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Synthesis and properties of ornithine- and lysine-based poly(*N*-propargylamides). Responsiveness of the helical structure to acids

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Abstract

Ornithine- and lysine-based novel *N*-propargylamides, *N*-α-*tert*-butoxycarbonyl-*N*-δ-fluorenylmethoxycarbonyl-L-ornithine-*N*′-propargylamide (**1**), *N*-α-*tert*-butoxycarbonyl-*N*-ε-fluorenylmethoxycarbonyl-L-lysine-*N*′-propargylamide (**2**), *N*-α-fluorenylmethoxycarbonyl-*N*-δ-*tert*-butoxycarbonyl-L-ornithine-*N*′-propargylamide (**3**), and *N*-α-fluorenylmethoxycarbonyl-*N*-ε-*tert*-butoxycarbonyl-L-lysine-*N*′-propargylamide (**4**) were synthesized and polymerized with a rhodium catalyst. Polymers with moderate molecular weights were obtained in good yields. Poly(**1**)–poly(**4**) showed strong Cotton effects in THF, whose sign and wavelength depended on the substituents. They were satisfactorily converted into the corresponding polymers [poly(**1a**)–poly(**4a**)] with free amino groups. Poly(**1a**) and poly(**2a**) also formed a helix, while poly(**3a**) and poly(**4a**) did not. Poly(**1a**) and poly(**2a**) decreased the CD intensity by the addition of *m*- and *o*-phthalic acids.

Keywords: Helix; pH-responsiveness; Polyacetylene

1. Introduction

Amino acids are not only biologically important but also useful substances for chiral auxiliaries and building blocks in organic synthesis. Amino acid-based synthetic polymers are expected to show biocompatibility and biodegradability similarly to those of polypeptides, and form secondary structures such as helices [1]. On the other hand, stimuli-responsive polymers gain much attention due to a wide range of potential applications including data storage, drug delivery, and artificial muscles [2]. Heat [2c,3], additive [4], and change of medium conditions such as polarity [2k,5] and pH are commonly employed as stimuli.

Polyacetylene derivatives exhibit unique properties based on the conjugated main chain and rigid structure, such as light emission by photo- and electroluminescence, nonlinear optical properties, high gas permeability, and formation of a helical structure [6,7]. We have reported the synthesis and polymerization of a series of amino acid-derived acetylene monomers catalyzed by a rhodium zwitterion complex; the polymers obtained take a helical structure with predominantly one-handed screw sense, some of which invert the helix sense or change the tightness, and/or transform the structure into random coil upon external stimuli such as heat, polar solvent, and light [8]. A glutamic acid-derived poly(*N*-propargylamide) changes the helical sense together with tightness upon addition of a base, presumably due to the change of electrostatic repulsion between the pendent carboxy groups [9]. It is expected that incorporation of free amino groups instead of carboxy groups in the side chain of poly(*N*-propargylamides) leads to development of acid-responsive helical polymers. The present study deals with the synthesis of ornithine- and lysine-based novel helical poly(*N*-propargylamides), and chiroptical responsiveness of the polymers to acids.

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2. Experimental section

2.1. Measurements

^{1}H and ^{13}C NMR spectra were recorded on a JEOL EX-400 spectrometer. IR spectra were measured on a JASCO FTIR-4100 spectrophotometer. High resolution mass spectra were recorded on a JEOL JMS-HX110A and a JMS-SX102A spectrometers. The number- and weight-average molecular weights (M_n and M_w) of polymers were determined by gel permeation chromatography (GPC) using THF as an eluent calibrated by polystyrene standards at 40 °C. Melting points were measured on a Yanaco micro melting point apparatus. Specific rotations ($[\alpha]_D$) were measured on a JASCO DIP-1000 digital polarimeter. CD and UV–vis spectra were recorded on a JASCO J-820 spectropolarimeter.

2.2. Materials

(nbd)Rh$^+$[η^6-$C_6H_5B^-(C_6H_5)_3$] was prepared as reported [10]. THF used for polymerization was distilled over CaH_2 prior to use. All other reagents were used as received without purification.

2.3. Monomer synthesis

2.3.1. *N*-α-*tert*-Butoxycarbonyl-*N*-δ-fluorenylmethoxycarbonyl-L-ornithine-*N*′-propargylamide (**1**)

N-α-*tert*-Butoxycarbonyl-*N*-δ-fluorenylmethoxycarbonyl-L-ornithine (7.37 g, 15 mmol) and propargylamine (0.83 g, 15 mmol) were dissolved in AcOEt (100 mL), and the resulting solution was stirred at room temperature for 10 min. 4-[4,6-Dimethoxy-1,3,5-triazine-2-yl]-4-methylmorpholinium chloride (4.2 g, 15 mmol) was added to the solution, and the resulting mixture was stirred at room temperature overnight. The mixture was subsequently washed with 0.5 M HCl, saturated aq. $NaHCO_3$, and saturated aq. NaCl, dried over anhydrous $MgSO_4$, and concentrated on a rotary evaporator. The residue was purified by silica gel column chromatography eluted with *n*-hexane/AcOEt (1/2, v/v) to obtain **1** as white powder in 61% yield. Mp 127–128 °C, $[\alpha]_D = +5.4°$ ($c = 0.1$ g/dL, $CHCl_3$, room temperature). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.38–2.02 [m, 15H, $(CH_3)_3$, $CH_2CH_2CH_2NH$], 3.13 (s, 1H, HC≡), 3.87 (s, 2H, ≡CCH_2), 4.18 (s, 2H, COC*H*NH, ArC*H*CH_2), 4.33 (s, 2H, ArCHC*H*$_2$), 5.13 (s, 1H, NHCO), 5.32 (s, 1H, NHCOO), 6.98 (s, 1H, NHCOO), 7.25–7.77 (m, 8H, Ar). ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.29, 26.44, 28.28, 29.02, 29.90, 41.38, 47.15, 49.62, 67.01, 71.50, 79.22, 119.95, 124.94, 127.00, 127.65, 141.23 (NHCOO), 141.70 (NHCOO), 172.10 (NHCO). IR (cm^{-1}, KBr): 3325 (HC≡), 2108 (C≡C), 1689 (NHCOO), 1655 (NHCO), 1539, 1465, 1369, 1296, 1261, 1164, 1018, 937, 863, 659. High resolution mass calcd for $C_{28}H_{34}N_3O_5$ $[M+H]^+$: 492.2498. Found: 492.2513.

2.3.2. *N*-α-*tert*-Butoxycarbonyl-*N*-ε-fluorenylmethoxycarbonyl-L-lysine-*N*′-propargylamide (**2**)

The title compound was synthesized from *N*-α-*tert*-butoxycarbonyl-*N*-ε-fluorenylmethoxycarbonyl-L-lysine and propargylamine in a manner similar to **1**. Yield 54% (white solid). Mp 142–143 °C, $[\alpha]_D = +8.3°$ ($c = 0.1$ g/dL, $CHCl_3$, room temperature). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.43–1.85 [m, 17H, $(CH_3)_3$, $CH_2CH_2CH_2CH_2NH$], 3.19 (s, 1H, HC≡), 3.98 (s, 2H, ≡CCH_2), 4.04 (s, 2H, COC*H*NH, ArC*H*CH_2), 4.24 (s, 2H, ArCHC*H*$_2$), 4.97 (s, 1H, NHCO), 5.25 (s, 1H, NHCOO), 6.72 (s, 1H, NHCOO), 7.29–7.82 (m, 8H, Ar). ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.40, 28.37, 29.05, 31.95, 40.34, 47.00, 67.06, 71.63, 79.15, 81.72, 119.90, 125.00, 127.00, 127.67, 141.26, 143.64, 156.65 (NHCOO), 158.95 (NHCOO), 171.61 (NHCO). IR (cm^{-1}, KBr): 3313 (HC≡), 2112 (C≡C), 1683 (NHCOO), 1654 (NHCO), 1542, 1473, 1373, 1261, 1157, 933, 814, 740, 659. High resolution mass calcd for $C_{29}H_{36}N_3O_5$ $[M+H]^+$: 506.2655. Found: 506.2658.

2.3.3. *N*-α-Fluorenylmethoxycarbonyl-*N*-δ-*tert*-butoxycarbonyl-L-ornithine-*N*′-propargylamide (**3**)

The title compound was synthesized from *N*-α-fluorenylmethoxycarbonyl-*N*-δ-*tert*-butoxycarbonyl-L-ornithine and propargylamine in a manner similar to **1**. Yield 47% (white solid). Mp 118.5–119.5 °C, $[\alpha]_D = +7.9°$ ($c = 0.1$ g/dL, $CHCl_3$, room temperature). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.46–2.17 [m, 15H, $(CH_3)_3$, $CH_2CH_2CH_2NH$], 3.08 (s, 1H, HC≡), 4.01 (s, 2H, ≡CCH_2), 4.21 (s, 2H, COC*H*NH, ArC*H*CH_2), 4.38 (s, 2H, ArCHC*H*$_2$), 4.81 (s, 1H, NHCO), 5.77 (s, 1H, NHCOO), 7.08 (s, 1H, NHCOO), 7.29–7.76 (m, 8H, Ar). ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.17, 26.42, 28.43, 29.03, 30.87, 41.38, 47.09, 49.68, 66.95, 71.50, 79.22, 79.41, 119.92, 125.08, 127.02, 127.65, 144.23 (NHCOO), 143.70 (NHCOO), 172.01 (NHCO). IR (cm^{-1}, KBr): 3305 (HC≡), 2114 (C≡C), 1689 (NHCOO), 1657 (NHCO), 1531, 1465, 1368, 1296, 1249, 1170, 1057, 1022, 863, 740. High resolution mass calcd for $C_{28}H_{34}N_3O_5$ $[M+H]^+$: 492.2498. Found: 492.2508.

2.3.4. *N*-α-Fluorenylmethoxycarbonyl-*N*-ε-*tert*-butoxycarbonyl-L-lysine-*N*′-propargylamide (**4**)

The title compound was synthesized from *N*-α-fluorenylmethoxycarbonyl-*N*-ε-*tert*-butoxycarbonyl-L-lysine and propargylamine in a manner similar to **1**. Yield 42% (white solid). Mp 158–159 °C, $[\alpha]_D = +10.1°$ ($c = 0.1$ g/dL, $CHCl_3$, room temperature). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.47–2.16 [m, 17H, $(CH_3)_3$, $CH_2CH_2CH_2CH_2NH$], 3.09 (s, 1H, HC≡), 4.01 (s, 2H, ≡CCH_2), 4.20 (s, 2H, COC*H*NH, ArC*H*CH_2), 4.40 (s, 2H, ArCHC*H*$_2$), 4.67 (s, 1H, NHCO), 5.62 (s, 1H, NHCOO), 6.71 (s, 1H, NHCOO), 7.30–7.77 (m, 8H, Ar). ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.39, 28.38, 29.12, 30.88, 40.34, 47.07, 67.04, 71.70, 79.15, 80.92, 119.95, 125.02, 127.06, 127.71, 141.25, 143.66, 156.18 (NHCOO), 171.46 (NHCO). IR (cm^{-1}, KBr): 3301 (HC≡), 2103 (C≡C), 1685 (NHCOO), 1653 (NHCO), 1535, 1458, 1369, 1246, 1169, 1064, 1018, 744, 651. High resolution mass calcd for $C_{29}H_{36}N_3O_5$ $[M+H]^+$: 506.2655. Found: 506.2653.

2.4. Polymerization

The polymerization was carried out in a glass tube equipped with a three-way stopcock under nitrogen. (nbd)$Rh^+[\eta^6$-$C_6H_5B^-(C_6H_5)_3]$ (10.3 mg, 0.02 mmol) was added to a solution of a monomer (1.0 mmol) in THF (5 mL). The resulting solution was kept at 30 °C for 3 h. After that, the resulting mixture was poured into *n*-hexane (250 mL) to precipitate a polymer. It was separated by filtration using a membrane filter (ADVANTEC H100A047A) and dried under reduced pressure.

2.5. Deprotection of the polymers

The FMOC group of the polymers was removed under a basic condition. A typical experimental procedure is given as follows. Piperidine (10 mL) was added to a solution of poly(**1**) (982 mg, 2 mmol) in CH_2Cl_2 (10 mL). The resulting mixture was stirred at room temperature for 45 min, and then poured into *n*-hexane (150 mL) to precipitate a polymer. It was collected by filtration using a membrane filter (ADVANTEC H100A047A) and dried under reduced pressure to obtain poly(**1a**).

2.6. Spectroscopic data of the polymers

Poly(**1**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.39 [br, 15H, $(CH_3)_3$, CH_2CH_2CH_2NH], 3.18 (br, 2H, CH_2NHCOO), 4.21 (br, 4H, COC*H*NH, CH_2COONH, C*H*CH_2COONH), 5.06 (br, 1H, NHCO), 6.15 (br, 1H, CH═), 6.87 (br, 2H, CH$_2$N*H*COO, CHN*H*COO), 7.39 (br, 8H, Ar). IR (cm^{-1}, KBr): 3325 (NHCO), 1701 (C═O), 1651 (NHCO), 1531, 1253, 1169. Poly(**2**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.42 [br, 17H, $(CH_3)_3$, CH_2CH_2CH_2CH_2NH], 3.19 (br, 2H, CH_2NHCOO), 4.04 (br, 4H, COC*H*NH, CH_2COONH, C*H*CH$_2$COONH,), 5.89 (br, 1H, CH═), 6.51 (br, 2H, CH$_2$N*H*COO, CHN*H*COO), 7.39 (br, 8H, Ar). IR (cm^{-1}, KBr): 3316 (NHCO), 1701 (C═O), 1649 (NHCO), 1531, 1369, 1249, 1165. Poly(**3**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.37 [br, 15H, $(CH_3)_3$, CH_2CH_2CH_2NH], 4.00 (br, 6H, CH_2NHCO, COC*H*NH, CH_2COONH, C*H*CH$_2$COONH), 5.01 (br, 1H, NHCO), 6.17 (br, 1H, CH═), 6.58 (br, 2H, CH$_2$N*H*COO, CHN*H*COO), 7.32 (br, 8H, Ar). IR (cm^{-1}, KBr): 3309 (NHCO), 1697 (C═O), 1653 (NHCO), 1519, 1249, 1169, 868, 744. Poly(**4**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.34 [br, 17H, $(CH_3)_3$, CH_2CH_2CH_2CH_2NH], 3.99 (br, 6H, CH_2NHCO, COC*H*NH, CH_2COONH, C*H*CH$_2$-COONH), 6.07 (br, 1H, CH═), 6.34 (br, 2H, CH$_2$N*H*COO, CHN*H*COO), 7.36 (br, 8H, Ar). IR (cm^{-1}, KBr): 3301 (NHCO), 1697 (C═O), 1652 (NHCO), 1246, 1167, 1012, 864. Poly(**1a**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.54 [br, 13H, $(CH_3)_3$, CH_2CH_2CH$_2$NH$_2$], 2.80 (br, 2H, CH_2NH$_2$), 3.88 (br, 7H, CH_2N*H*CO, COC*H*N*H*COO, CH$_2$NH_2), 6.15 (br, 1H, CH═). Poly(**2a**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.54 [br, 15H, $(CH_3)_3$, CH_2CH_2CH_2CH$_2$NH$_2$], 2.81 (br, 2H, CH_2NH$_2$), 3.89 (br, 7H, CH_2N*H*CO, COC*H*N*H*COO, CH$_2$NH_2), 6.16 (br, 1H, CH═). Poly(**3a**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.52 [br, 13H, $(CH_3)_3$, CH_2CH_2CH$_2$NH$_2$], 2.79 (br, 2H, CH_2NH$_2$), 4.05 (br, 7H, CH_2N*H*CO, COC*H*N*H*COO, CH$_2$NH_2), 6.08 (br, 1H, CH═). Poly(**4a**): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.56 [br, 15H, $(CH_3)_3$, CH_2CH_2CH_2CH$_2$NH$_2$], 3.07 (br, 2H, CH_2NH$_2$), 4.64 (br, 7H, CH_2N*H*CO, COC*H*N*H*COO, CH$_2$NH_2), 6.05 (br, 1H, CH═).

3. Results and discussion

3.1. Polymerization

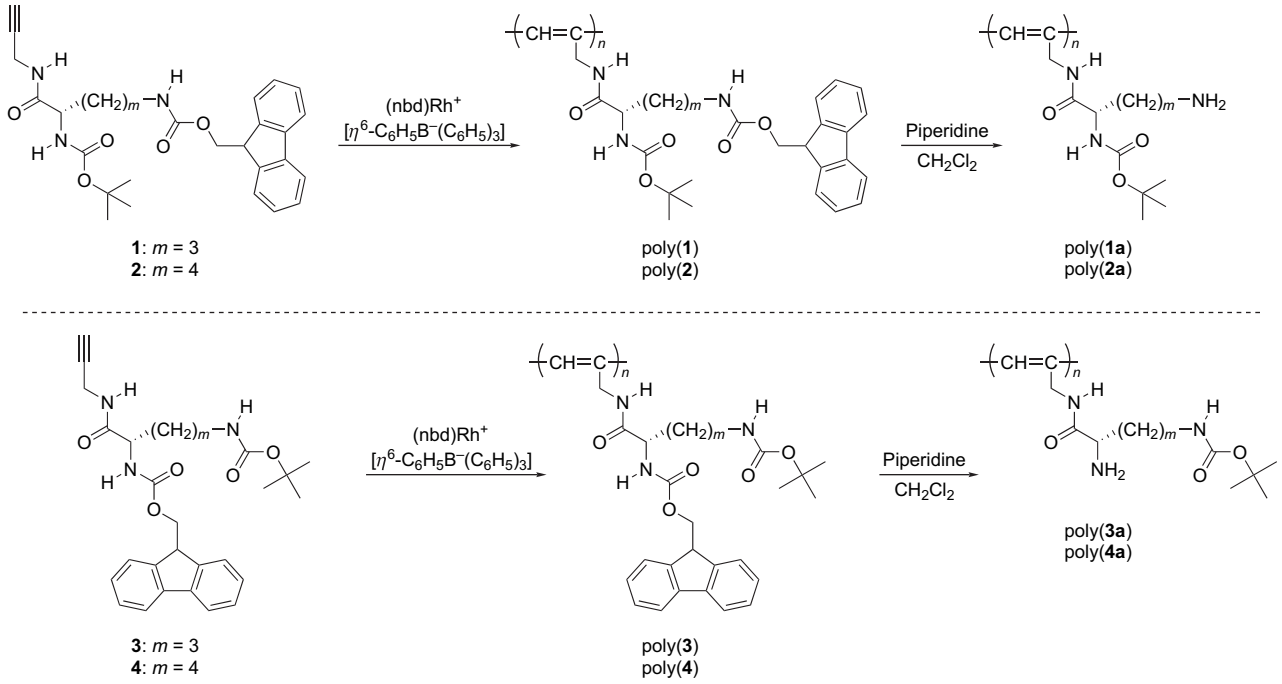
The polymerization of monomers **1**–**4** was conducted with (nbd)$Rh^+[\eta^6$-$C_6H_5B^-(C_6H_5)_3]$ as a catalyst in THF at 30 °C for 3 h (Scheme 1). The corresponding polymers [poly(**1**)–poly(**4**)] with M_n values ranging from 7000 to 11 000 were obtained in 79–87% yields as listed in Table 1. The polymer structures 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 the other proton signals, because all the signals appeared very broadly. Since rhodium complexes efficiently catalyze the polymerization of monosubstituted acetylenes by the insertion mechanism to give *cis*-polyacetylenes [11], and several poly(*N*-propargylamides) obtained using the catalysts are confirmed to have *cis*-structure [12], it is assumed that the geometric structure of poly(**1**)–poly(**4**) is also the case.

3.2. Secondary structure of poly(*1*)–poly(*4*)

The secondary structure of poly(**1**)–poly(**4**) was examined by polarimetry, CD, and UV–vis spectroscopies. Table 2 summarizes the specific rotations of poly(**1**)–poly(**4**) measured in $CHCl_3$, THF, and DMF, together with those of poly(**1a**)–poly(**4b**) as described later. Poly(**1**), poly(**2**), and poly(**4**) showed minus signed specific rotations, and poly(**3**) showed plus signed ones, all of which were much larger than those of the monomers. This result suggests that the polymers take a helical structure with predominantly one-handed screw sense in the solvents.

Fig. 1 depicts the CD and UV–vis spectra of poly(**1**)–poly(**4**) measured in THF at various temperatures. Poly(**1**), poly(**2**), and poly(**4**) exhibited an intense minus Cotton effect around 310, 380, and 310 nm, respectively, and poly(**3**) exhibited a plus one around 425 nm. Since the polymers exhibited UV–vis absorption peaks at the same region as the CD signals, it is concluded that the CD signals originated from the conjugated polyacetylene backbone forming a helix with predominantly one-handed screw sense. It seems that the order of degree of conjugation, i.e., looseness (pitch/diameter ratio) of the helix, is poly(**3**) > poly(**2**) > poly(**1**), poly(**4**) [13]. According to the modeling data optimized by the molecular mechanics calculation and the wavelength of UV–vis absorption, it is assumed that the pitch/diameter ratio of polyacetylene backbone of poly(**2**) is ca. 3 [14].

It is assumed that such different CD spectroscopic patterns between ornithine-based poly(**1**), poly(**3**) [–(CH$_2$)$_3$– spacer] and lysine-based poly(**2**), poly(**4**) [–(CH$_2$)$_4$– spacer] are brought about by the steric effect between the protected amino



Scheme 1. Polymerization of ornithine- and lysine-based *N*-propargylamides, and FMOC removal from the obtained polymers.

groups in the side chain. The odd and even methylene chains between the chiral center and the protected amino groups cause an opposite direction of the FMOC group each other in poly(**1**) and poly(**2**), and that of the BOC group in poly(**3**) and poly(**4**), which should differently interact with the polyacetylene backbones.

We have previously estimated the energy difference between the right- and left-handed helical poly(*N*-propargylamides) carrying chiral substituents to find a right-handed helical poly(*N*-propargylamide) exhibits a plus CD signal around 400 nm [15]. We have also confirmed the relationship between the helix sense and CD sign of porphyrin-carrying poly(*N*-propargylamides) on the basis of the exciton coupling theory [16]. If we could satisfactorily perform semiempirical molecular orbital calculations of the present polymers, we could explain how the molecular structures affect the helical sense more clearly. Unfortunately, the molecular sizes of the present polymers are too large to do it.

Poly(**2**) and poly(**3**) decreased the intensity of the CD and UV–vis signals by raising temperature from 0 to 40 °C as shown in Fig. 1, indicating that they decreased the helix content upon heating. Meanwhile, the temperature effect on the CD and UV–vis spectra of poly(**4**) was small compared to that of poly(**2**) and poly(**3**), and almost none in the case of poly(**1**). The higher stability of helical structure of poly(**1**) and poly(**4**) to heat than that of poly(**2**) and poly(**3**) may be due to the tighter helical structure of the former two polymers than that of the latter two.

Helical poly(*N*-propargylamides) stabilize the conformation by intramolecular hydrogen bonding between the amide groups at the side chains as well as steric repulsion in THF and $CHCl_3$; MeOH breaks the hydrogen-bonding strands to deform the structure [14,17]. Fig. 2 displays the CD and UV–vis spectra of poly(**1**)–poly(**4**) measured in THF/MeOH with various compositions at 20 °C. The CD intensities of poly(**1**) and poly(**2**) were almost the same irrespective of the solvent compositions. It was confirmed that the helical structure of poly(**1**) and poly(**2**) was stable to MeOH, unlike most of helical poly(*N*-propargylamides) reported so far [14,17]. Meanwhile, the CD intensities of poly(**3**) and poly(**4**) decreased together with the UV–vis absorption by

Table 1
Polymerization of **1**–**4**[a]

Monomer	Yield[b] (%)	M_n[c]	M_w/M_n[c]
1	79	7400	1.78
2	83	10 100	1.79
3	87	7000	1.72
4	82	11 000	1.83

[a] Conditions: $[M]_0 = 0.2$ M, catalyst (nbd)$Rh^+[\eta^6\text{-}C_6H_5B^-(C_6H_5)_3]$, $[M]_0/[cat] = 50$ in THF at 30 °C for 3 h.
[b] *n*-Hexane-insoluble part.
[c] Determined by GPC eluted with THF calibrated by polystyrene standards.

Table 2
Specific rotations of poly(**1**)–poly(**4a**)[a]

Polymer	$[\alpha]_D$ (degree)		
	$CHCl_3$	THF	DMF
Poly(**1**)	−175	−189	−194
Poly(**2**)	−301	−287	−292
Poly(**3**)	+190	+197	+103
Poly(**4**)	−65	−77	−94
Poly(**1a**)	−147	−142	−170
Poly(**2a**)	−185	−161	−256
Poly(**3a**)	−32	+17	+22
Poly(**4a**)	−17	+21	−10

[a] Measured at room temperature ($c = 0.10$–0.11 g/dL).

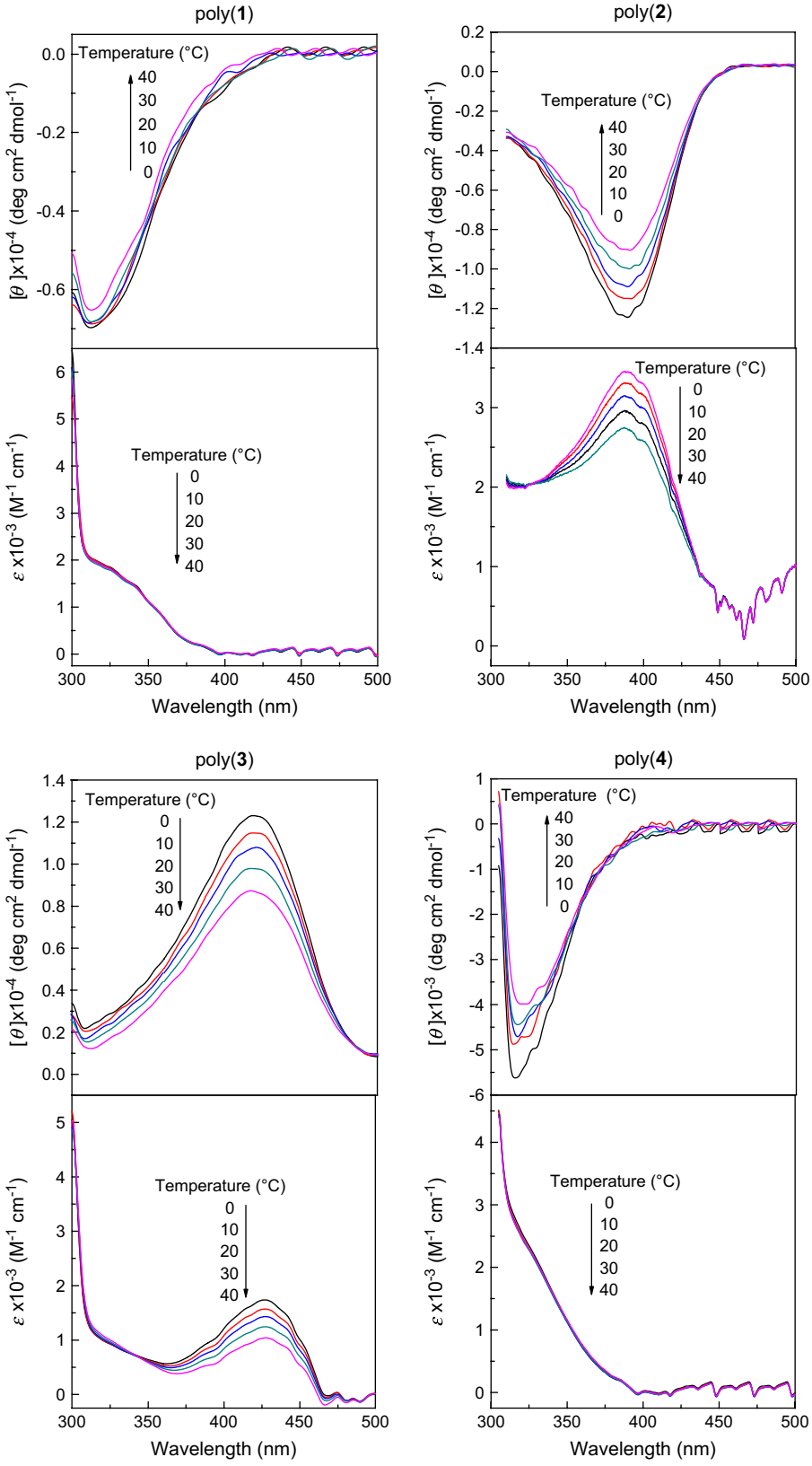


Fig. 1. Temperature-variable CD and UV–vis spectra of poly(**1**)–poly(**4**) measured in THF ($c = 2.48 \times 10^{-4}$ mol/L). The small signals at 450–500 nm are the instrumental noises.

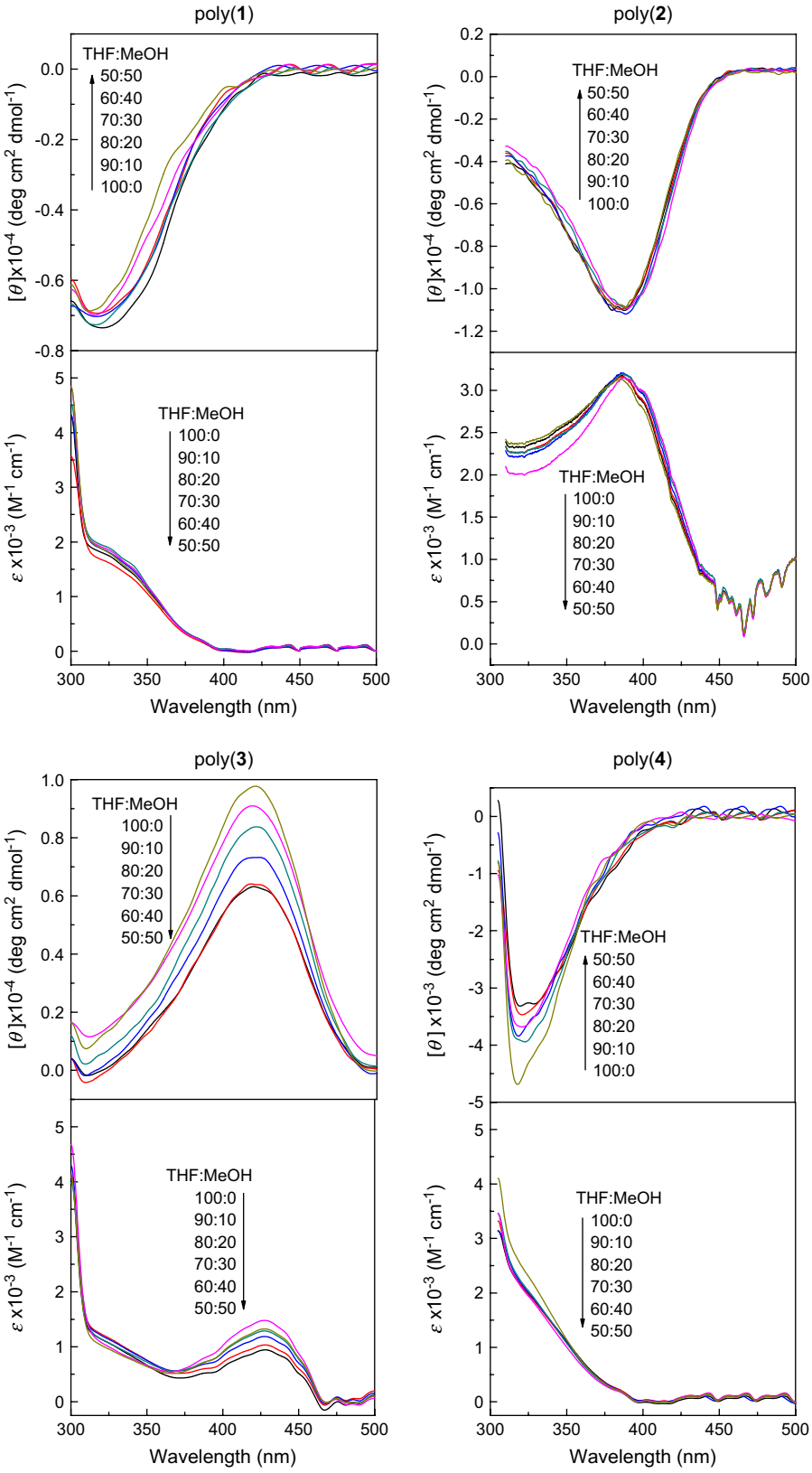


Fig. 2. CD and UV–vis spectra of poly(**1**)–poly(**4**) measured in THF/MeOH ($c = 2.48 \times 10^{-4}$ mol/L) at 20 °C. The small signals at 450–500 nm are the instrumental noises.

raising MeOH content, indicating that they gradually lost the helicity. It seems that δ- and ε-FMOC groups can shield the hydrogen-bonding strands from MeOH more largely than α-FMOC group. The bulky FMOC groups at δ- and ε-positions may take a conformation that is more suitable to wrap the amide groups than that at α-position.

3.3. FMOC removal from poly(*1*)–poly(*4*)

The amino groups of poly(**1**)–poly(**4**) are protected by BOC and FMOC groups, which are removable with acids and bases, respectively. We examined the removal of the BOC group using trifluoroacetic acid and HCl to find that the molecular weight remarkably decreased. Although disubstituted acetylene polymers are highly tolerant to these acids [18], the backbone of monosubstituted acetylene polymers seems to be intolerant to such strong acids [19]. We then tried to remove the FMOC group using piperidine. The FMOC was satisfactorily removed from poly(**1**)–poly(**4**) to give the corresponding polymers with free amino groups, poly(**1a**)–poly(**4a**). At first, we attempted to obtain these polymers directly by the polymerization of monomers **1a**–**4a** with free amino groups, which had been synthesized by FMOC removal from **1**–**4**. Unfortunately, however, no polymerization took place at all, presumably because the amino group intramolecularly participated in the coordination of the monomer to the rhodium catalyst, preventing the monomer from polymerization. Therefore, we abandoned the method and employed a polymer reaction to obtain the free amine polymers. The removal of FMOC group was confirmed by ^{1}H NMR spectroscopy; the aromatic proton signals based on fluorene completely disappeared in every case.

Table 3
FMOC removal from poly(**1**)–poly(**4**)

Polymer	Yield[a] (%)	M_n[b]	M_w/M_n[b]
1a	84	2900	2.05
2a	79	3400	1.88
3a	77	3900	2.04
4a	81	5000	2.33

[a] *n*-Hexane-insoluble part.
[b] Determined by GPC eluted with DMF calibrated by polystyrene standards.

Table 3 summarizes the results of FMOC removal from poly(**1**)–poly(**4**). The corresponding polymers, poly(**1a**)–poly(**4a**) were obtained in good yields. The GPC (DMF)-determined M_n values of the polymers after deprotection were lower than those of the polymers before deprotection. This is partly because of FMOC removal from the pendent, and also probably the larger interaction between the pendent amino groups and polystyrene gels, resulting in long elution times. In fact, poly(**1a**)–poly(**4a**) were eluted at an extraordinarily low molecular weight region (several hundreds) when THF was used as an eluent.

Poly(**1a**) and poly(**2a**) showed large minus signed specific rotations in $CHCl_3$, THF, and DMF as listed in Table 2. Both polymers exhibited an intense Cotton effect in THF as shown in Figs. 3 and 4. Consequently, it is concluded that

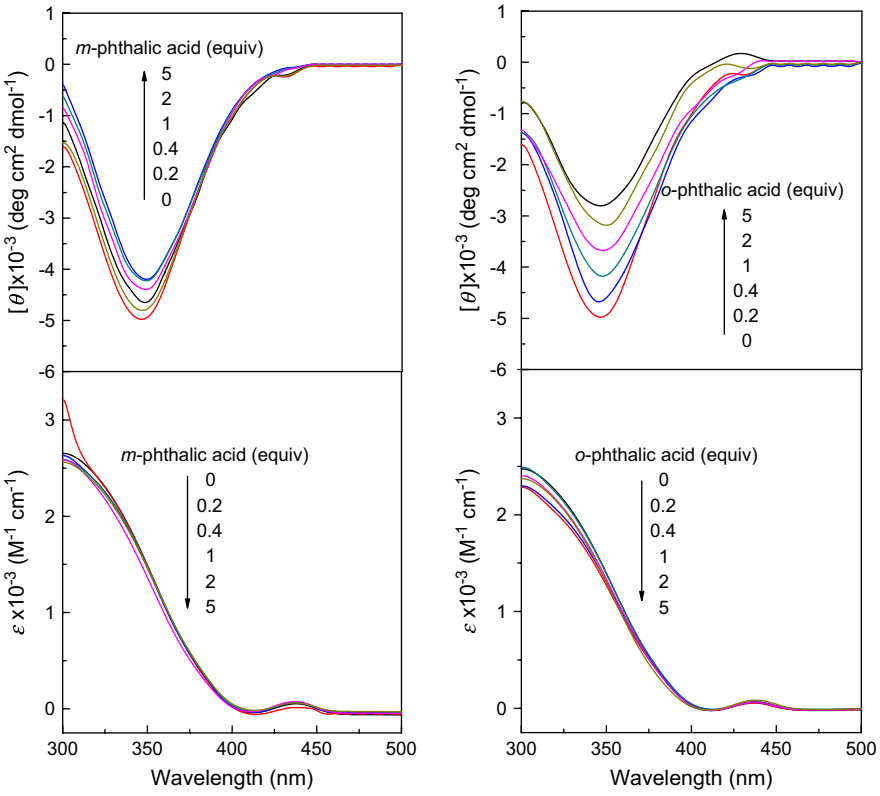


Fig. 3. CD and UV–vis spectra of poly(**1a**) upon addition of *m*- and *o*-phthalic acids measured in THF/MeOH = 1/1 (v/v, $c = 2.48 \times 10^{-4}$ mol/L) at 20 °C.

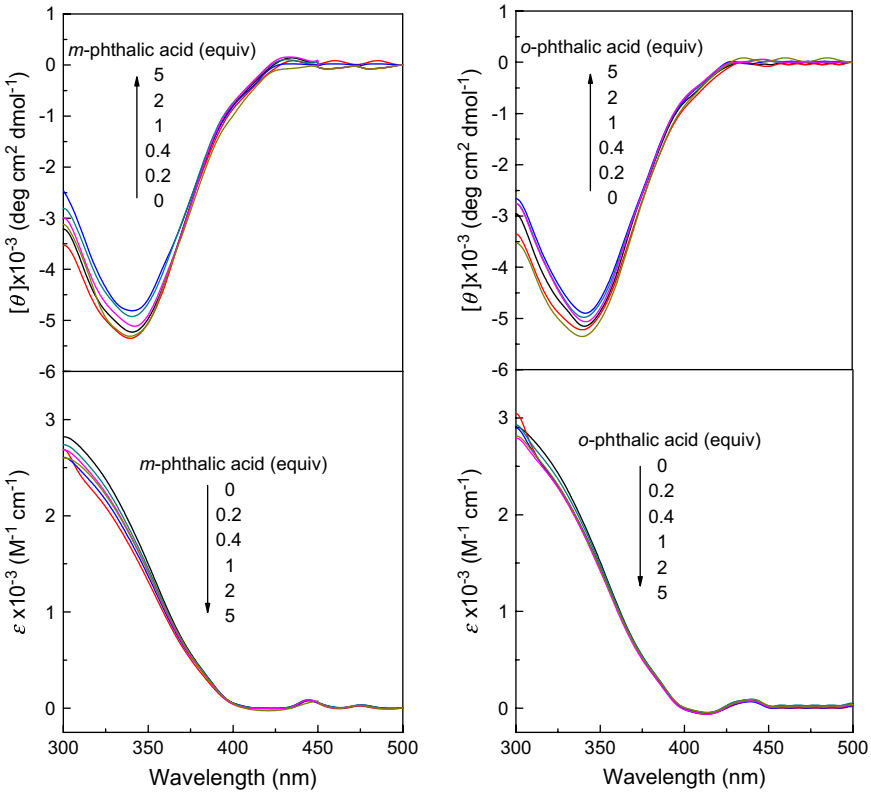


Fig. 4. CD and UV–vis spectra of poly(**2a**) upon addition of *m*- and *o*-phthalic acids measured in THF/MeOH = 1/1 (v/v, $c = 2.48 \times 10^{-4}$ mol/L) at 20 °C.

they take a helical conformation with an excess of predominantly one-handed screw sense in the solvents. It should be noted that poly(**1**) and poly(**2**) shifted the Cotton effect to higher and lower wavelength regions after deprotection, respectively, and the resulting free amine polymers [poly(**1a**) and poly(**2a**)] exhibited the Cotton effect at the same wavelength (340 nm). This result implies that the amino group does not play a dominant role in deciding the helical structure, differently from the FMOC group before deprotection of the amino group. Comparing the CD intensities of the polymers before and after deprotection, they seem to decrease the degree of predominance of one-handedness of screw sense. On the other hand, poly(**3a**) and poly(**4a**) showed small specific rotations in $CHCl_3$, THF, and DMF compared to poly(**3**) and poly(**4**) as shown in Table 2. Along with the CD spectra of poly(**3a**) and poly(**4a**) exhibiting almost no signal (not shown), it seems that the polymers do not form a helical structure any more.

3.4. Responsiveness to acids

Polyacetylenes carrying free carboxy groups in side chains change the conformation according to pH [2k,9,20]. In a similar fashion, poly(**1a**) and poly(**2a**) are expected to be responsive to acids. We expected that diacids form chelated structures at the amine moieties of the polymers to cause a large conformational change. Figs. 3 and 4 depict the changes of CD and UV–vis spectra upon addition of *m*- and *o*-phthalic acids to solutions of poly(**1a**) and poly(**1b**) in THF/MeOH = 1/1 (v/v). As shown in Fig. 3, one equivalent of *m*-phthalic acid decreased the [θ] of poly(**1a**) at 340 nm from −5135 to −4432 deg cm^2 dmol^{-1} (−14%), while the same amount of *o*-phthalic acid decreased it to −3672 deg cm^2 dmol^{-1} (−28%). The simultaneous decrease of UV–vis absorption around 340 nm indicates the decrease of helix content of poly(**1a**). *p*-Phthalic acid caused almost the same CD spectral change (not shown) as *m*-one. Chelation may be one possible reason why *o*-phthalic acid largely affected the helicity of the polymer. Namely, the two carboxy groups of *o*-phthalic acid cooperatively interact with one amino group of the polymer to form a pseudo-cyclic structure, while *m*- and *p*-counterparts cannot form such a chelating structure due to the larger distance between the two carboxy groups. Therefore, *o*-phthalic acid can possibly interact with the polymer strongly than *m*- and *p*-phthalic acids, leading to the higher responsiveness of helicity. We also measured the CD and UV–vis spectra of poly(**1a**) and poly(**2a**) upon addition of benzoic acid to find that the signal changes caused by the acid were almost the same as those by *m*-phthalic acid.

After the addition of 5 equiv of *m*- and *o*-phthalic acids to poly(**1a**) and poly(**2a**) solutions, NaOH was added to the resulting solutions. When 10 equiv of NaOH were added, the CD spectroscopic patterns almost returned to the ones before acid addition. Thus, we could confirm the reversible conformational change of the polymers according to pH.

As shown in Fig. 4, poly(**2a**) also decreased the helix content upon addition of *m*- and *o*-phthalic acids. The degrees of helix collapse were smaller than the cases of poly(**1a**). This

may have resulted from the distance between the amino group and helical main chain of poly(**2a**) larger than that of poly(**1a**).

4. Conclusion

We have synthesized ornithine- and lysine-based novel *N*-propargylamides **1**–**4**, and polymerized them using (nbd)$Rh^{+}[\eta^{6}$-$C_6H_5B^{-}(C_6H_5)_3]$ as a catalyst in THF to obtain poly(**1**)–poly(**4**) with M_n values in the range of 7000–11 000 in 79–87% yields. Large optical rotations and intense CD signals indicated that the polymers formed helical structures with predominantly one-handed screw sense. The methylene chain lengths and positions of FMOC and BOC groups strongly affected the wavelength of the CD signals, i.e., helix tightness. The helical structure of the polymers was unusually stable against heat and MeOH compared to that of poly(*N*-propargylamides) reported so far. It is considered that the FMOC groups at δ- and ε-positions of poly(**1**) and poly(**2**) effectively shield the intramolecualr hydrogen-bonding strands between the amide groups at the side chain from MeOH. All the polymers were satisfactorily converted into the corresponding polymers [poly(**1a**)–poly(**4a**)] with free amino groups. Poly(**1a**) and poly(**2a**) kept the helical conformation accompanying the change of tightness after FMOC removal, while poly(**3a**) and poly(**4a**) turned into a random structure. Poly(**1a**) and poly(**2a**) underwent reversible transformation of helicity upon addition of *m*- and *o*-phthalic acids, followed by NaOH addition.

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