Macromolecules **2003,** *36,* 4735−4742

Free-Radical Polymerization of (*R*)-(−)-1-(1-Naphthyl)ethyl(2-methacryloyloxyethyl)urea and Chiral Recognition Ability

Yong-Kyung Lee, Yuji Nakashima, Kenjiro Onimura, Hiromori Tsutsumi, and Tsutomu Oishi*

Department of Applied Chemistry and Chemical Engineering, Faculty of Engineering, Yamaguchi University, 2-16-1 Tokiwadai, Ube, Yamaguchi, 755-8611 Japan

Received October 29, 2002; Revised Manuscript Received April 8, 2003

ABSTRACT: (*R*)-(−)-1-(1-Naphthyl)ethyl(2-methacryloyloxyethyl)urea (NEMOU) was synthesized from 2-methacryloyloxyethyl isocyanate (MOI) and (*R*)-(+)-1-(1-naphthyl)ethylamine. Radical homopolymerizations of NEMOU were performed in several solvents to obtain the corresponding chiral polymers that have hydrogen bonds based on urea moieties. Specific optical rotations of poly(NEMOU) changed by the measurement temperature, which may be attributed in part to change of conformation. From the results of radical copolymerizations of NEMOU with styrene (ST, M_2) or methyl methacrylate (MMA, M_2), monomer reactivity ratios (r_1, r_2) and Alfrey−Price $Q-e$ were determined: $r_1 = 0.48$, $r_2 = 0.20$, $Q_1 = 1.41$, $e_1 = 0.74$ for the NEMOU−ST system; $r_1 = 0.55$, $r_2 = 0.16$, $Q_1 = 9.02$, $e_1 = 1.96$ for the NEMOU−MMA system. The chiroptical property of the copolymers was strongly influenced by comonomer units. To examine the chiral recognition ability of poly(NEMOU), chiral stationary phases (CSPs) for high-performance liquid chromatography (HPLC) were prepared from silica gel and poly(NEMOU). The CSPs resolved some racemates such as 1,2,3,4-tetrahydro-1-naphthol and *N*-benzyl-1-(1-methyl-2-methoxycarbonyl)ethylamine in *n*-hexane/2-propanol as mobile phase by HPLC. The chiral recognition ability of poly(NEMOU) may be ascribed not only to the interaction between the low molecular weight chiral selector and the racemates but also to the secondary and/or higher-ordered structure of the polymer.

Introduction

Many kinds of 2-methacryloyloxyethyl isocyanate (MOI) derivatives have been synthesized from several alcohols and amino compounds and polymerized.[1] The authors have reported on the syntheses and polymerizations of some chiral methacrylates from MOI and chiral alcohols or amines, such as cholesterol, L-menthol, amino acid derivatives, 2-hydroxy-2′-methoxy-1,1′-binaphthalene, (*S*)-methylbenzylamine, L-phenylalanine methyl ester, and cinchona alkaloid derivatives, and chiroptical properties of the polymers.[2−6] MOI is a bifunctional monomer with both a reactive isocyanate group and a polymerizable double bond and is convenient and widely used for cross-linking agents and materials for molecular design of new polymers.[7] However, there have been few reports on the synthesis of MOI derivatives bearing an optically active group.[8,9] To our knowledge, no chiroptical properties of MOI derivatives with optically active groups have been reported, except for our previous works. MOI is also useful for preparing macromonomers.[10] We synthesized and polymerized N-substituted maleimide (RMI) macromonomers and examined the polymers thermal stability.[11] Optically active acrylamide macromonomers were also synthesized and polymerized and applied to the chiral stationary phase for high-performance liquid chromatography (HPLC).[12] A wide variety of chiral stationary phases have been developed for the separation of enantiomers by HPLC.[13] Although many kinds of synthetic chiral polymers have been applied to the chiral stationary phases, there have been few reports on preparation of chiral stationary phases for HPLC from poly(methacrylate)s bearing a chiral pendant group.[14] This may be due to the low chiral recognition ability of the chiral pendant group used and/or the absence of stable higher-ordered structures of the polymers.[14] The authors reported previously on preparations of new chiral stationary phases with chiral poly(methacrylate)s having urethane[3,4,6] or urea[5] bonds in the side chain and their chiral recognition abilities by HPLC. The poly(methacrylate)s having urea bonds in the side chain were synthesized from MOI and chiral amines such as (*S*)-methylbenzylamine and L-phenylalanine methyl ester, and the optical resolution abilities of the chiral stationary phases prepared from the polymers were very low in normal phase such as *n*-hexane/2-propanol.[5] Miyano et al.[15] synthesized optically active poly(methacrylate)s bearing a pendant 1,1′-binaphthalene group and investigated the optical resolution ability as a chiral adsorbent for HPLC. Liu et al.[16] reported on optical resolution of racemates by chiral poly(methacrylate) having (+)-5-oxobornyl moieties.

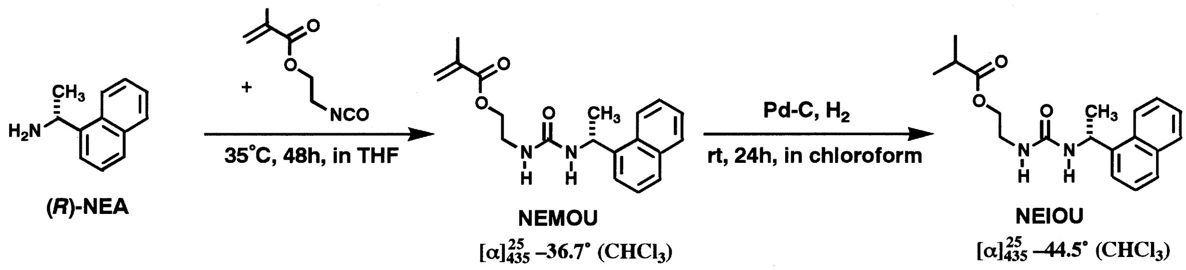
This article describes the synthesis and polymerization of new chiral methacrylate bearing an urea bond, i.e., (*R*)-(−)-1-(1-naphthyl)ethyl(2-methacryloyloxyethyl)urea (NEMOU), from MOI and (*R*)-(+)-1-(1-naphthyl)ethylamine [(*R*)-NEA] (Scheme 1), and chiroptical properties of the polymers obtained are discussed. Three types of chiral stationary phases for HPLC, poly(NEMOU)-*bonded*-silica gel (CSP-I), poly(NEMOU)-*coated*-silica gel (CSP-II), and (*R*)-(+)-1-(1-naphthyl)ethylamine-*bonded*-silica gel (CSP-III), were prepared by synthetic routes shown in Scheme 2, and their optical resolution abilities are also investigated.

---

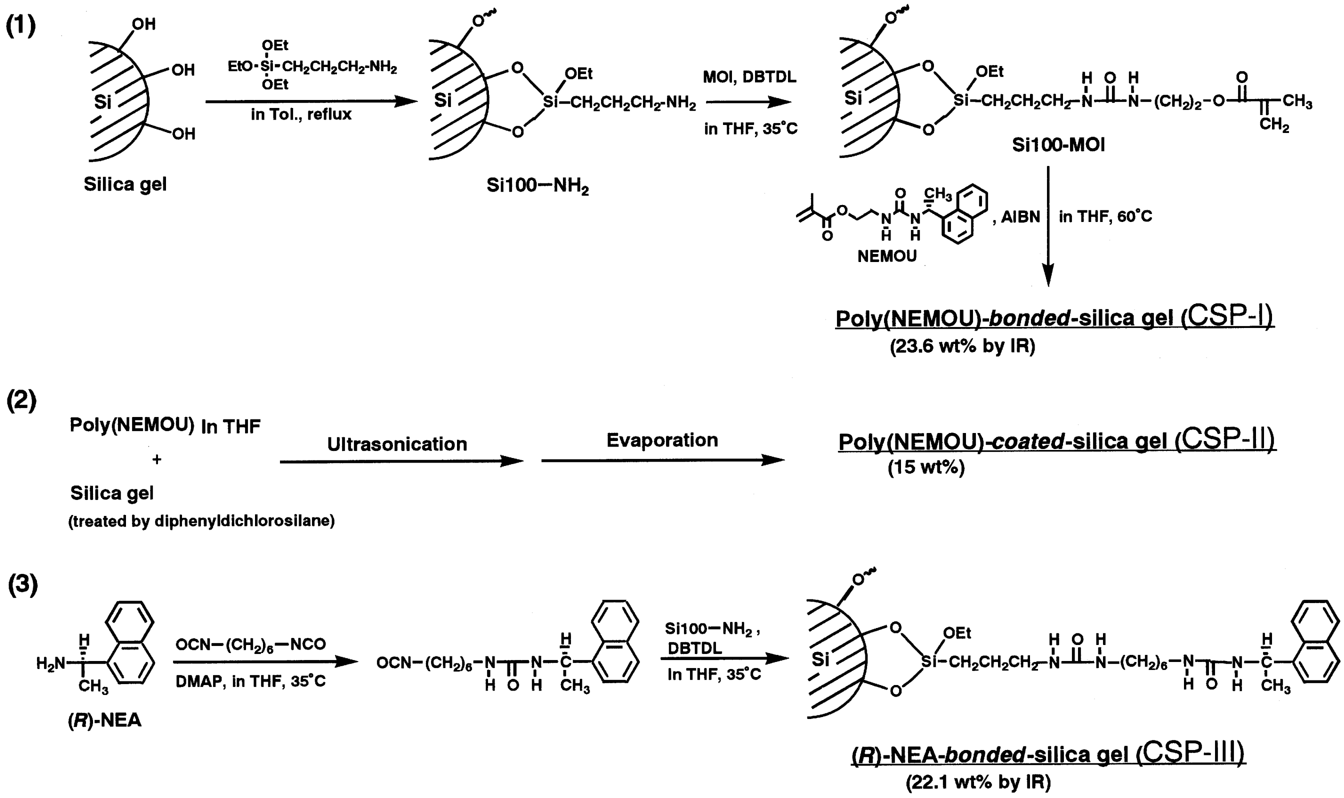
* To whom all correspondence should be addressed: Tel +81-836-85-9281; Fax +81-836-85-9201; e-mail oishi@yamaguchi-u.ac.jp.

10.1021/ma0216371 CCC: $25.00

Scheme 1



Scheme 2



Experimental Section

General Methods. Reagents and solvents were purified as follows: MOI (Showa Denko Co. Ltd.) was purified by distillation under reduced pressure. Styrene (ST) was washed with 5 wt % aqueous sodium thiosulfate solution, distilled water, 5 wt % aqueous sodium hydroxide solution, and distilled water, dried with barium oxide, and then used after distillation under reduced pressure.[17] Methyl methacrylate (MMA) was washed with 5 wt % aqueous sodium sulfite solution, 5 wt % aqueous sodium hydroxide solution, and 20 wt % aqueous sodium chloride solution, dried with anhydrous sodium sulfate, and then used after distillation under reduced pressure.[17] Tetrahydrofuran (THF) and toluene were dried over sodium metal and then used after distillation. *N*,*N*-Dimethylformamide (DMF) and chloroform (CHCl$_3$) were used after distillation. 2,2′-Azobis(isobutyronitrile) (AIBN) was purified by recrystallization from methanol. Other reagents were obtained commercially and used without further purification.

The ^{1}H and ^{13}C NMR spectra were recorded at 25 °C using a JEOL EX-270 (270 MHz). Infrared spectra were recorded using a Shimadzu FT IR-8100A. Elemental analysis was carried out with a Perkin-Elmer 2400II CHN apparatus. Gel permeation chromatography (GPC) measurements for the homopolymers were carried out at a flow rate of 0.8 mL min^{-1} at 50 °C using DMF as an eluent on a Shimadzu SPD-10A equipped with a UV detector, a Shimadzu HSG-60 column (i.d., 7.9 mm; length, 30 cm; particle size of gel, 10 μm; theoretical plate numbers, >10 000), and a Jasco-OR 990 with a polarimetric detector. GPC measurements for the copolymers were carried out at a flow rate of 0.8 mL min^{-1} at 50 °C using chloroform as an eluent on a Shimadzu SPD-10A equipped with a UV detector, a Shodex KF-802.5 column (i.d., 8.0 mm; length, 30 cm; particle size of gel, 6 μm; theoretical plate numbers, >16 000), and a Jasco-OR 990 with a polarimetric detector. Specific optical rotations were measured with a Jasco DIP-140 at 25 °C (5 and 10 cm quartz cell lengths, $c = 1.0$ g dL^{-1} in chloroform). HPLC measurements were carried out at a flow rate of 0.1 mL min^{-1} with the columns (i.d., 2.0 mm; length, 15 cm) packed CSP-I, CSP-II, and CSP-III at 25 °C using *n*-hexane/2-propanol (9.5/0.5, 9/1, 8/2) or methanol/water (7/3, 5/5) as eluent on a Shimadzu LC-10AT equipped with UV detection at 254 nm.

(*R*)-(−)-1-(1-Naphthyl)ethyl(2-methacryloyloxyethyl)urea (NEMOU). A solution of MOI (2.2 g, 1.4 × 10^{-2} mol) in THF (5 mL) was added dropwise to a stirred solution of (*R*)-(+)-1-(1-naphthyl)ethylamine (2.0 g, 1.2 × 10^{-2} mol) in THF (10 mL) under nitrogen at room temperature (rt). The solution was heated at 40 °C and stirred for 90 h under nitrogen. The reaction mixture was evaporated under reduced pressure to give the crude product. Purification by recrystallization from dichloromethane/*n*-hexane gave (*R*)-(−)-1-(1-naphthyl)ethyl(2-methacryloyloxyethyl)urea (NEMOU) as a white powder: yield 93.2%; mp 140−143 °C; [α]$^{25}_{435}$ −36.7° (*c* 1.0, chloroform). ^{1}H NMR (δ, ppm from TMS in CDCl$_3$): 8.02−7.19 (m, 5H, in

Table 1. Radical Homopolymerizations of NEMOU for 24 h at 60 °C[a]

run	polym solvent (mL)	yield[b] (%)	found elemental analysis of polymer			M_n[c] × 10^{-4}	M_w/M_n[c]	$[\alpha]_{435}^{25}$ [d] (deg)
			C	H	N			
1	THF (5)	88.8	71.01	7.08	8.65	0.86	7.54	−34.9
2	$CHCl_3$ (5)	79.8	69.10	6.80	8.11	0.51	6.20	−41.3
3	DMF (5)	76.5	69.68	7.15	8.53	1.14	7.14	−44.6
4	toluene (5)	66.0		ND[e]		0.86	7.54	−23.0

[a] NEMOU = 0.5 g, initiator; AIBN, [AIBN]/[NEMOU] = 0.03. [b] Methanol-insoluble part. [c] By GPC with poly(styrene) standard in DMF. [d] c 1.0, chloroform. [e] ND = not determined.

Table 2. Radical Copolymerizations of NEMOU (M_1) with ST (M_2) and MMA (M_2) in THF (5 mL) at 60 °C[a]

run	M_2	M_1 in monomer (mol %)	polym time (h)	yield[b] (%)	found elemental analysis of copolymer			M_1 in copolymer[c]		M_n[d] × 10^{-4}	M_w/M_n[d]	$[\alpha]_{435}^{25}$ [e] (deg)
					C	H	N	mol %	wt %			
1	ST	19.8	3.0	9.9	75.72	7.27	5.43	35.5	63.3	ND[f]	ND	−4.9
2	ST	40.0	5.0	14.0	72.58	7.19	6.62	51.9	77.1	1.58	2.67	−1.1
3	ST	60.1	5.0	28.0	69.17	7.01	7.03	59.1	81.9	1.28	2.06	−2.1
4	ST	78.8	4.5	44.7	69.23	7.13	7.70	73.6	89.7	1.43	2.59	−10.3
1	MMA	22.0	6.0	20.8	64.63	7.74	5.12	31.2	59.7	0.34	1.31	−19.8
2	MMA	44.4	4.0	18.6	66.11	7.43	7.16	60.7	83.4	0.42	1.36	−11.3
3	MMA	66.8	3.3	23.5	67.28	7.11	7.63	71.1	88.9	0.45	1.36	−16.7
4	MMA	88.9	4.0	20.2	68.08	7.07	8.11	84.0	94.5	0.52	1.31	−24.3

[a] $M_1 + M_2$ = 0.5 g, initiator: 2,2-α-azobis(isobutyronitrile) (6.0 × 10^{-3} mol L^{-1}). [b] Methanol-insoluble part. [c] By elemental analysis. [d] By GPC with poly(styrene) standard in chloroform. [e] c 1.0, chloroform. [f] ND = not determined.

naphthyl group), 5.83 (s, 1H, (trans) $CH_2{=}C$), 5.50−5.45 (m, 1H, C*−H), 5.36 (s, 1H, (cis) $CH_2{=}C$), 5.21−5.10 (d, J = 6.92, 1H, C*−NH), 4.82−4.78 (t, J = 5.61,5.60, 1H, $CH_2{-}NH$), 3.99−3.95 (t, J = 5.28, 5.61, 2H, $O{-}CH_2$), 3.33−3.18 (m, 2H, $N{-}CH_2$), 1.72 (s, 3H, $={C}{-}CH_3$), 1.47−1.45 (d, J = 6.93, 3H, $C^*{-}CH_3$). ^{13}C NMR (δ, ppm from TMS in $CDCl_3$): 167.28 (C=O), 157.41 (N−C=O), 139.16, 133.86, 130.66, 128.75, 127.94, 125.84, 125.68, 125.28, 123.06, 122.17 (in naphthyl group), 135.76 ($CH_2{=}\mathit{C}$), 126.33 ($\mathit{C}H_2{=}C$), 64.01 ($O{-}CH_2$), 46.08 (C*−H), 39.18 ($N{-}CH_2$), 22.16 ($C^*{-}\mathit{C}H_3$), 18.12 ($={C}{-}\mathit{C}H_3$). Anal. Calcd for $C_{19}H_{22}N_2O_3$: C, 69.92; H, 6.79; N, 8.58. Found: C, 70.04; H, 6.91; N, 8.55.

(*R*)-(−)-1-(1-Naphthyl)ethyl(isopropyloyloxyethyl)urea (NEIOU). Palladium-activated carbon (Pd/C, 0.02 g,) was added to a solution of NEMOU (0.125 g, 3.8 × 10^{-4} mol) in dry chloroform (20 mL). The reaction mixture was stirred for 24 h under hydrogen at rt and filtered. After evaporation of the solvent under reduced pressure, the residue was purified by recrystallization from dichloromethane/*n*-hexane and gave (*R*)-(−)-1-(1-naphthyl)ethyl(isopropyloyloxyethyl)urea (NEIOU) as white powder: yield 95.1%; $[\alpha]_{435}^{25}$ −44.5° (c 1.0, chloroform). ^1H NMR (δ, ppm from TMS in $CDCl_3$): 8.13−7.25 (m, 7H, in naphthyl group), 5.57 (m, 1H, C*−H), 4.88−4.86 (d, J = 6.27, 1H, C*−NH), 4.55 (bs, 1H, $CH_2{-}NH$), 4.05−4.02 (m, 2H, $O{-}CH_2$), 3.40−3.35 (m, 2H, $N{-}CH_2$), 2.37−2.27 (m, 1H, C−H), 1.62 (d, J = 6.92, 3H, $C^*{-}CH_3$), 1.03−1.00 (d, 6H, J = 6.92, $C{-}(CH_3)_2$). Anal. Calcd for $C_{19}H_{24}N_2O_3$: C, 69.49; H, 7.37; N, 8.53. Found: C 69.16; H, 7.40; N, 8.22.

General Procedure for Radical Homopolymerization. NEMOU (0.500 g, 1.53 × 10^{-3} mol), AIBN (0.0075 g, 4.6 × 10^{-5} mol), and THF (5 mL) were added in a sealed glass tube (run 1 in Table 1). After the mixture was degassed three times by freeze−thaw cycles, the tube was sealed under a nitrogen atmosphere and then was kept for 24 h in a water bath at 60 °C to conduct the polymerization. After the tube was cooled in ice water to stop the polymerization, the polymer solution was poured into a large amount of methanol to precipitate the polymer and then purified by reprecipitating it twice from the DMF solution to excess methanol. The polymer was dried in vacuo for 3 days: yield 88.8%; M_n = 8600, M_w/M_n = 7.54; $[\alpha]_{435}^{25}$ −34.9° (c 1.0, chloroform). Found: C, 71.01; H, 7.08; N, 8.65.

General Procedure for Copolymerization. NEMOU (0.412 g, 1.26 × 10^{-3} mol), ST (0.088 g, 8.5 × 10^{-4} mol), AIBN (0.0049 g, 3.0 × 10^{-5} mol), and THF (5 mL) were added in a sealed glass tube (run 3 in Table 2). After the mixture was degassed three times by freeze−thaw cycles, the tube was sealed under a nitrogen atmosphere and then was kept for 5 h in a water bath at 60 °C to conduct the polymerization. After the tube was cooled in ice water to stop the polymerization, the polymer solution was poured into a large amount of methanol to precipitate the copolymer and then purified by reprecipitating it twice from the DMF solution to excess methanol. The copolymer was dried in vacuo for 3 days: yield 28.0%; NEMOU feed in copolymer 59.1 mol % by elemental analysis; M_n = 12 800, M_w/M_n = 2.06; $[\alpha]_{435}^{25}$ −2.1° (c 1.0, chloroform). Found: C, 69.17; H, 7.01; N, 7.03.

Preparation of Chiral Stationary Phases for HPLC and Column Packing. *CSP-I.* Macroporous silica gel (TOSOH, TSK-GEL SI 100: mean particle size 5 μm; pore size 100 Å) was silanized with 3-aminopropyltriethoxysilane according to a literature method.[18] MOI (16 mL) was added to a slurry of the silanized silica gel (8.0 g) under nitrogen. The mixture was heated at 35 °C, stirred for 45 h under nitrogen, and then cooled to rt. The reaction mixture was filtered, washed with dichloromethane, acetone, and methanol, and then dried in vacuo to obtain silica gel containing vinyl groups on the surface (Si100-MOI: C, 13.02%; H, 2.24%; N, 3.05%).

Si100-MOI (1.0 g) and NEMOU (0.50 g) were weighed in a Shlenk tube. A solution of AIBN (3.0 mol % against monomer) in THF (10 mL) was added to the mixture under nitrogen. The slurry was shaken at 60 °C for 24 h and cooled to rt. The reaction mixture was filtered, washed with DMF, THF, acetone, and methanol, and then dried in vacuo to afford poly(NEMOU)-*bonded*-silica gel (CSP-I). The content (wt %) of polymer segment on CSP-I was 23.6 wt %, which was estimated from IR spectra by ordinary methods.[3−6]

CSP-II. Macroporous silica gel (TOSOH, TSK-GEL SI 100: mean particle size, 5 μm; pore size, 100 Å) was silanized with dichlorodiphenylsilane according to a literature method.[19] Poly(NEMOU) (0.15 g, 15 wt %) was dissolved in 10 mL of THF. Then, the silanized silica gel (0.85 g) was immersed in the polymer solution. After irradiation of the mixture with ultrasound for 20 min, the solution was evaporated under reduced pressure to afford poly(NEMOC)-*coated*-silica gel (CSP-II).

CSP-III. Hexamethylene diisocyanate (HDI, 0.20 mL, 1.2 × 10^{-3} mol) was added to a mixture solution of (*R*)-(+)-1-(1-naphthyl)ethylamine (0.20 g, 1.2 × 10^{-3} mol) and DMAP (0.010 g, 8.2 × 10^{-5} mol) in THF (10 mL) under nitrogen. The mixture was heated at 35 °C and stirred for 20 h under nitrogen. And Si100−NH_2 (1.0 g) and di-*n*-butyltin dilaurate (DBTDL, 0.010

g, 1.6 × 10^{-5} mol) were added to the reaction mixture. The mixture was further stirred for 48 h at 35 °C under nitrogen and then cooled to rt. The reaction mixture was filtered, washed with DMF, THF, acetone, and methanol, and then dried in vacuo to obtain (*R*)-(+)-1-(1-naphthyl)ethylamine-*bonded*-silica gel (CSP-III). The content (wt %) of (*R*)-(+)-1-(1-naphthyl)ethylamine segment on CSP-III was 22.1 wt % by IR spectra.

The chiral stationary phases were packed in a stainless steel HPLC column (i.d., 2.0 mm; length, 15 cm) by a slurry method. Theoretical plate numbers of the columns packed CSP-I, CSP-II, and CSP-III were 740, 1040, and 1540, respectively, which were measured using toluene in methanol or *n*-hexane/2-propanol (9/1) as eluent at a flow rate of 0.1 or 0.5 mL min^{-1} at 25 °C.

Results and Discussion

Radical Polymerizations of NEMOU and Chiroptical Property of Poly(NEMOU). Radical homopolymerizations of NEMOU were performed with AIBN as an initiator at 60 °C in various solvents, as summarized in Table 1. The polymerizations proceeded homogeneously expect for run 4, and all obtained polymers were white powders. Number-average molecular weights (M_n) and specific optical rotations ($[\alpha]_{435}^{25}$) of poly(NEMOU) were 5100 to 11 400 and −23.0° to −44.6°, respectively. Especially, the specific optical rotations of poly(NEMOU) were strongly influenced by polymerization solvents. It is difficult to explain clearly the reason at present, but it may result from difference in dielectric constant of solvents. As the dielectric constant, i.e., polarity, of solvents increased, the absolute values of specific optical rotations for poly(NEMOU) increased and approached the specific optical rotation of the polymer model of NEIOU (−44.5°). That is, the polarity of the solvents may influence the conformations of polymers through the polymerization reaction. Figure 1 shows the ^{1}H NMR spectra of NEMOU and poly(NEMOC). The peaks at 5.83 and 5.36 ppm assigned to vinyl groups ($CH_2{=}C(CH_3){-}$) disappeared after polymerization, indicating that the radical polymerization went to completion.

The expanded IR spectra of NEMOU (A) and poly(NEMOU) (B) determined in chloroform are shown in Figure 2. NEMOU exhibited absorption due to stretching vibration of N−H at 3530 cm^{-1} to 3330 cm^{-1} having a peak minimum at 3440 cm^{-1}. Poly(NEMOU) showed a broad peak at 3470 cm^{-1} to 3220 cm^{-1} having a peak minimum at 3340 cm^{-1}. The displacement of this peak indicates that poly(NEMOU) may have hydrogen bonds caused by urea segments.

Figure 3 shows relationships between measurement temperatures and specific optical rotations of poly(NEMOU) and NEIOU in chloroform. For NEIOU the absolute values of specific optical rotations increased linearly with increasing temperature ($|\Delta[\alpha]/\Delta T| = 0.207$), and the changes were reversible. For poly(NEMOU) the absolute values of specific optical rotations decreased linearly with increasing temperature ($|\Delta[\alpha]/\Delta T| = 0.182$), and the changes were reversible. These results indicate that change of specific optical rotation for poly(NEMOU) may be attributed to change of conformation caused by hydrogen bonds based on urea segments and/or interaction between naphthyl groups. Previously, we reported[2] that the temperature dependence of specific optical rotation of poly(ChMOC) might be in part due to conformation changed by both strong hydrogen bonds based on the urethane groups and interaction between cholesteryl groups.

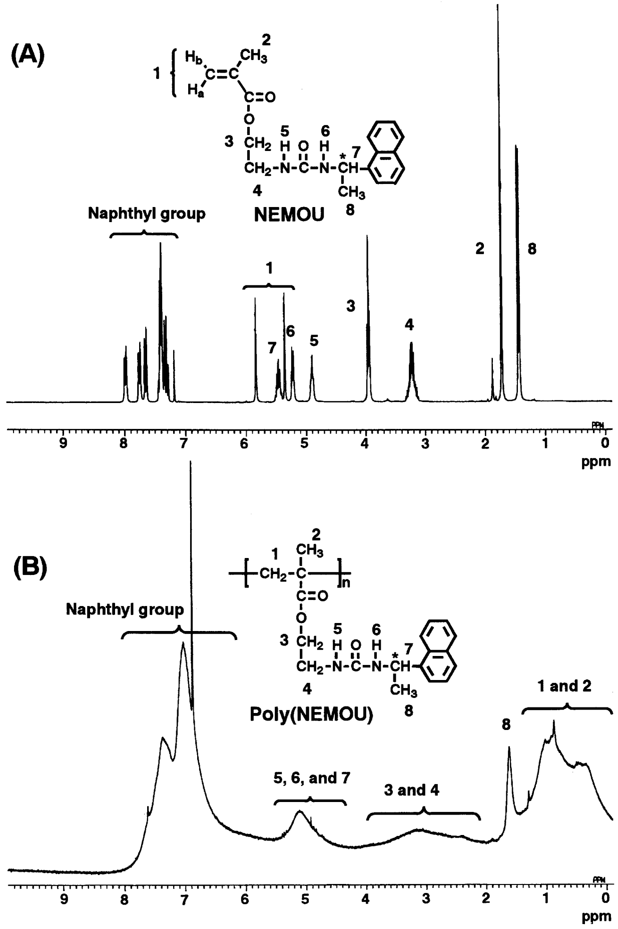


Figure 1. ^{1}H NMR spectra of (A) NEMOU and (B) poly(NEMOU) in $CDCl_3$ at 23.5 °C (270 MHz).

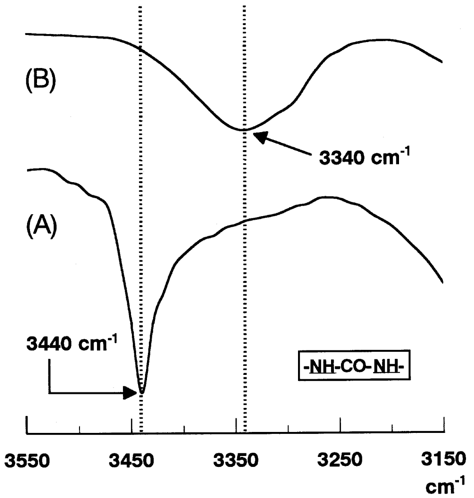


Figure 2. Expanded IR spectra of (A) NEMOU and (B) poly(NEMOU) in $CHCl_3$.

Figure 4 shows ^{1}H NMR spectra of poly(NEMOU) at various temperatures. The shift of broad peaks due to N−H was not observed when the temperature was raised. However, the peaks due to methyl groups neighboring to chiral carbon shifted to high magnetic field with increasing temperature. Furthermore, the peak due to naphthyl groups of poly(NEMOU) partially split into two bands with increasing temperature. These results suggest that the extent of interaction between naphthyl groups may change by temperature. Namely,

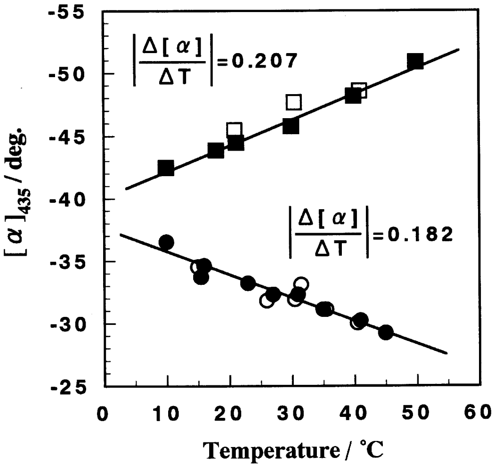


Figure 3. Dependence of specific optical rotation of (●, ○) poly(NEMOU) and (■, □) NEIOU on the measurement temperature in $CHCl_3$: $c = 1.0$ g dL^{-1}, $l = 10$ cm: (●, ■) increasing and (○, □) decreasing temperature.

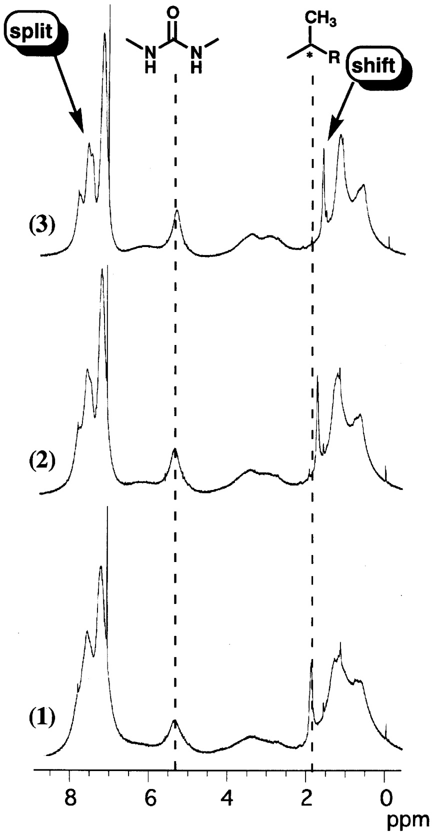


Figure 4. ^{1}H NMR spectra of poly(NEMOU) in $CDCl_3$ at (1) 20, (2) 40, and (3) 50 °C.

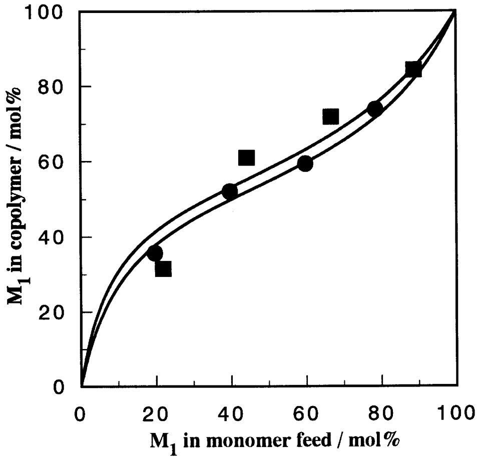


Figure 5. Copolymer composition curves of poly(NEMOU-*co*-M_2); M_2 = (●) ST and (■) MMA.

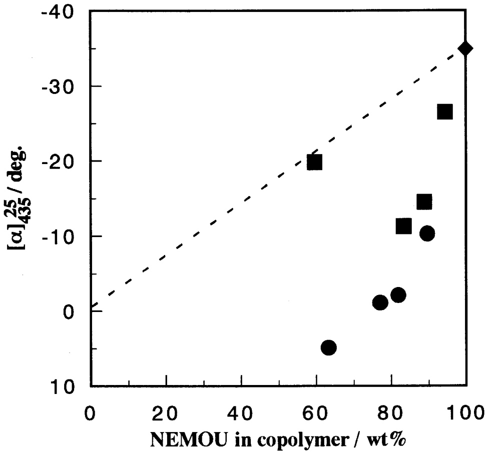


Figure 6. Relationships between specific optical rotations ($[\alpha]^{25}_{435}$) and the content (wt %) of the monomeric unit of NEMOU in poly(NEMOU-*co*-M_2); M_2 = (●) ST and (■) MMA; (◆) poly(NEMOU).

the dependence of specific optical rotation on temperature for poly(NEMOU), as shown in Figure 3, may be attributed to change of conformation caused by the interaction between naphthyl groups rather than hydrogen bonds based on urea segments.

Copolymerizations of NEMOU with ST or MMA and Chiroptical Property of the Copolymers. The results of radical copolymerizations of NEMOU (M_1) with ST (M_2) or MMA (M_2) using AIBN in THF at 60 °C are summarized in Table 2. The copolymerizations proceeded heterogeneously except for run 1. That is, the copolymer precipitated during the polymerization. The obtained copolymers were colorless powders and insoluble in organic solvents such as THF, acetone, benzene, and ethyl acetate but soluble in chloroform and DMF.

Copolymer composition curves for the polymerizations of NEMOU with ST or MMA are shown in Figure 5. Monomer reactivity ratios (r_1, r_2) calculated from the high-conversion method reported by Tüdös et al.[20] and Alfrey–Price Q–e values[21] for NEMOU were determined as follows: $r_1 = 0.48$, $r_2 = 0.20$, $Q_1 = 1.41$, $e_1 = 0.74$ in the NEMOU–ST system; $r_1 = 0.55$, $r_2 = 0.16$, $Q_1 = 9.02$, $e_1 = 1.96$ in the NEMOU–MMA system. Q_1 and e_1 values in the NEMOU–ST system were apparently different from those in the NEMOU–MMA system. The reason may result from no consideration of steric effect in the Alfrey–Price Q and e theory. It seems that NEMOU has relatively high steric hindrance because of a large substituent group such as a 1-(1-naphthyl)ethyl group.

Figure 6 shows relationships between specific optical rotations and the content (wt %) of monomeric unit of NEMOU in poly(NEMOU-*co*-M_2)s. A broken line connecting 0° with $[\alpha]^{25}_{435}$ of poly(NEMOU) refers to relationships between the specific optical rotation and the contents (wt %) of monomeric unit in a mixture of poly(NEMOU) and poly(ST) [or poly(MMA)]. In Figure 6, the specific optical rotations of copolymers showed a

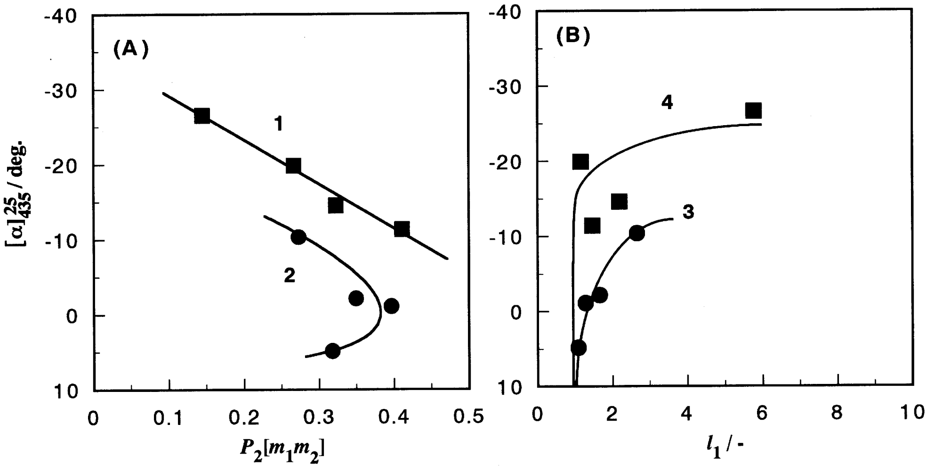
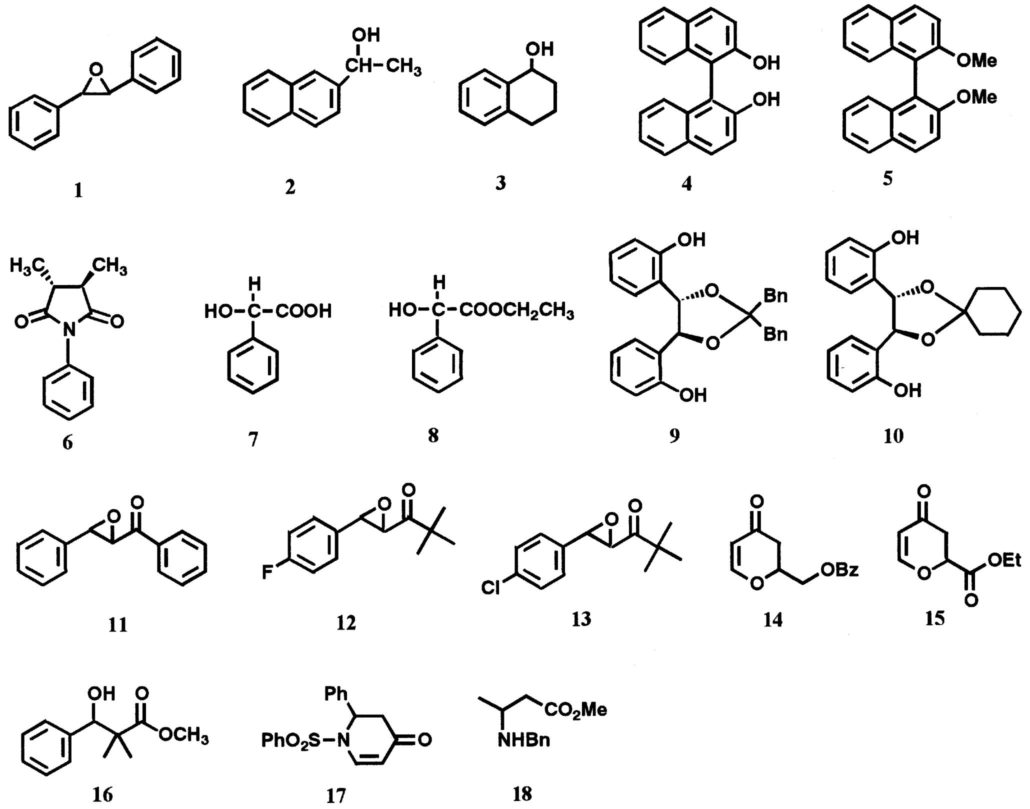


Figure 7. Relationships between specific optical rotations ($[\alpha]^{25}_{435}$) and (A) diad sequence ($P_2[m_1m_2]$) and (B) average sequence length (l_1) in poly(NEMOU-*co*-M_2); M_2 = (●) ST and (■) MMA.

Scheme 3



large deviation from the line, suggesting that chiroptical property of the copolymers depends strongly on comonomer units (ST or MMA monomeric unit).

Figure 7 shows the dependence of specific optical rotations of poly(NEMOU-*co*-M_2)s on a diad sequence ($P_2[m_1m_2]$)[22,23] and average sequence length of NEMOU units (l_1).[24] $P_2[m_1m_2]$ indicates probability of a M_1-M_2 diad sequence. $P_2[m_1m_2]$ was derived as follows:

$$P_1[m_1] + P_1[m_2] = 1$$

$$P_2[m_1m_2] = P_1[m_1]P(m_1m_2)$$

$$P(m_1m_2) = 1/(1 + r_1X)$$

where $P_1[m_1]$ and $P_1[m_2]$ are molar fractions of the copolymer, $P(m_1m_2)$ is given by the monomer molar ratio in the feed ($X = M_1/M_2$), and r_1 is the monomer reactivity ratio of NEMOU. In NEMOU−MMA, absolute values of specific optical rotations decreased with increasing the diad sequence, and the relationships showed good linearity (line 1), indicating that chiroptical properties of the polymers were strongly influenced by the NEMOU−MMA sequence. On the other hand, such a relationship was not observed for the NEMOU−ST system (line 2), suggesting that chiroptical properties of the copolymers were influenced by both the NEMOU−ST diad sequence and the average sequence length of NEMOU units in poly(NEMOU-*co*-ST)s, as shown in Figure 7B, line 3.

Chiral Recognition Ability of Poly(NEMOU). To investigate the chiral recognition ability of poly(NEMOU), two types of chiral stationary phases, poly(NEMOU)-

Table 3. Chromatographic Resolution of Racemates 1−18 on the CSP-I, CSP-II, and CSP-III[a]

	CSP-I				CSP-II				CSP-III			
racemate	k_1[b]	k_2[b]	α[c]	R_S[d]	k_1	k_2	a	R_S	k_1	k_2	α	R_S
1	0.37	0.37	1.0		0.13	0.13	1.0		0.21	0.21	1.0	
2	2.55[e]	2.55	1.0		ND				0.86	0.86	1.0	
3	0.88	0.88	1.0		0.50	0.73	1.46	0.60	0.36	0.36	1.0	
4	3.31[f]	3.31	1.0		0.78	0.78	1.0		3.30	3.85	1.17	0.39
5	1.43[e]	1.43	1.0		0.12	0.12	1.0		ND			
6	ND[g]				0.69	0.69	1.0		0.59	0.59	1.0	
7	0.58	0.58	1.0		1.32	1.32	1.0		0.71	0.71	1.0	
8	0.59[e]	0.59	1.0		0.28[e]	0.28	1.0		0.37	0.37	1.0	
9	0.91	0.91	1.0		0.45	0.45	1.0		0.47	0.47	1.0	
10	1.07[f]	1.07	1.0		0.16	0.16	1.0		2.36	2.36	1.0	
11	1.05	1.05	1.0		0.80	0.80	1.0		0.75	0.75	1.0	
12	0.56	0.56	1.0		0.18	0.18	1.0		0.32	0.32	1.0	
13	1.54[e]	1.54	1.0		0.22	0.22	1.0		0.84	0.84	1.0	
14	2.26	2.26	1.0		1.82	1.82	1.0		0.71	0.71	1.0	
15	3.11	3.11	1.0		1.95	1.95	1.0		0.73	0.83	1.14	0.15
16	0.75	0.75	1.0		0.70	0.70	1.0		0.47	0.47	1.0	
17	0.57	0.57	1.0		1.97	1.97	1.0		1.17	1.17	1.0	
18	0.35	0.35	1.0		0.54	0.54	1.84	1.17	0.20	0.26	1.28	0.22

[a] CSP-I; poly(NEMOU)-*bonded*-silica gel, CSP-II; poly(NEMOU)-*coated*-silica gel, CSP-III; (*R*)-NEA-*bonded*- silica gel, mobile phase; *n*-hexane/2-propanol = 9/1, flow = 0.1 mL min^{-1}. [b] Capacity factor of enantiomer eluting first (k_1) and second (k_2) = (retention time of enantiomer − void time of column)/(retention time of 1,3,5-*tert*-butylbenzene). [c] Separation factor: $\alpha = k_2/k_1$. [d] Resolution factor = 2 × (distance between the peaks of more and less retained enantiomers)/(sum of bandwidth of two peaks). [e] Mobile phase; *n*-hexane/2-propanol = 9.5/0.5. [f] Mobile phase; *n*-hexane/2-propanol = 8/2. [g] ND = not determined.

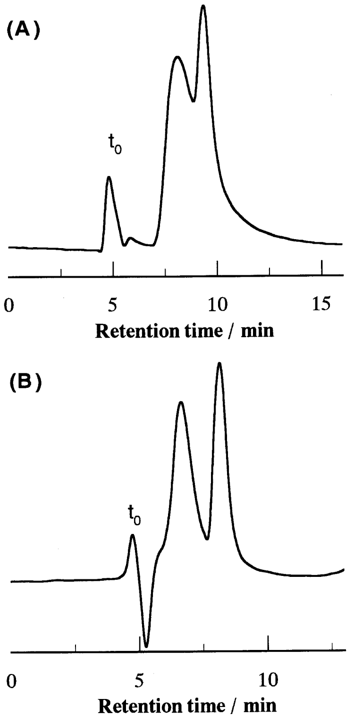


Figure 8. HPLC chromatograms of racemate (A) **3** and (B) **18** with poly(NEMOU)-*coated*-silica gel (CSP-II) in *n*-hexane/2-propanol (9.0/1.0$_{\text{volume}}$) mobile phase; racemate **3**: 1,2,3,4-tetrahydro-1-naphthol; racemate **18**: *N*-benzyl-1-(1-methyl-2-methoxycarbonyl)ethylamine; column size: 150 mm × 2 mm; flow = 0.1 mL min^{-1}.

bonded-silica gel (CSP-I) and poly(NEMOU)-*coated*-silica gel (CSP-II), were prepared according to synthetic routes (1) and (2) of Scheme 2. Poly(NEMOU) has urea bonds and naphthyl moieties which can serve as π-electron donors. Hence, hydrogen bonds and $\pi-\pi$ interactions are expected between the chiral stationary phases and racemates having a carbonyl, a hydroxyl, and an aromatic group. The abilities of the chiral stationary phases for chiral recognition of racemates **1**−**18** (Scheme 3) were examined with HPLC. The CSP-I and CSP-II resolved some racemates in normal phase such as *n*-hexane/2-propanol but did not resolve any of the racemates in reversed phase such as methanol/water. The results of chromatographic resolution in *n*-hexane/2-propanol are summarized in Table 3. Namely, CSP-I did not resolve any of the racemates listed in Scheme 3, but CSP-II resolved racemates **3** and **18** using 10% 2-propanol in *n*-hexane as eluent. The chromatogram of the resolution of racemate **3** and **18** on CSP-II is shown in Figure 8. We reported previously that the chiral stationary phase prepared from poly(methacrylate) having urea bonds and the (*S*)-methylbenzyl group in the side chain could not resolve any of the racemates using *n*-hexane/2-propanol as eluent.[5] To examine the difference of chiral recognition ability between the polymeric chiral selector and the corresponding low molecular weight chiral selector, (*R*)-(+)-1-(1-naphthyl)-ethylamine-*bonded*-silica gel (CSP-III) was prepared by the synthetic route (3) of Scheme 2. CSP-III could resolve racemates **4**, **15**, and **19** using 10% 2-propanol in *n*-hexane as eluent. From the results of difference of optical resolution abilities between CSP-II and CSP-III, the chiral recognition ability of poly(NEMOU) on the CSP-II may be ascribed not only to the interaction between the low molecular weight chiral selector and the racemates but also to the secondary and/or higher-ordered structures of the polymer.

Conclusion

A new monomer, (*R*)-(−)-1-(1-naphthyl)ethyl(2-methacryloyloxyethyl)urea (NEMOU), was synthesized from MOI and (*R*)-(+)-1-(1-naphthyl)ethylamine. Radical homopolymerizations of NEMOU were carried out in various solvents to obtain the corresponding chiral polymers with hydrogen bonds caused by urea segments. From the results of the copolymerizations of NEMOU with ST or MMA, monomer reactivity ratios, *Q*, and *e* values were determined. Chiroptical properties of the copolymers were significantly influenced by comonomer units. Chiral stationary phases prepared from silica gel and poly(NEMOU) resolved racemates **3** and **18** in normal phase such as *n*-hexane/2-propanol by HPLC. The chiral recognition ability may be attributed to the interaction between (*R*)-1-(1-naphthyl)ethyl units and racemates and/or higher-ordered structures of the polymer.

Acknowledgment. This work was carried out under the Research Program for Special Promotion of the Venture Business Laboratory, Yamaguchi University. The authors are thankful to Showa Denko Co. Ltd. for supplying the MOI.

References and Notes

(1) (a) Kamogawa, H.; Kohno, H.; Kitagawa, R. *J. Polym. Sci., Part A: Polym. Chem.* **1989**, *27*, 487. (b) Decker, C.; Moussa, K. *Eur. Polym. J.* **1991**, *27*, 881. (c) Francis, I.; Arjen, S.; Israel, C.; Johannes, S. *J. Polym. Sci., Part A: Polym. Chem.* **1993**, *31*, 239.
(2) Lee, Y. K.; Onimura, K.; Tsutsumi, H.; Oishi, T. *J. Polym. Sci., Part A: Polym. Chem.* **2000**, *38*, 4315.
(3) Lee, Y. K.; Onimura, K.; Tsutsumi, H.; Oishi, T. *Polym. J.* **2000**, *32*, 1007.
(4) Lee, Y. K.; Onimura, K.; Tsutsumi, H.; Oishi, T. *Polym. J.* **2001**, *33*, 411.
(5) Lee, Y. K.; Hisamitsu, N.; Onimura, K.; Tsutsumi, H.; Oishi, T. *Polym. J.* **2002**,*34*, 9.
(6) Lee, Y. K.; Yamashita, K.; Eto, M.; Onimura, K.; Tsutsumi, H.; Oishi, T. *Polymer* **2002**, *43*, 7539.
(7) Matsuhiro, S. *Konbatekku* **1997**, *5*, 8.
(8) Bamford, C. H.; Al-Lamee, K. G.; Middleton, I. P.; Paprotny, J.; Carr, R. *Bull. Soc. Chim. Belg.* **1990**, *99*, 919.
(9) Kimitsuka, Y.; Iwata, K.; Suzuki, H. *Jpn. Kokai Tokkyo Koho* JP 6-308108 (Nov 4, 1994).
(10) (a) Albrecht, H.; Wunderlich, W. *Angew. Makromol. Chem.* **1986**, *145/146*, 89. (b) Savaskan, S.; Hazer, B. *Angew. Makromol. Chem.* **1996**, *239*, 13. (c) Monzner, N.; Fischer, U. K.; Volkel, T.; Rheinberger, V. *Angew. Makromol. Chem.* **1997**, *245*, 155.
(11) Oishi, T.; Lee, Y. K.; Nakagawa, A.; Onimura, K.; Tsutsumi, H. *Polym. J.* **2001**, *33*, 81.
(12) Oishi, T.; Lee, Y. K.; Nakagawa, A.; Onimura, K.; Tsutsumi, H. *J. Polym. Sci., Part A: Polym. Chem.* **2002**, *40*, 1726.
(13) (a) Allenmark, S. G. *Chromatographic Enantioseparation*: Ellis Howood Ltd: Chichester, 1988. (b) Oi, N. *Chiral Chromatography Nyumon*; Maruzen Ltd: Kyoto, Japan, 1996; pp 27−48.
(14) For example: Okamoto, Y. *CHEMTECH* **1987**, 176.
(15) Tamai, Y.; Qian, P.; Matsunaga, K.; Miyano, S. *Bull. Chem. Soc. Jpn.* **1992**, *65*, 817.
(16) Liu, J. H.; Tsai, F. J. *J. Appl. Polym. Sci.* **1999**, *72*, 677.
(17) Otsu, T.; Kinoshita, M. *Koubunshigousei no Jikkenhou;* Kagakudoujin: Kyoto, Japan, 1972; pp 69−91.
(18) Okamoto, Y.; Yashima, E.; Ishihara, M.; Hatada, K. *Bull. Chem. Soc. Jpn.* **1988**, *61*, 255.
(19) Okamoto, Y.; Honda, S.; Okamoto, I.; Yuki, H. *J. Am. Chem. Soc.*, **1981**, *103*, 6971.
(20) Tüdös, F.; Kelen, T.; Foldes-Berezsnich, T.; Turcsanyi, B. *J. Macromol. Sci. Chem.* **1976**, *A10*, 1513. The monomer reactivity rations were determined by method 6 described in this paper.
(21) Alfrey, T., Jr.; Price, C. C. *J. Polym. Sci.* **1947**, *2*, 101.
(22) Harwood, H. J.; Ritchey, W. M. *J. Polym. Sci., Polym. Lett. Ed.* **1964**, *2*, 601.
(23) Kurokawa, M.; Yamaguchi, H.; Minoura, Y. *J. Polym. Sci., Polym. Ed.* **1979**, *17*, 2241.
(24) Majumdar, R. N.; Carlini, C.; Bertucci, C. *Makromol. Chem.* **1982**, *183*, 2047.

MA0216371