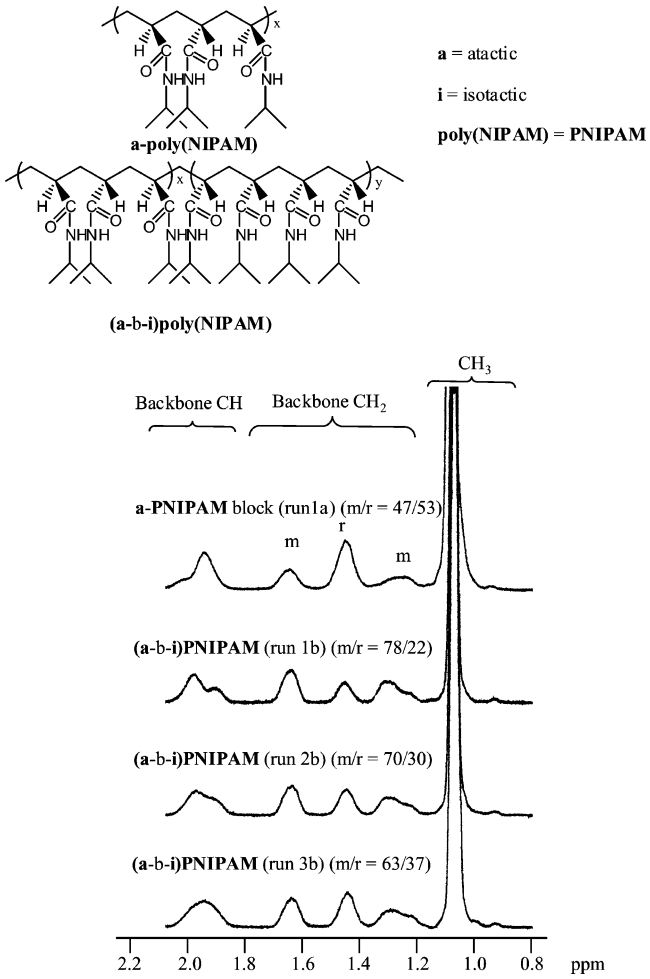


Figure 7. ^{1}H NMR (400 MHz, DMSO-d_6, 170 °C) spectra of atactic poly(NIPAM) block and stereoblock poly(NIPAM) with different block lengths (Table 2).

but these have different solubilities in water. The stereoblock 1b with the longest isotactic block is insoluble in water, while the stereoblock 2b with a 1.5 times longer chain length of isotactic block than that of atactic block is swelled in water and the stereoblock 3b with almost the same chain lengths of atactic and isotactic block forms an emulsion in water. Therefore, it will be possible to synthesize the stereoblock copolymers of NIPAM in one step using the RAFT polymerization. These block copolymers may be employed as an emulsifier in the emulsion polymerization process or as a stabilizer in the dispersion polymerization process.

Synthesis of Diblock Copolymer of NIPAM and Styrene. The synthesis of a diblock copolymer of NIPAM and styrene was also performed successfully using atactic and isotactic poly(NIPAM)s prepared with PEPD as the macro-chain-transfer agent. Table 4 shows the overall results. The molecular weights of the atactic and isotactic poly(NIPAM) prepolymers were 2.24×10^4 ($M_w/M_n = 1.22$) (run 1) and 2.33×10^4 ($M_w/M_n = 1.67$) (run 2), respectively. The polymerization was performed

Table 3. Solubility of Poly(NIPAM)s and Stereoblock Atactic-*b*-Istactic Poly(NIPAM)s with Different Block Lengths[a]

sample ID	water	methanol	acetone	THF	DMF	DMSO	1,4-dioxane
atactic poly(NIPAM) (m = 47%)	+	+	+	+	+	+	+
isotactic poly(NIPAM) (m = 80%)	−	+	+	+	+	+	+
stereblock 1b[b]	−	+	+	+	+	+	+
stereblock 2b[b]	s	+	+	+	+	+	+
stereblock 3b[b]	m	+	+	+	+	+	+

[a] "+" = soluble, "−" = insoluble, "s" = swelled, "m" = emulsion, THF = tetrahydrofuran, DMF = *N*,*N*-dimethylformamide, DMSO = dimethyl sulfoxide. [b] Stereoblock atactic-*b*-isotactic poly(NIPAM)s of runs 1b, 2b, and 3b of Table 2.

Table 4. Synthesis of Poly(NIPAM-*b*-St) Diblock Copolymers Using RAFT Polymerization[a]

run	poly(NIPAM) prepolymer	$M_n \times 10^{-4}$ (M_w/M_n)[b]	styrene convn (%)[c]	M_n(theor)[d] $\times 10^{-4}$	M_n(expt)[b] $\times 10^{-4}$	M_w/M_n[b]	X_{PS}(NMR)[e]
1	atactic (PEPD)	2.24 (1.22)	26.3	4.89	5.73	1.58	0.56
2	isotactic (PEPD)	2.33 (1.67)	16.18	4.03	4.02	1.90	0.34

[a] Poly(NIPAM) = 0.1 g, styrene = 0.5 mL, [AIBN] = 0.2 mg, tetrahydrofuran = 2 mL, polymerization temperature = 60 °C, polymerization time = 48 h. [b] Determined by SEC in DMF containing 0.1 M LiCl at 40 °C (PS standard). [c] Determined by ^{1}H NMR at RT in $CDCl_3$ (run 1) and in DMSO-d_6−$CDCl_3$ (1/1) mixture (run 2). [d] M_n(theor) = mol wt of poly(NIPAM) + ([styrene]$_0$/[poly(NIPAM)]$_0$ × styrene convn (%) × mol wt of styrene. [e] Determined by ^{1}H NMR in DMSO-d_6 at 170 °C.

Table 5. Solubility of Poly(NIPAM) Prepolymers and Diblock Copolymers of NIPAM and Styrene in Different Solvents[a]

sample ID	water	methanol	acetone	THF	DMF	DMSO	1,4-dioxane
a-poly(NIPAM) (m = 47%)	+	+	+	+	+	+	+
i-poly(NIPAM) (m = 80%)	−	+	+	+	+	+	+
poly(a-NIPAM-*b*-St)	−	−	+	+	+	+	+
poly(i-NIPAM-*b*-St)	−	−	+	+	+	+	s

[a] "+" = soluble, "−" = insoluble, "s" = swelled, THF = tetrahydrofuran, DMF = *N*,*N*-dimethylformamide, DMSO = dimethyl sulfoxide.

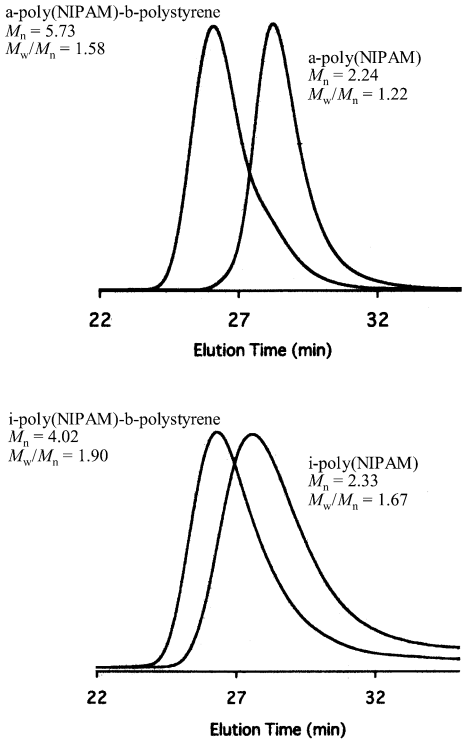


Figure 8. SECs (RI) of prepolymers and final polymers in the synthesis of diblock copolymer of NIPAM and styrene (Table 4).

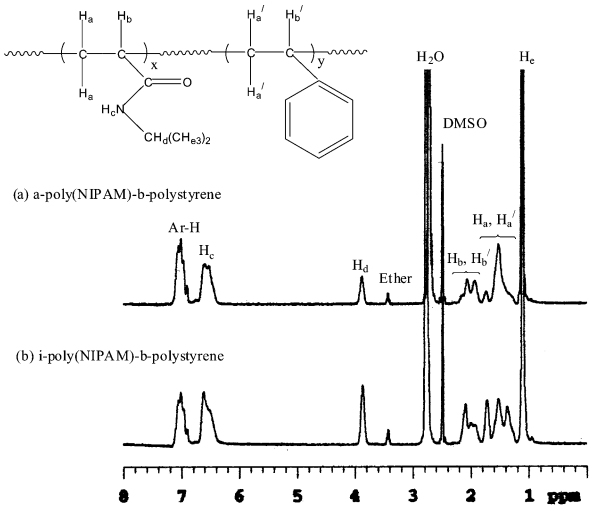


Figure 9. ^{1}H NMR (400 MHz, DMSO-d_6, 170 °C) spectra of diblock copolymers of NIPAM and styrene (Table 4).

in THF at 60 °C for 48 h. The conversion of styrene was 26.3 and 16.2%, respectively. The molecular weights of the diethyl ether insoluble corresponding block copolymers were 5.73 × 10^4 (M_w/M_n = 1.58) and 4.02 × 10^4 (M_w/M_n = 1.90), respectively. SEC (RI) of the prepolymers and the corresponding block copolymers are shown in Figure 8. Molecular weights shifted to higher values in both cases. There is an increase in the polydispersity value for both diblock copoly(NIPAM-*b*-St)s. After purification from acetone (solvent for diblock copolymer but nonsolvent for polystyrene) the observed molecular weight of the a-poly(NIPAM)-*b*-polystyrene was almost the same (5.60 × 10^4 with M_w/M_n = 1.57), indicating almost the absence of polystyrene homopolymers; but, the observed molecular weight of the i-poly(NIPAM)-*b*-polystyrene was slightly higher (4.51 × 10^4 with M_w/M_n = 1.76) than the diethyl ether insoluble one, indicating the removal of some low molecular weight polystyrene homopolymers. These results indicate that some chain termination occurred during polymerization or the polymer contained some homopolymers. The compositions of styrene in the diethyl ether insoluble block copolymers were 0.56 and 0.34 mole fractions (run 1 and run 2, respectively) (Table 4). Styrene composition was measured from the ^{1}H NMR of the diblock copolymer in DMSO-d_6 at 170 °C. Figure 9 shows the ^{1}H NMR spectra of the diblock copolymers

a-poly(NIPAM)-*b*-polystyrene and i-poly(NIPAM)-*b*-polystyrene.

The solubility of the prepolymer and block copolymers (Table 5) should be different due to their different structures. All polymers are soluble in acetone, THF, DMF, and DMSO, but only atactic poly(NIPAM) is soluble in water; others are insoluble. All polymers are soluble in 1,4-dioxane except poly(i-NIPAM-*b*-St), which swelled. Both macro-chain-transfer agents are soluble in methanol, while both diblock copolymers are insoluble. These differences in solubility properties confirm the formation of diblock copolymers. Therefore, it is possible to synthesize the diblock copolymer a-poly(NIPAM)-*b*-polystyrene and i-poly(NIPAM)-*b*-polystyrene using the RAFT process.

Conclusions

Simultaneous control of molecular weight and steric structure was achieved in the radical polymerization of NIPAM using RAFT agents such as PEPD and CPDT in the presence of $Y(OTf)_3$. The polymers had controlled molecular weights ($M_n = 5 \times 10^3 - 3 \times 10^4$, $M_w/M_n = 1.4-1.9$) and high isotactic content ($m = 80-84\%$) while those obtained without the Lewis acid were atactic ($m = 47\%$). The addition of $Y(OTf)_3$ thus changes the stereostructure of poly(NIPAM) without significant loss of molecular weight control in the RAFT polymerization. This can be applied to one-pot synthesis of stereoblock poly(NIPAM) by addition of the Lewis acid during the RAFT polymerization. The isotactic poly(NIPAM) can be employed as a macro-RAFT agent for styrene polymerization resulting in i-poly(NIPAM)-*b*-polystyrene.

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