Synthesis and Properties of Serine- and Threonine-Based Helical Polyacetylenes

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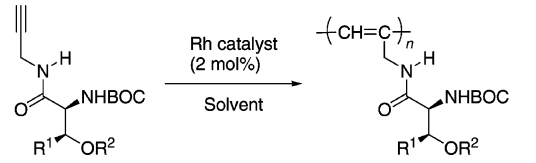
ABSTRACT: Serine- and threonine-based acetylene monomers carrying hydroxyl group, *N*-*tert*-butoxycarbonyl-L-serine *N*′-propargylamide (**1**), *N*-*tert*-butoxycarbonyl-L-threoine *N*′-propargylamide (**2**), and their *O*-silylated monomers, *N*-*tert*-butoxycarbonyl-*O*-triethylsilyl-L-serine *N*′-propargylamide (**3**) and *N*-*tert*-butoxycarbonyl-*O*-triethylsilyl-L-threonine *N*′-propargylamide (**4**), were polymerized with a rhodium zwitterion catalyst in THF, MeOH, CH_2Cl_2, and toluene to afford the corresponding optically active poly(*N*-propargylamides) with moderate number-average molecular weights (4200−12 800) in good yields. The polymers exhibited large specific rotations (−172° to −955°) and clear CD signals at the absorption region of polyacetylene main chains. The CD signals of poly(**1**) and poly(**2**) appeared around 270−350 nm, while those of poly(**3**) and poly(**4**) appeared around 400 nm. It is considered that these polymers take helical structures with predominantly one-handed screw sense, whose helical pitches are different. The presence of intramolecular hydrogen bonding of poly(**1**) and poly(**2**) was confirmed by IR spectroscopy measured in $CHCl_3$. Desilylation of poly(**3**) and poly(**4**) satisfactorily proceeded to afford the polymers exhibiting the same CD spectroscopic patterns as those of poly(**1**) and poly(**2**).

Introduction

Amino acids are constituents of proteins, typical biological polymers, and not only biologically important but also useful as chiral auxiliaries and building blocks in organic synthesis.[1,2] Amino acid-based synthetic polymers are expected to show biocompatibility and biodegradability similarly to polypeptides.[3,4] On the other hand, polyacetylenes possess alternating double bonds in the main chain, which endows them with conductivity, gas permeability, etc.[5,6] It is expected that amino acid-containing polyacetylenes will combine these characteristics together and lead to the development of new functions. Yashima et al.[7] and Aoki et al.[8] have reported that several poly(phenylacetylenes) can form helical structures with one-handed screw sense, which are induced by the chiral centers at the side chains and/or chiral auxiliaries. Tang and co-workers have focused on helical poly(phenylacetylenes) carrying amino acid moieties, some of which exhibit unique properties including self-assembling,[9] forming superhelical fibers,[9] chirality transcription,[10] and tuning the helicity by pH change.[11] We have recently reported the polymerization of an alanine-derived *N*-propargylamide catalyzed with an Rh complex.[12,13] The formed polymer takes a helical conformation in chloroform solution, where hydrogen bonding involving N−H linkage plays an important role in stabilizing the helical structure. Meanwhile, the hydroxyl group assists the formation of higher order structures in macromolecules, commonly by hydrogen bonding to cause inter- and/or intramolecular interaction. Serine and threonine carry a hydroxyl group and play a key role in the helix−coil transition of some peptides.[14] Since the helix of poly(*N*-propargylamides) is based on intramolecular hydrogen bonding between the amide groups similar to peptides, serine- and threonine-based poly(*N*-propargylamides) may take different helical structures due to participation of the hydroxyl groups in hydrogen bonding. Although many acetylene monomers substituted with a wide variety of functional groups have been reported, only a few acetylene monomers carrying hydroxyl group have been examined so far, most of which are α-hydroxyl-ω-alkynes such as propargyl alcohol. They undergo polymerization with Pd,[15] Ni, Mo,[16,17] W,[17] and Rh[18] catalysts and by γ-ray and plasma[19,20] to afford the corresponding hydrophilic polymers applicable to optical and medical materials. However, as far as we know, there is no report concerning the chiroptical properties and higher order structures of polyacetylenes carrying hydroxyl groups. The present article deals with polymerization of novel serine- and threonine-derived optically active *N*-propargylamides **1**−**4** (Scheme 1) and characterization of the formed polymers including the higher order structures.

Scheme 1



1: R^1 = H, R^2 = H
2: R^1 = Me, R^2 = H
3: R^1 = H, R^2 = $SiEt_3$
4: R^1 = Me, R^2 = $SiEt_3$

Poly(**1**): R^1 = H, R^2 = H
Poly(**2**): R^1 = Me, R^2 = H
Poly(**3**): R^1 = H, R^2 = $SiEt_3$
Poly(**4**): R^1 = Me, R^2 = $SiEt_3$

Experimental Section

Measurements. ^{1}H NMR spectra were recorded in chloroform-*d* ($CDCl_3$) or acetone-d_6 on a JEOL EX-400 spectrometer. IR spectra were measured using a Shimadzu FTIR-8100 spectrophotometer. Melting points (mp) were measured on a Yanaco micro-melting point apparatus. Elemental analysis was done at the Kyoto University Elemental Analysis Center. Specific rotations ($[\alpha]_D$) were measured on a JASCO DIP-100 digital polarimeter with a sodium lamp as a light source. The number- and weight-average molecular weights (M_n and M_w) of polymers were determined by gel permeation chromatography (GPC) on a JASCO Gulliver system (PU-980, CO-965, RI-930, and UV-1570) equipped with polystyrene gel columns

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(Shodex columns K804, K805, and J806), using THF as an eluent at a flow rate of 1.0 mL/min, calibrated by polystyrene standards at 40 °C. CD and UV−vis spectra were measured in a quartz cell (thickness: 1 cm) at room temperature using a JASCO J-800 spectropolarimeter and a Shimadzu UV-2200 spectrophotometer, respectively.

Materials. All the reagents in monomer synthesis were used as purchased without purification. (nbd)$Rh^+[\eta^6$-$C_6H_5B^-$-$(C_6H_5)_3]$ (nbd = 2,5-norbornadiene) was prepared by the reaction of $[(nbd)RhCl]_2$ with $NaB(C_6H_5)_4$ as described in the literature.[21] Solvents used in polymerization were distilled by the standard procedure.

Monomer Synthesis. *N-tert*-Butoxycarbonyl-L-serine *N′*-Propargylamide (1). *N*-Methylmorpholine (4.04 g, 44 mmol) was added to a solution of *N-tert*-butoxycarbonyl-L-serine (9.06 g, 44 mmol) in THF (300 mL) at room temperature. Isobutyl chloroformate (6.00 g, 44 mmol) was added to the solution to precipiate *N*-methylmorpholine hydrochloride as a white mass. Then, propargylamine (2.42 g, 44 mmol) was added, and the resulting mixture was stirred at room temperature for 1 h. The precipitate was removed by filtration, and the filtrate was concentrated by rotary evaporation. The resulting residue was dissolved in ethyl acetate (400 mL) and washed three times with water and dried over anhydrous $MgSO_4$. After filtration, the solvent was removed to obtain crude product. It was purified by recrystallization from ethyl acetate/hexane = 1/3 (volume ratio). Yield 70%; mp 158.0−159.0 °C; $[\alpha]_D = 6.5°$ ($c = 0.30$ g/dL, THF). IR (KBr): 3440 (O−H), 3331 (N−H), 3304 (H−C≡C), 3096 (C≡C), 1711 (C=O), 1663 (C=O), 1570, 1536 (N−H), 1509, 1474, 1458, 1431, 1394, 1369, 1306, 1284, 1252, 1178, 1083, 1055, 1045, 1020, 929, 862, 787, 679, 657, 644, 601, 526, 418 cm^{-1}. ^1H NMR (acetone-d_6) δ: 1.37 (s, 9H, CH_3), 2.59 (s, 1H, HC≡C), 2.83 (s, 1H, O−H), 3.65−3.45 (m, 2H, CH_2), 3.95 (s, 1H, CH_2), 4.10 (s, 1H, CH), 5.95 (s, 1H, N−H), 7.58 (s, 1H, N−H). ^{13}C NMR (acetone-d_6) δ: 28.66, 29.09, 57.21, 63.37, 72.14, 79.54, 81.16, 156.24, 171.06. Anal. Calcd for $C_{11}H_{18}N_2O_4$: C, 54.53; H, 7.49; N, 11.56. Found: C, 54.49; H, 7.53; N, 11.55.

***N-tert*-Butoxycarbonyl-L-threoine *N′*-Propargylamide (2).** The compound was synthesized from *N-tert*-butoxycarbonyl-L-threonine and propargylamine in a manner similar to **1**. Yield 87%; mp 95.0−96.0 °C; $[\alpha]_D = -12.0°$ ($c = 0.103$ g/dL, MeOH). IR (KBr): 3304 (O−H, H−C≡C, N−H), 2978 (C≡C), 1711 (C=O), 1641 (C=O), 1533 (N−H), 1454 (C−N), 1367, 1342, 1176, 1103, 1064, 1047, 1022, 960, 870, 684, 459 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.14 (d, 3H, CH_3, $J = 6.3$ Hz), 1.43 (s, 9H, CH_3), 2.02 (br, 1H, O−H), 2.21 (s, 1H, HC≡C), 4.05 (m, 3H, CH, CH_2), 4.33 (dd, 1H, CH, $J = 2.2$ Hz, 6.5 Hz), 5.57 (s, 1H, N−H), 7.05 (s, 1H, N−H). ^{13}C NMR ($CDCl_3$) δ: 17.23, 27.93, 28.69, 57.70, 66.33, 71.29, 78.68, 80.20, 170.80, 184.91. Anal. Calcd for $C_{12}H_{20}N_2O_4$: C, 56.23; H, 7.87; N, 10.93. Found: C, 56.07; H, 7.65; N, 10.72.

***N-tert*-Butoxycarbonyl-*O*-triethylsilyl-L-serine *N′*-Propargylamide (3).** Triethylsilyl chloride (4.14 g, 27.5 mmol) was added to a solution of **1** (6.06 g, 25 mmol) and imidazole (2.04 g, 30 mmol) in *N*,*N*-dimethylformamide (DMF, 5 mL) at room temperature. The reaction mixture was stirred at 5 h, and then water (150 mL) was added to the mixture. It was extracted with ether (50 mL × 3), and the combined organic phase was dried over $MgSO_4$. It was concentrated by rotary evaporation, and the obtained mass was purified by silica gel column chromatography eluted with hexane/ethyl acetate (1/1, volume ratio), followed by recrystallization from hexane. Yield 68%; mp 65.5−67.0 °C; $[\alpha]_D = -6.6°$ ($c = 0.25$ g/dL, MeOH). IR (KBr): 3310(H−C≡C, N−H), 2953, 2876, 1701 (C=O), 1655 (C=O), 1545 (N−H), 1458 (C−N), 1394, 1365, 1340, 1302, 1244, 1176, 1122, 1049, 1018, 816, 729, 626 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 0.62 (q, 6H, CH_2, $J = 8.0$ Hz), 0.95 (t, 9H, CH_3, $J = 8.0$ Hz), 1.46 (s, 9H, CH_3), 2.23 (s, 1H, HC≡C), 3.62 (br, 2H, CH_2), 4.04 (br, 2H, CH_2), 4.15 (s, 1H, CH), 5.39 (s, 1H, N−H), 6.77 (s, 1H, N−H). ^{13}C NMR ($CDCl_3$) δ: 4.14, 6.65, 28.26, 29.21, 55.29, 62.74, 71.70, 79.05, 80.16, 155.47, 170.35. Anal. Calcd for $C_{17}H_{32}N_2O_4Si$: C, 57.27; H, 9.05; N, 7.86. Found: C, 57.20; H, 8.87; N, 7.77.

***N-tert*-Butoxycarbonyl-*O*-triethylsilyl-L-threonine *N′*-Propargylamide (4).** The compound was synthesized from **2** in a manner similar to **3**. Yield 69%; mp 93.0−93.5 °C; $[\alpha]_D = +19.2°$ ($c = 0.31$ g/dL, toluene). IR (KBr): 3296 (H−C≡C, N−H), 2957, 2878, 1701 (C=O), 1662 (C=O), 1541 (N−H), 1458 (C−N), 1419, 1365, 1340, 1300, 1250, 1207, 1178, 1142, 1113, 1099, 1047, 1022, 987, 939, 906, 864, 798, 742, 723, 686, 657, 628, 601, 488, 434 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 0.64 (q, 6H, CH_2, $J = 8.0$ Hz), 0.95 (t, 9H, CH_3, $J = 8.0$ Hz), 1.11 (d, 3H, CH_3, $J = 5.7$ Hz), 1.46 (s, 9H, CH_3), 2.23 (s, 1H, HC≡C), 4.10 (br, 3H, CH_2, CH), 4.40 (m, 1H, CH), 5.43 (s, 1H, N−H), 6.88 (s, 1H, N−H). ^{13}C NMR ($CDCl_3$) δ: 4.63, 6.75, 18.95, 28.28, 29.10, 54.60, 59.22, 67.94, 71.64, 80.05, 155.73, 169.90. Anal. Calcd for $C_{18}H_{34}N_2O_4Si$: C, 58.34; H, 9.25; N, 7.56. Found: C, 58.45; H, 9.20; N, 7.50.

Polymerization (Typical Procedure). All the polymerizations were carried out in a glass tube equipped with a three-way stopcock under nitrogen. A solution of **1** (242 mg, 1.0 mmol) in THF (3.0 mL) was added to (nbd)$Rh^+[\eta^6$-$C_6H_5B^-$-$(C_6H_5)_3]$ (10.2 mg, 0.02 mmol), and the resulting mixture was vigorously stirred. It was kept in a water bath at 30 °C for 1 h. The resulting mixture was poured into a large amount of ether (250 mL) to precipitate a polymer. It was separated by filtration using a membrane filter (ADVANTEC H100A047A) and dried under reduced pressure. Yield: 223 mg (92%).

Spectroscopic Data of the Polymers. Poly(1). IR (KBr): 3600−3200 (O−H, N−H), 2978, 2934, 1700 (C=O), 1655 (C=O), 1525 (N−H), 1458, 1394, 1367, 1250, 1167, 1062, 858 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1.43 (br, 9H, CH_3), 1.98 (br, 1H, O−H), 3.50−4.75 (m, 5H, CH_2, CH), 6.02 (br, 2H, N−H, C=CH), 7.78 (br, 1H, N−H). **Poly(2).** IR (KBr): 3600−3200 (O−H), 2978, 2934, 1702 (C=O), 1655 (C=O), 1510 (N−H), 1458, 1394, 1367, 1252, 1167, 1064, 877, 536 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 1,21 (br, 3H, CH_3), 1.43 (br, 9H, CH_3), 2.32 (br, 1H, O−H), 3.35−4.80 (m, 4H, CH_2, CH), 6.01 (br, 2H, N−H, CH=C), 7.62 (br, 1H, N−H). **Poly(3).** IR (KBr): 3600−3200 (O−H), 2955, 2878, 1718 (C=O), 1655 (C=O), 1508 (N−H), 1491, 1473, 1458, 1365, 1244, 1170, 1111, 1016, 744, 418 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 0.61 (br, 6H, CH_2), 0.93 (br, 9H, CH_3), 1.43 (br, 9H, CH_3), 3.47−4.60 (m, 5H, CH_2, CH), 6.10 (br, 2H, N−H, C=CH), 7.73 (br, 1H, N−H). **Poly(4).** IR (KBr): 3600−3200 (O−H), 2950, 2878, 1718 (C=O), 1655 (C=O), 1508 (N−H), 1473, 1458, 1365, 1244, 1172, 1101, 1016, 744, 418 cm^{-1}. ^1H NMR ($CDCl_3$) δ: 0.54 (br, 6H, CH_2), 0.92 (br, 9H, CH_3), 1.05−1.67 (m, 12H, CH_3), 3.80−4.65 (m, 4H, CH_2, CH), 5.15 (br, 1H, CH=C), 6.60 (br, 1H, N−H), 8.19 (br, 1H, N−H).

Desilylation of Poly(3) and Poly(4) (Typical Procedure). Tetrabutylammonium fluoride (TBAF, 1 M solution in THF, 0.48 mL) was added to a mixture of poly(**3**) (142 mg, 0.4 mmol repeating unit) in THF (8 mL) at room temperature, and the resulting mixture was stirred for 1 h. The heterogeneous mixture became homogeneous after the reaction. The mixture was poured into a large amount of hexane to precipitate a polymer. The polymer was isolated by filtration and immersed in water for 30 min. It was filtrated and dried to obtain poly(**1′**).

Molecular Mechanics Calculations. All the calculations were carried out with MMFF94 force field,[22] using Wavefunction, Inc., Spartan '04 Windows version 1.01. A detailed procedure of the calculations is described in the Results and Discussion section.

Results and Discussion

Monomer Synthesis. We first tried to synthesize the novel serine- and threonine-derived *N*-propargylamide monomers **1** and **2** by the method using 1-(3-(dimethylamino)propyl)-3-ethylcarbodiimide hydrochloride (EDC·HCl) similarly to our previous report,[12] but the product yield was terribly low (ca. 10%) because it was difficult to separate the organic and water phases due to the formation of poorly soluble mass during the workup process. This seems due to some side reactions such as condensation between the hydroxyl group of the *N-tert*-

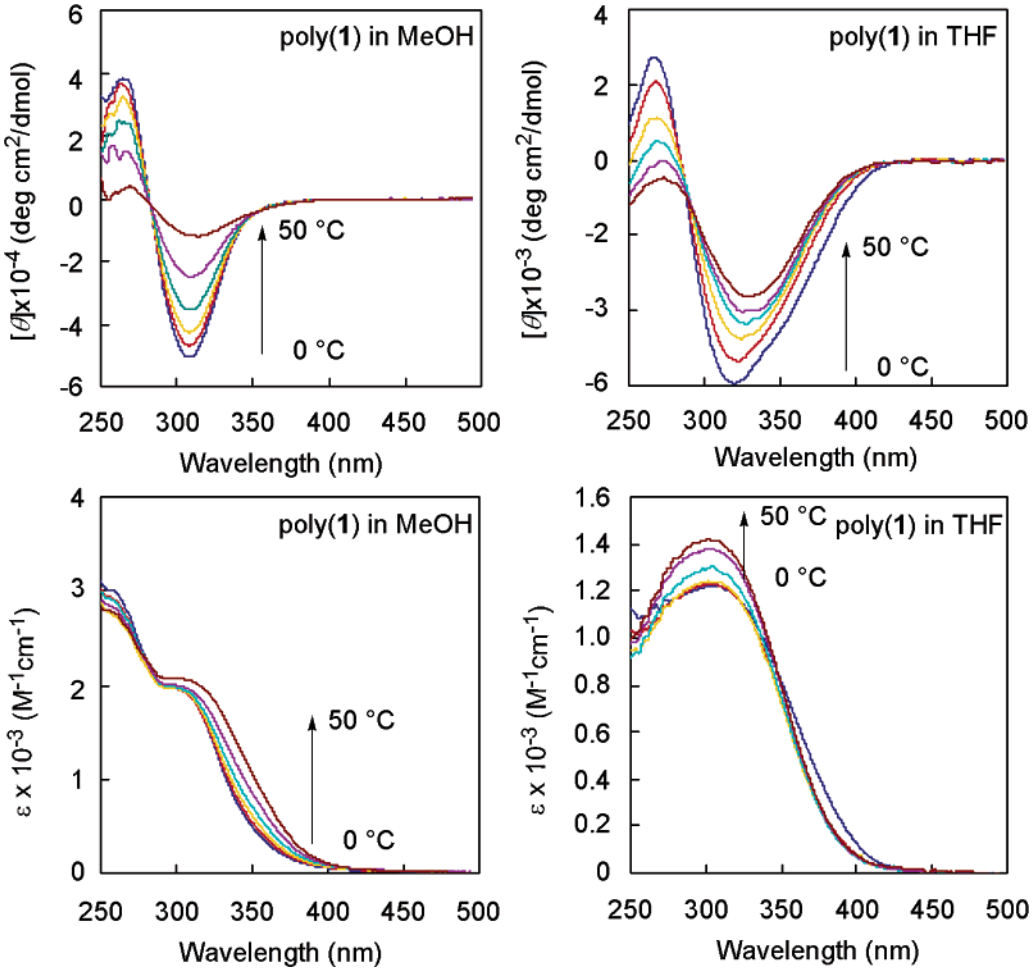


Figure 1. CD and UV−vis spectra of poly(**1**) measured in MeOH and THF at 0−50 °C (c = (4.55−5.29) × 10^{-4} mmol/L).

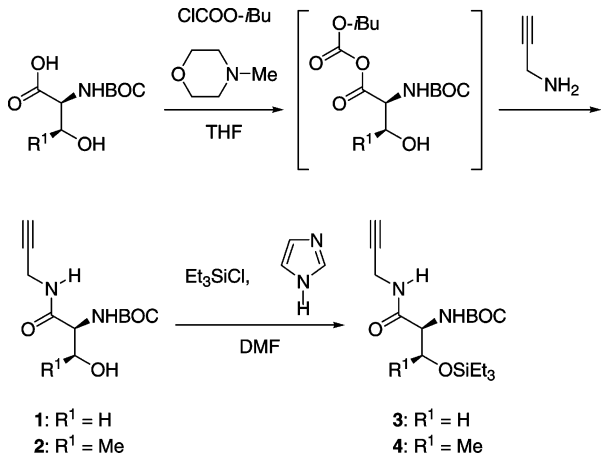
Table 1. Polymerization of L-Serine- and L-Threonine-Derived Monomers 1−4[a]

run	monomer	solvent	$[M]_0$ (mol/L)	yield[b] (%)	M_n[c]	M_w/M_n[c]	$[\alpha]_D$[d] (deg)
1	**1**	THF	0.33	91	9200	1.36	−232
2	**1**	MeOH	0.33	52	4200	1.88	−361[k]
3	**1**	THF/MeOH = 1/1	0.33	99	11200	1.63	−172
4[e]	**1**	THF	0.33	37	7800[f]	1.28	−174
5	**2**	THF	0.33	99	10000	1.50	−218
6	**2**	THF/MeOH = 1/1	0.33	98	10500	1.53	−325
7	**2**	CH_2Cl_2	0.20	97	8100	1.78	−324
8[e]	**2**	THF	0.33	44	12800[g]	1.43	−174
9	**3**	THF	0.33	87	9400[h]	1.15	−680
10	**3**	toluene	0.10	70	11000	1.25	
11	**4**	THF	0.33	89	8500[i]	1.12	−947
12	**4**	THF	0.20	95	7200	1.15	−837[l]
13	**4**	THF	0.10	90	7500	1.14	−879[l]
14	**4**	toluene	0.10	50	9900[j]	1.17	−955[l]

[a] Conditions: catalyst: (nbd)$Rh^+[\eta^6$-$C_6H_5B^-(C_6H_5)_3]$, nbd = norbornadiene, $[M]_0/[Rh]$ = 50, at 30 °C for 1 h under N_2. [b] Insoluble part in ether (runs 1−4), hexane (runs 5−8) MeOH/H_2O = 1/1 (v/v) (runs 9, 11−13), or acetone (runs 10 and 14). [c] Determined by GPC eluted with THF based on polystyrene standards. [d] Measured by polarimetry at room temperature, c = 0.10−0.30 g/dL (runs 1−8) or c = 0.004 g/dL (runs 9 and 11) in THF. [e] $[(nbd)RhCl]_2$ (0.033 mol/L) and Et_3N (0.016 mol/L) were used instead of (nbd)$Rh^+[\eta^6$-$C_6H_5B^-(C_6H_5)_3]$. [f] Contained a fraction of M_n = 800 (23% area ratio). [g] Contained a fraction of M_n = 300 (29% area ratio). [h] Contained a fraction of M_n = 700 (52% area ratio). [i] Contained a fraction of M_n = 600 (48% area ratio). [j] Contained a fraction of M_n = 500 (14% area ratio). [k] Measured in MeOH, c = 0.109 g/dL. [l] Measured in toluene, c = 0.025−0.03 g/dL.

butoxycarbonylamino acid with the carboxyl group to form oligomers because EDC·HCl cannot selectively condense carboxyl group with amino group in the presence of hydroxyl group.[23] We therefore examined

Scheme 2



isobutyl chloroformate/*N*-methylmorpholine as condensation agents (Scheme 2), which is reported to successfully give alkynylamides from *N*-*tert*-butoxycarbonylamino acids.[24] Monomers **3** and **4** were synthesized by *O*-silylation of **1** and **2**, respectively. The desired monomers could be successfully obtained in relatively good yields, whose structures were confirmed by IR and NMR spectroscopies besides elemental analysis.

Table 1 summarizes the conditions and results of the polymerization of L-serine- and L-threonine-derived monomers **1** and **2**, and the silylated monomers **3** and **4** using (nbd)$Rh^+[\eta^6$-$C_6H_5B^-(C_6H_5)_3]$ or $[(nbd)RhCl]_2$ as a catalyst in THF, MeOH, THF/MeOH mixed solvent,

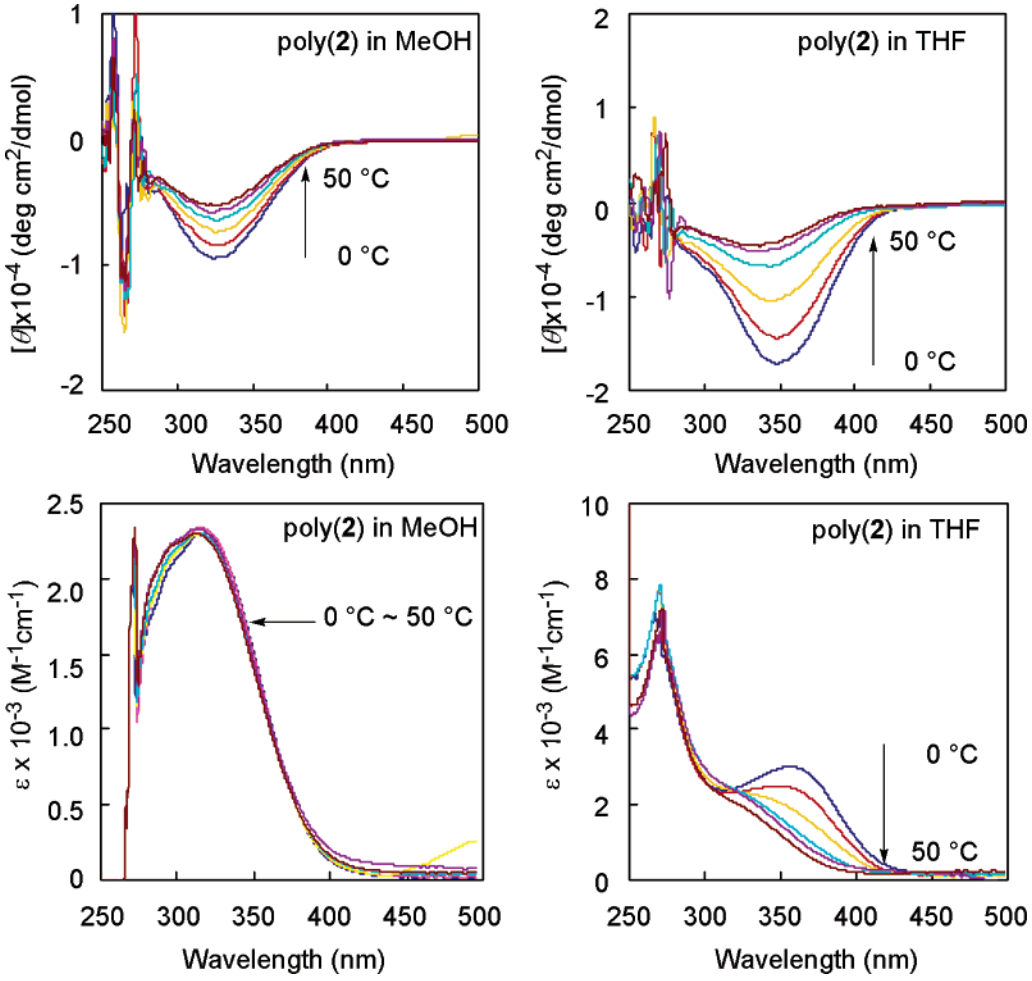


Figure 2. CD and UV−vis spectra of poly(**2**) measured in MeOH and THF at 0−50 °C (c = (4.10−5.46) × 10^{-4} mmol/L).

CH_2Cl_2, or toluene. In the polymerization of **1** and **2**, (nbd)$Rh^+[\eta^6$-$C_6H_5B^-(C_6H_5)_3]$ successfully afforded the polymers with M_n's ranging from 4200 to 11 200 in almost quantitative yields (runs 1−3 and 5−7). The polymerization proceeded homogeneously throughout the reaction. As far as the yield and M_n of the polymers concern, we can say that the hydroxyl group of the monomers does not hamper the polymerization at all. The Rh zwitterion catalyst is highly tolerant to the hydroxyl group as well as the amide and carbamate groups in acetylene polymerization. On the other hand, $[(nbd)RhCl]_2$ afforded poly(**1**) and poly(**2**) showing multimodal GPC traces in low yields (37% and 44%, runs 4 and 8); presumably, the polymerization was accompanied by dimerization or trimerization of the monomers as similarly observed in the Rh-catalyzed polymerization of the alanine-derived *N*-propargylamide.[12] Meanwhile, in the polymerization of *O*-silylated monomers **3** and **4**, the polymerization mixture became heterogeneous during the reaction. The polymers were also obtained in good yields, but they exhibited bimodal GPC traces in some cases.

The structures of poly(**1**)−poly(**4**) were examined by ^{1}H NMR spectroscopy. We could not clearly determine the cis contents from the integrated peak ratios between the cis vinyl proton at the main chain and other proton signals because all the signals appeared very broadly. Since Rh catalysts commonly afford polyacetylenes with cis-transoidal structure,[25] and several poly(*N*-propargylamides) are confirmed to have this structure, we assume the steric structures of the present polymers are also the case.

Figures 1 and 2 depict the CD and UV−vis spectra of poly(**1**) and poly(**2**) measured in MeOH and THF at the temperature ranging from 0 to 50 °C. Poly(**1**) exhibited strong CD signals at 265 and 309 nm in positive and negative signs at 0 °C, respectively, when MeOH was employed as the measuring solvent. The intensities gradually decreased to 20% of the value at 0 °C as raising temperature to 50 °C, showing an isosbestic point at 280 nm. On the other hand, in THF poly(**1**) exhibited CD signals in positive and negative signs around 270 and 320 nm. The intensities were 1 order smaller than that in MeOH and decreased as the temperature was raised. These data strongly suggest that the polymer takes a helical structure, and the helix content is larger in MeOH than in THF. In fact, the $[\alpha]_D$ measured in MeOH was −455°, which was larger than the value in THF (−232°, run 1 in Table 1). The wavelength and the solvent dependence of the Cotton effect of poly(**1**) were quite unusual compared with the poly(*N*-proparglyamides) we have reported so far. Namely, all the helical poly(*N*-propargylamides) including the L-alanine-derived one[7,8] do not exhibit a CD signal below 320 nm but 380−400 nm irrespective of measuring solvents including MeOH, THF, CH_2Cl_2, and $CHCl_3$. Further, the addition of MeOH commonly decreases the helicity because it prevents intramolecular hydrogen bonding between the amide side chains, which is necessary for poly(*N*-propargylamides) to form a helix.

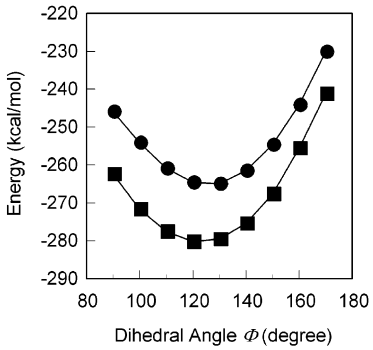
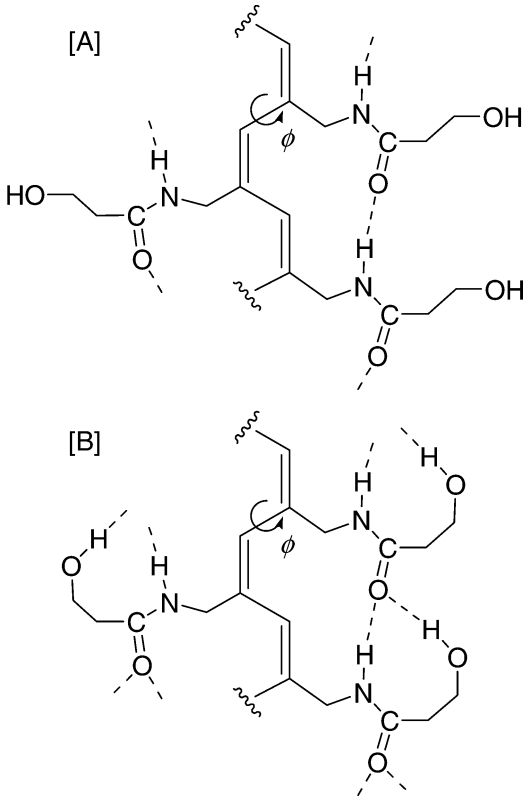


Figure 3. Relationships between the energies and dihedral angles (ϕ) at the single bonds of the main chain of the 10-mer of *N*-propargyl 3-hydroxypropanamide, calculated by molecular mechanics using MMFF94 force field. (●) Hydrogen bonding exists between ⟩C=*O* at *n*th and *H*−N⟨ at (*n* + 2)th units (Chart 1A). (■) Hydrogen bonding exists between ⟩C=*O* at *n*th and *H*−N⟨ at (*n* + 2)th units and between ⟩C=*O* at *n*th and *H*−O− at (*n* + 2)th units (Chart 1B).

Chart 1



We have previously presented the possible helix conformation on the basis of the wormlike touched-bead model theory and molecular mechanics and semiempirical molecular orbital calculations.[26] That is, the dihedral angle at the double bond of the main chain is 0°, and that of the single bond is 140° in the most stable conformer (cis-transoidal structure). The main chain takes a one-handed helical structure, and the amide groups of the side chains form hydrogen bonds along the helix axis between *n*th and (*n* + 2)th repeating units, where the amide groups form two helical hydrogen-bond strands. The CD absorption at 390−400 nm of the previously reported poly(*N*-propargylamides) should be derived from the conjugated double bonds of the polyacetylene main chain. Consequently, it is suggested that the dihedral angle at the single bond of the main chain of poly(**1**) is smaller than those of the poly(*N*-propargylamides) previously reported,[12,26] resulting in the decrease of conjugation length. Participation of hydroxyl group in the intramolecular amide−amide hydrogen bond may be responsible for this. Poly(**2**) exhibited a CD signal in negative sign at 330 and 350 nm in MeOH and THF, respectively. The intensities decreased in both MeOH and THF by raising the temperature. The UV−vis absorption peaks of the polymers were observed around 310 nm, which also supports the idea that the conjugation lengths; i.e., helical pitches of poly(**1**) and poly(**2**) are shorter than those of poly(*N*-propargylamides) without hydroxyl groups.

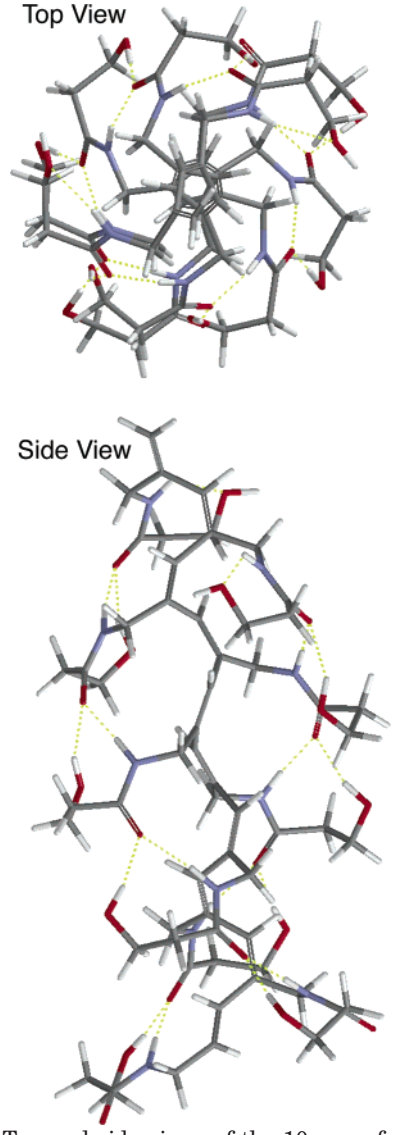


Figure 4. Top and side views of the 10-mer of *N*-propargyl 3-hydroxypropanamide optimized by MMFF94. The dihedral angles at the single bonds of the main chain (ϕ) are fixed at 120°. The green dotted lines represent hydrogen bonding.

The IR spectra of **1**, **2**, poly(**1**), and poly(**2**) were measured in $CHCl_3$ solutions (26.6−53.8 mM) to obtain information on hydrogen bonding. It was confirmed that the amide $\nu_{C=O}$ absorption peak of poly(**1**) shifted to lower wavenumber than that of **1**, while the carbamate $\nu_{C=O}$ peak did not. Considering the low sample concentration, it can be concluded that the amide group of poly(**1**) forms intramolecular hydrogen bonding in a manner similar to poly(*N*-propargylamides) previously reported.[12,26] The solution IR spectra of **2** and poly(**2**) exhibited a similar tendency to those of **1** and poly(**1**).

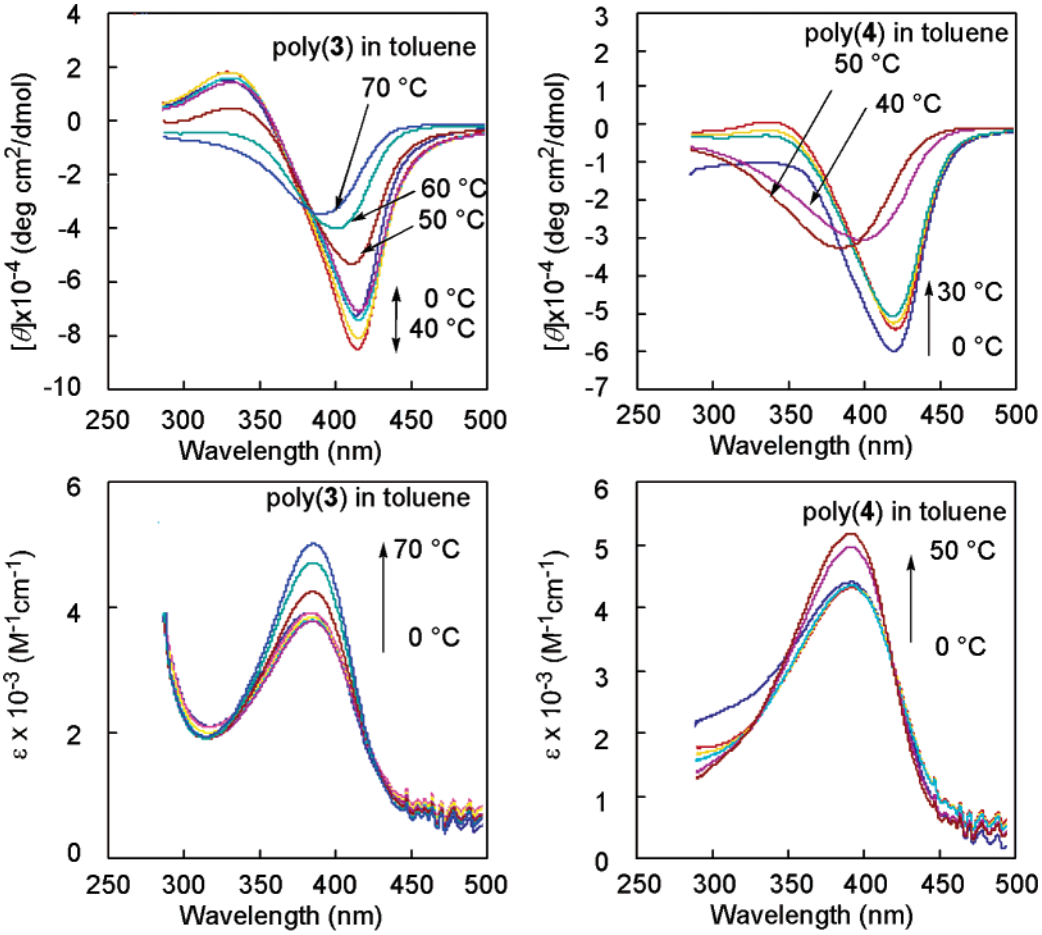


Figure 5. CD and UV−vis spectra of poly(**3**) and poly(**4**) measured in toluene at 0−70 °C or 0−50 °C (c = (3.29−4.32) × 10^{-4} mmol/L).

The results of IR measured in THF were similar to those obtained in $CHCl_3$. We also tried to measure the IR spectra in MeOH but failed to obtain reliable data because the absorption of MeOH hid the absorption peaks of the compounds.

Conformational Analysis by Molecular Mechanics Calculation. Molecular mechanics calculations were carried out to assume the higher order structure of the hydroxyl group containing polymers. The MMFF94 force field was employed to take account of stabilization effect by hydrogen bonding.[22] Figure 3 depicts the relationships between the dihedral angle at the single bond of the main chain (ϕ) and the energy of 10-mers of *N*-propargyl 3-hydroxypropanamide, a simplified structure of poly(**1**). *t*-BuOCONH groups were omitted in order to make modeling easy and save the calculation time. Both end groups of the polyacetylene main chin were terminated with hydrogen. The dihedral angle at the double bond of the main chain was fixed at 0°, and ϕ was varied from 170° to 90° with 10° decrement, i.e., so-called cis-transoidal structure. Otherwise, all the other geometries were optimized. The side-chain conformation of the initial geometry was arranged to form hydrogen bonding between the amide groups at nth and (n + 2)th units (Chart 1A), where the distance between ⟩C═O oxygen and H−N⟨ hydrogen atoms of the eight pairs was set at 1.9 Å. The other series of conformers also form hydrogen bonding between the amide carbonyl oxygen atoms and hydroxyl groups at nth and (n + 2)-th units (Chart 1B). It is obvious that the latter series of conformers are more stable than the formers (ca. 2 kcal/mol per a unit), which is explainable by the additional stabilization effect due to the intramolecular hydrogen bonding, ⟩C═O- - -H−O−. The conformer with ϕ of 120° is the most stable among all the conformers. This value is 20° smaller than that of a poly(*N*-propargylamide) without hydroxyl groups.[26] Consequently, it can be considered that the hydroxyl group containing poly(*N*-propargylamides) in the present study show CD and UV−vis absorption peaks at shorter wavelength region (i.e., shorter conjugation length) than the poly(*N*-propargylamides) without hydroxyl groups. The helical structures of poly(*N*-propargylamides) without hydroxyl groups commonly transform into random coil by the addition of MeOH, while poly(**1**) forms helix not only in THF but also in MeOH. The amide carbonyl groups of poly(**1**) likely to form hydrogen bond strands both with H−N⟨ and H−O− hydrogen atoms as suggested by the molecular modeling study, resulting in tolerance against MeOH.

Figure 4 illustrates the 10-mer of *N*-propargyl 3-hydroxypropanamide after the geometry was optimized, in which ϕ was constrained at 120°. It takes one-handed helical structure, wherein all the eight pairs of ⟩C═*O* at nth and *H*−N⟨, H−O− at (n + 2)th units are located at the positions possibly to form hydrogen bonds (displayed with green dotted lines corresponding to Chart 1B); i.e., the distances between the oxygen and hydrogen atoms range from 1.6 to 2.1 Å, and the angles of O- - -H−N and O- - -H−O are larger than 120°. It clearly shows the intramolecular hydrogen bonds contribute to the formation of helical structure, although steric effects

should be also taken into consideration as reported in poly(*N*-propargylamides) with phenyl groups.[27]

Figure 5 shows the CD and UV−vis spectra of *O*-silylated polymers, poly(**3**) and poly(**4**). At higher temperature [poly(**3**) 70 °C, poly(**4**) 50 °C], the silylated polymers exhibited CD signals in negative sign at 390 nm, which indicates that they take a helical form in a fashion similar to those of poly(*N*-propargylamides) previously reported.[12,26] On the contrary, the CD signals apparently changed into another pattern at temperatures lower than those mentioned above. A positive signed signal appeared at 325 nm and increased in magnitude as lowering the temperature in accordance with the increase of intensity of the negative signed signal, whose wavelength shifted to 420 nm. When the measurement was carried out after the sample solution was filtered with a PTFE membrane (pore size 0.45 μm), this change of CD spectroscopic pattern was not observed. It is therefore concluded that the drastic change of CD is due to aggregation of the polymers. This is also supported by the fact that the λ_{max} of the UV−vis spectra was constant at 390 nm irrespective of temperature. Such an abrupt change of CD spectroscopic patterns based on aggregation has been reported concerning several optically active helical polymers, including poly(fluorene),[28] polythiophene,[29] and poly(*p*-phenyleneethynylene).[30]

When the polymer solution was concentrated, and the residual polymer was dissolved again in toluene, the polymer solution only showed a CD signal at 390 nm. Once the aggregated polymers were filtered off, the residual polymers could not aggregate any longer even after evaporation of the solvent. This was also confirmed by CD measurement of the films made on quartz glass plates by casting from the polymer solutions before and after filtration. Both films exhibited the same CD spectroscopic patterns with those of the corresponding polymer solutions. We isolated the polymer again by pouring the filtered polymer solution into ether and measured the CD spectrum to find that no aggregation took place. We can therefore assume that the aggregates form during the polymerization process.[31]

The silyl groups of poly(**3**) and poly(**4**) could be quantitatively removed by TBAF treatment in THF. The CD spectroscopic patterns of the polymers after desilylation became almost the same as those of poly(**1**) and poly(**2**). We can say that the memory of the higher order structures of the *O*-silylated polymers is lost by desilylation, and the resulting polymers take the same structures as those of the nonsilylated polymers synthesized by the polymerization of the nonsilylated monomers.

In summary, we have demonstrated the synthesis and chiroptical properties of serine- and threonine-derived novel poly(*N*-propargylamides). The polymers with hydroxyl groups exhibited clear CD signals, indicating that they took helical structure. It is suggested that the helical pattern of the polymers with hydroxyl groups is different from that of the polymers with protected hydroxyl groups. Namely, participation of hydroxyl groups in intramolecular hydrogen bonding more stabilizes the helical structure of the hydroxyl group-carrying poly(*N*-propargylamides) to shorten the helix pitch compared with that of the *O*-silylated poly(*N*-propargylamides).

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Supporting Information Available: IR spectra of **1**, poly(**1**), **2**, and poly(**2**) measured in $CHCl_3$ (Figures S1 and S2). This material is available free of charge via the Internet at http://pubs.acs.org.

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(31) The authors had planned to perform light scattering (LS) measurement of the polymer solutions for confirmation of the presence of aggregates. However, filtration of a sample solution with a filter, whose pore size is less than 0.1 μm, is indispensable to obtain reliable data because particles with these sizes disturb LS measurement. The size of the aggregates in the present study should be larger than 0.45 μm as described, so we did not perform LS measurement. The M_n's in Table 1 were measured by GPC after filtering the sample solution with a PTFE membrane filter (pore size 0.45 μm).

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