Synthesis of Helical Polyisocyanides Bearing Aza-Crown Ether Groups as Pendant

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Received 14 October 2017; accepted 19 November 2017; published online 00 Month 2017
DOI: 10.1002/pola.28919

ABSTRACT: We, herein, present a novel synthesis of responsive helical poly(aryl isocyanide)s bearing aza-crown ethers as pendant groups. Chiral aryl isocyanide monomers bearing an aza-crown ether as a pendant were designed and synthesized, piror to polymerization using a Pd-Pt μ-ethynediyl complex as an initiator to give the corresponding polymers in good yield. The resulting polyisocyanides adopted a stable helical structure in solution, as confirmed by circular dichroism spectroscopic analysis. In addition, the polymers were soluble in various solvents. Furthemore, the addition of suitable alkali metal ions to the crown ether of the sidechain on the helical polyisocyanide to form host-gest complexes resulted in deformation of the helix due to electrostatic repulsion, and these phenomena depended on the size of metal cations. © 2017 Wiley Periodicals, Inc. J. Polym. Sci., Part A: Polym. Chem. **2017**, *00*, 000–000

KEYWORDS: chiral; crown ether; helical polymer; molecular recognition; polyisocyanides; synthesis

INTRODUCTION Chiral helical polymers have received a great deal of attention in polymer chemistry, as naturally occurring polymers often form sophisticated helical structures. Such structures act as foundations for the construction of higher-ordered structures that often determine the characteristic functions of biomacromolecules. In artificial polymers, the precise synthesis of helical polymers has also been reported for the preparation of potential functional materials.[1–5] To date, various types of helical polymers have been synthesised,[6–9] for use in chiral catalysts,[10–12] and molecular recognition materials as well as in biomimetic applications.

In this context, polyisocyanides consist of an sp^2-hybridised carbon main chain and imino side groups, which can adopt a stable helical conformation in solution when bulky substituents are present.[13,14] Indeed, optically active helical polyisocyanides have been synthesized using chiral monomers and chiral initiators,[15–24] and have been widely applied in many fields.[25–31] In addition, we previously developed a living polymerization of aryl isocyanide using a Pd-Pt μ-ethynediyl complex (**I**)[32] as an initiator,[33,34] where polyisocyanides exhibiting predominantly one-handed helical structures were produced by polymerization of the isocyanide monomers with chiral groups.[35–38] As this polymerization system was applicable to a range of substituents, helical poly(aryl isocyanide)s bearing various functional groups have been synthesized.[39–41] For example, the polymerization was successful using a monomer bearing a bulky tetraphenyl porphyrin as a substituent,[39] and the porphyrin pendants were regularly arranged to form stacked columns through the helical main chain of the polyisocyanides. Additionally, intramolecular energy transfer from zinc-porphyrin to the free-base-porphyrins has also been observed.[42] As a result, novel properties that were not observed for simple monomers would be expected upon the expansion of this system.

Although these poly (aryl isocyanide)s conventionally form stable one-handed helical structures in solution, it is possible to alter their conformation by derivatization of the side chain. Indeed, we previously presented the synthesis of chiral poly(isocyanide)s bearing ferrocenyl pendants [Scheme 1(a)], which exhibited response towards oxidation of ferrocenyl groups through transformation from a stable helical structure to a disordered one through electronic stimulus of the ferrocenium cation.[41] Moreover, the conformational changes of polyisocyanides using external stimuli can be potentially applied not only in the area of stimulus-responsive polymers, but also in the synthesis of new type of novel types of polymers through the combination with conventional polyisocyanide functionalities. However, example of stimuli-responsive poly-isocyanides accompanied by structural change are limited due to the

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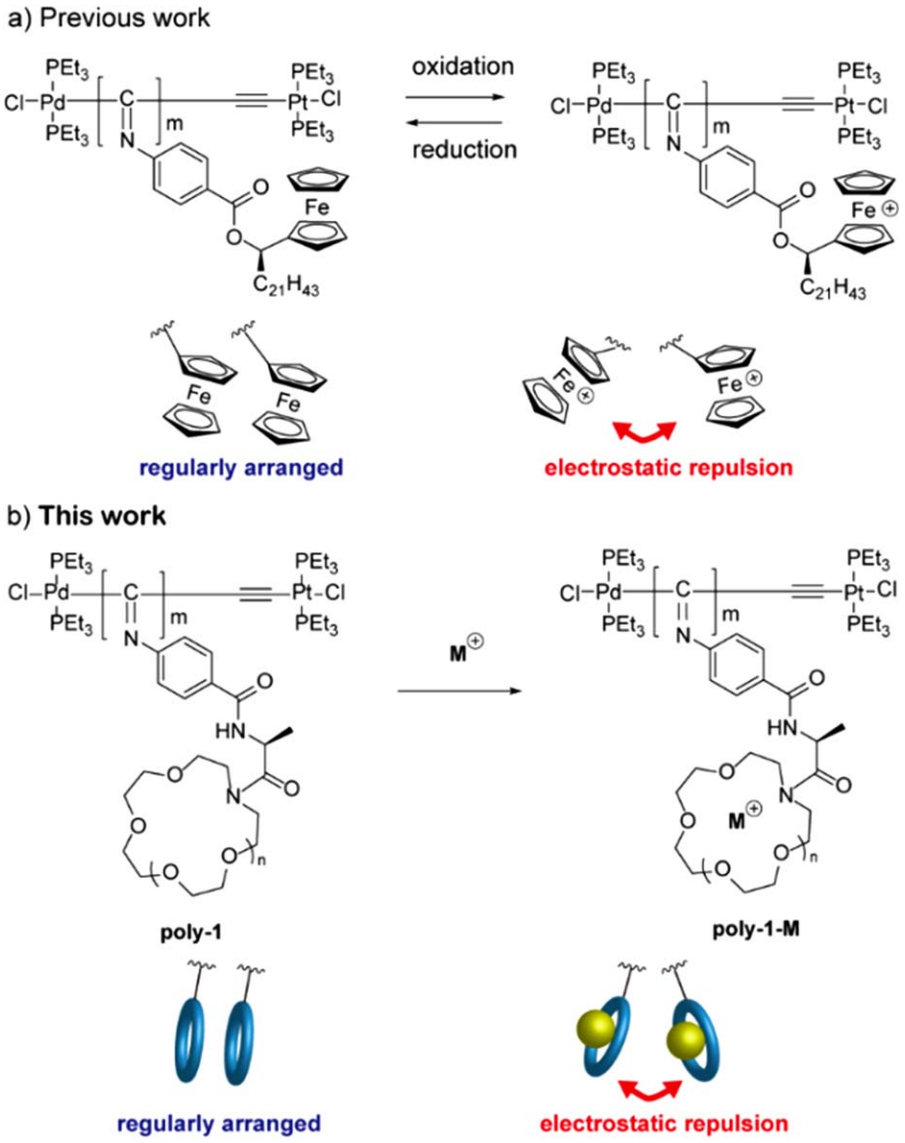


SCHEME 1 Responsive poly(arylisocyanode)s using (a) oxidation and (b) complexation with metal cation. [Color figure can be viewed at wileyonlinelibrary.com]

difficulty in synthesizing the polymer.[42] Thus, we herein present the synthesis of one-handed helical poly(aryl isocyanide)s bearing aza-crown ether groups as stimuli-responsive pendants. Furthermore, we demonstrate the response of the helical conformation of these novel chiral polymers to the addition of specific alkali metal ions [Scheme 1(b)].

EXPERIMENTAL

General

^{1}H and ^{13}C NMR spectra were recorded on JEOL GSX-400 and JEOL ECA-500 spectrometers. HR-MS measurement was carried out on PerkinElmer/Sciex Q-Star mass spectrometer. Polymerization progress was checked by size exclusion chromatography (SEC) equipped with TOSOH α-M using Shimadzu LC-6AD and Shimadzu SPD-10A UV–vis detector. DMF was used for eluting solvent, the flow velocity was configured to 0.8 mL/min, and the temperature was kept at 50 °C. IR spectra were measured on Shimadzu IR Prestage 21. CD and UV–vis spectra were measured on JASCO J-720WO and Shimadzu UV 3100PC, respectively.

Materials

1-Aza-15-crown-5 and 1-aza-18-crown-6 were commercially available. Pt-Pd dinuclear complex was prepared according to the literature.[32]

Synthesis of 1a

(S)-2-(Benzyloxycarbonylamino)-1-(1,4,7,10-tetraoxa-13-azacyclopentadecan-13-yl)propan-1-one (2a)

To a dry DMF solution (2 mL) of benzyloxycarbonyl-L-alanine (0.20 g, 0.91 mmol) and benzo-aza-15-crown-5 (0.20 g, 0.91 mmol) was added 4-(4,6-dimethoxy-1,3,5-triazin-2-yl)-4-methylmorpholinium chloride (DMT-MM) (0.416 g, 1.37 mmol) at room temperature. After the reaction mixture was stirred for

3 h, the suspended solution was filtrated. The filtrate was added to water and extracted with CH_2Cl_2 three times. The organic phase was washed with brine, then dried over Na_2SO_4, and concentrated. The residue was purified by alumina chromatography (CH_2Cl_2/MeOH = 20: 1) to give yellow oil (0.317 g, 82%).^{1}H NMR ($CDCl_3$, 500 MHz): δ 7.35–7.31 (m, 5H, Ph), 5.61 (d, 1H, J = 7.8 Hz, N—H), 5.11 (d, 1H, J = 12.3 Hz, CH_2Ph), 5.08 (d, 1H, J = 12.3 Hz, CH_2Ph), 4.74 (quart, 1H, J = 6.7 Hz, NCHCO) 3.98–3.46 (m, 20H, azacrown), 1.34 (d, 3H, J = 6.7 Hz, CHCH_3).

(S)-2-Amino-1-(1,4,7,10-tetraoxa-13-azacyclopentadecan-13-yl)propan-1-one (3a)

A methanol solution (20 mL) of **2a** (0.597 g, 1.4 mmol) and 10% Pd/C (0.075 g, 0.070 mmol) was stirred under 0.7 MPa atmosphere of H_2 overnight at room temperature. The mixture was filtrated with Celite. The solution was concentrated under reduced pressure to give colorless oil (0.317 g, 77%). ^{1}H NMR ($CDCl_3$, 400MHz): δ 3.90–3.35 (m, 20H, azacrown), 1.25 (d, 3H, J = 6.7 Hz, CHC**H$_3$**).

(S)-N-(1-(1,4,7,10-Tetraoxa-13-azacyclopentadecan-13-yl)-1-oxopropan-2-yl)-4-formamidobenzamide (4a)

To a dry DMF solution (1 mL) of **3a** (0.12 g, 0.41 mmol) and *p*-formamidobenzoic acid[14] (0.067 g, 0.41 mmol) was added DMT-MM (0.135 g, 0.49 mmol) at room temperature. After the reaction mixture was stirred overnight, the suspended solution was filtrated. The filtrate was added to water and extracted with CH_2Cl_2. The organic phase was washed with brine. After dried over Na_2SO_4, the solution was concentrated to give white solid (0.135 g, 76%). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.78 (d, 1H, J = 11.2 Hz, CHO, minor), 8.41 (d, 1H, J = 1.6 Hz, CHO, major), 7.82–7.78 (m, 2H, Ar, major and minor), 7.60 (d, 2H, J = 8.7 Hz, Ar, major), 7.17–7.13 (m, 1H, N—H), 7.09 (d, 2H, J = 8.7 Hz, Ar, minor), 5.12 (quart, 1H, J = 6.7 Hz, N—CH—CO), 3.95–3.57 (m, 20H, azacrown), 1.44 (d, 3H, J = 6.7 Hz, CHCH_3). ^{13}C NMR (CDCl3, 125 MHz): δ 173.6, 165.9, 162.1, 140.5, 128.8, 128.1, 119.2, 71.2, 70.6, 70.3, 70.1, 70.0, 70.0, 69.6, 69.0, 50.0, 49.4, 45.9, 19.0.

(S)-N-(1-(1,4,7,10-Tetraoxa-13-azacyclopentadecan-13-yl)-1-oxopropan-2-yl)-4-isocyanobenzamide (1a)

To a dry CH_2Cl_2 solution (18 mL) of **4a** (0.191 g, 0.44 mmol) was added dry Et_3N (0.5 mL, 3.6 mmol) and triphosgene (0.194 g, 0.65 mmol) with cooling in ice bath, and the reaction mixture was stirred for 1 h at room temperature under Ar atomosphere. After quenched with water, the solution was washed with $NaHCO_3$ aq and NaCl aq, successively. The organic layer was dried over Na_2SO_4, and concentrated. The residue was purified by alumina chromatography (CH_2Cl_2/MeOH = 200:1) to give brown oil (0.138 g, 76%). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.85 (d, 2H, J = 8.7 Hz, Ar), 7.43 (d, 2H, J = 8.7 Hz, Ar), 7.22 (d, 1H, J = 7.0 Hz, NH), 5.11 (quint, 1H, J = 7.0 Hz, NCHCO), 3.95–3.45 (m, 20H, azacrown), 1.45 (d, 3H, J = 7.0 Hz, CHCH_3). ^{13}C NMR ($CDCl_3$, 125 MHz): δ 173.16, 166.69, 164.51, 135.22, 129.00, 128.54, 126.66, 71.66, 70.89, 70.60, 70.42, 70.28, 70.25, 69.79, 69.27, 50.12, 49.60, 46.41, 19.39. IR: 3296 cm^{-1} (N—H), 2123 cm^{-1} (C≡N), 1651, 1633 cm^{-1} (C═O). HRMS (ESI): Calcd for $C_{21}H_{29}N_3NaO_6$ ([M + Na]$^+$): m/z 442.1954, Found: m/z 442.1959.

Synthesis of 1b

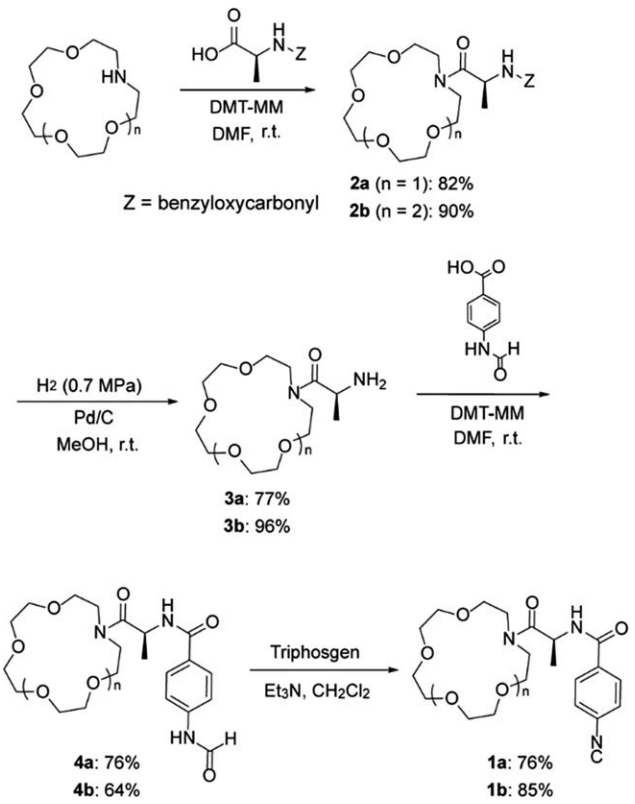
(*S*)-2-(Benzyloxycarbonylamino)-1-(1,4,7,10,13-pentaoxa-16-azacyclooctadecan-16-yl)propan-1-one (**2b**). To a dry DMF solution (10 mL) of benzyloxycarbonyl-L-alanine (2.20 g, 9.83 mmol) and 1-aza-18-crown-6 (2.59 g, 9.83 mmol) was added DMT-MM (3.26 g, 11.8 mmol) at room temperature. After the reaction mixture was stirred for 6 h, the suspended solution was filtrated. The filtrate was added to water and extracted with CH_2Cl_2 three times. The organic phase was washed with brine, then dried over Na_2SO_4, and concentrated. The residue was purified by alumina chromatography (CH_2Cl_2/MeOH = 20:1) to give yellow oil (3.74 g, 90%).^{1}H NMR ($CDCl_3$) δ: 7.35–7.29 (m, 5H, Ph), 5.61 (d, 1H, J = 7.8 Hz, N—H), 5.11 (d, 1H, J = 12.1 Hz, CH_2Ph), 5.07 (d, 1H, J = 12.1 Hz, CH_2Ph), 4.74 (quart, 1H, J = 7.1 Hz, NCHCO), 3.75–3.50 (m, 24H, azacrown), 1.35 (d, 3H, J = 6.7 Hz, CHCH_3).

(S)-N-(1-(1,4,7,10,13-Pentaoxa-16-azacyclooctadecan-16-yl)-1-oxopropan-2-yl)-4-formamidobenzamide (4b)

To a dry DMF solution (10 mL) of **3b** (2.25 g, 6.73 mmol) and *p*-formamidobenzoic acid[14] (1.11 g, 6.73 mmol) was added DMT-MM (2.23 g, 8.08 mmol) at room temperature. After the reaction mixture was stirred overnight, the suspended solution was filtrated. The filtrate was added to water and extracted with CH_2Cl_2. The organic phase was washed with brine. After dried over Na_2SO_4, the solution was concentrated to give white solid (2.12 g, 64%). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 8.78 (d, 1H, J = 11.3 Hz, CHO, minor), 8.42 (d, 1H, J = 1.4 Hz, CHO, major), 7.82–7.78 (m, 2H, Ar, major and minor), 7.61 (d, 2H, J = 8.6 Hz, Ar, major), 7.20–7.16 (m, 1H, N—H), 7.10 (d, 2H, J = 8.6 Hz, Ar, minor), 5.15 (quart, 1H, J = 7.2 Hz, NCHCO), 3.78–3.67 (m, 24H, azacrown), 1.45 (d, 3H, J = 6.7 Hz, CHCH_3). ^{13}C NMR ($CDCl_3$, 125 MHz): δ 172.9, 166.5, 164.3, 135.0, 128.7, 128.3, 126.4, 71.0, 70.7, 70.7, 70.7, 70.7, 70.6, 70.5, 70.4, 69.5, 69.4, 48.8, 46.8, 46.1, 19.1.

(S)-N-(1-(1,4,7,10,13-Pentaoxa-16-azacyclooctadecan-16-yl)-1-oxopropan-2-yl)-4-isocyanobenzamide (1b)

To a dry CH_2Cl_2 solution (15 mL) of **4b** (0.214 g, 0.43 mmol) was added dry Et_3N (0.15 mL, 1.1 mmol) and triphosgene (0.061 g, 0.22 mmol) with cooling over ice bath, and the reaction mixture was stirred for 1 h at room temperature under Ar atomosphere. After quenched with water, the solution was washed with $NaHCO_3$ aq and NaCl aq, successively. The organic layer was dried over Na_2SO_4, and concentrated. The residue was purified by alumina chromatography (CH_2Cl_2/MeOH = 200:1) to give brown oil (0.169 g, 85%). ^{1}H NMR ($CDCl_3$, 400 MHz): δ 7.85 (d, 2H, J = 8.5 Hz, Ar), 7.43 (d, 2H, J = 8.5 Hz, Ar), 7.21–7.23(m, 1H, J = 7.0 Hz, NH), 5.15 (quint, 1H, J = 7.0 Hz, NCHCO), 3.80–3.55 (m, 24H, azacrown), 1.47 (d, 3H, J = 7.0 Hz, CHCH_3). ^{13}C NMR ($CDCl_3$, 125 MHz): δ 172.9, 166.5, 164.3, 135.0, 128.7, 128.3, 126.4, 71.0, 70.7, 70.7, 70.7, 70.7, 70.6, 70.5, 70.5, 69.5, 69.4, 53.4,



SCHEME 2 Synthesis of isocyanide monomer **1**.

48.8, 46.8, 46.1. IR: 3296 cm^{-1} (N—H), 2123 cm^{-1} (C≡N), 1651, 1633 cm^{-1} (C═O). HRMS (ESI): Calcd for $C_{23}H_{33}N_3NaO_7$ ($[M + Na]^+$): m/z 486.2216, Found: m/z 486.2215.

Polymerization of 1a

To a dry THF solution (2 mL) of **1a** (135 mg, 0.32 mmol) was added Pt-Pd dinuclear complex (**I**) (2.8 mg, 3.2 μmol) under Ar atmosphere. The solution was stirred under reflux for 12 h. The solution was added to hexane to give yellow solid (90 mg, 66%). ^{1}H NMR (DMSO-d_6): δ 9.0–7.9 (broad, 1H, NH), 7.4–6.4 (broad, 2H, Ar), 4.8–6.2 (broad, 2H, Ar), 5.0–4.5 (broad, 1H, CH) 4.3–3.1 (broad, 20H, aza-crown ether moiety), 1.47 (broad, 3H, CH_3). IR (KBr, cm^{-1}): 3247 cm^{-1} (N—H), 1629, 1604 cm^{-1} (C═O), 1536 cm^{-1} (C═N).

Polymerization of 1b

To a dry THF solution (2 mL) of **1a** (94 mg, 0.20 mmol) was added Pt-Pd dinuclear complex (1.76 mg, 2.0 μmol) under Ar atmosphere. The solution was stirred under 55 °C for 12 h. The solution was added to hexane to give yellow solid (56 mg, 66%). ^{1}H NMR (DMSO-d_6): δ 9.0–7.9 (broad, 1H, NH), 7.8–6.5 (broad, 2H, Ar), 4.8–6.2 (broad, 2H, Ar), 5.0–4.5 (broad, 1H, CH), 4.3–3.1 (broad, 24H, aza-crown ether moiety), 1.51 (broad, 3H, CH_3). IR (KBr, cm^{-1}): IR (KBr, cm^{-1}): 3247 cm^{-1} (N—H), 1629, 1605 cm^{-1} (C═O), 1543 cm^{-1} (C═N).

CD and UV Spectra

UV and CD spectra were recorded on a JASCO J-720WO using 10 mm path length quartz cuvettes. Ten scans were averaged for each sample. $\Delta\varepsilon$ (mol L^{-1} cm^{-1}) was calculated using the equation:

$$\Delta\varepsilon = (4\pi \log e \times \theta_{obs} \times M_0) / (180l \times 1000c)$$

where θ_{obs} is the measured ellipticity in millidegrees, while M_0 is the molecular weight or molecular weight per unit in the polymer, l is path length in 10 mm, and c is the concentration of the sample.

Complexation of Poly-1 with Metal Cations

An acetonitrile solution of **poly-1** (1.95×10^{-6} M) and metal tetraphenyl borate (1.95×10^{-5} M) was heated at 50 °C in a sealed quartz cell with 10 mm optical path length and the spectra change was monitored by the UV and CD spectra.

RESULTS AND DISCUSSION

Crown ethers are cyclic oligo(ethylene oxide)s, that can form stable complexes with alkali metals or organic cations through ionic and dipole-dipole interactions.[43] The combination of helical polymers, such as poly(phenyl acetylene), and crown ethers has also been reported for the preparation of potential functional materials.[44–49] In our case, if crown ethers can be stably positioned based on a chiral helical structure, novel responsive chiral polymer could be create. We began to our study by designing the chiral isocyanide monomers bearing aza-crown ether groups (**1a** and **1b** in Scheme 2). As indicated synthetic route shown in Scheme 1, *N*-benzyloxycarbonyl-L-alanine was employed as the chiral source for condensation with two different sized aza-crown ethers in the presence with 4-(4,6-dimethoxy-1,3,5-triazin-2-yl)-4-methylmorpholinium chloride (DMT-MM) as the coupling reagent. The benzyloxycarbonyl (Z) groups of the protected amine on products **2a** and **2b** were deprotected in the presence of a Pd/C catalyst under 0.7 MPa H_2 to yield chiral amines **3a** and **3b.** Subsequent, condensation with *p*-formamidobenzoic acid in the presence of DMT-MM and dehydration of **4a** and **4b** using triphosgene in the presence of triethylamine to yield desired monomers **1a** and **1b**.

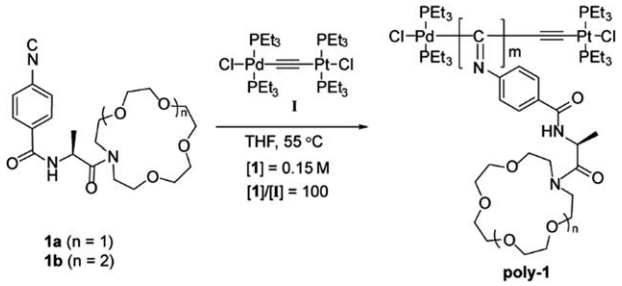
The polymerization of **1a** was carried out in the presence of Pd–Pt μ-ethynediyl complex (**I**) based on previously reported conditions; [**1a**] = 0.05 M, [**1a**]/[**I**] = 100, in THF at 55 °C.[36] However, after allowing the reaction to proceed 4 days, the monomer was not completely consumed (77% conv.) and both polymeric and oligomeric product were formed, and the further polymerization did not proceeded.[50] The concentration of **1a** was increased (0.15 M) and attempting the polymerization reaction under same conditions (see Table 1, entry 1), polymerization proceeded smoothly with 92% monomer conversion after 12 h to give the desired polymer with a unimodal profile, as determined by SEC in DMF (see Supporting Information). After purification by reprecipitation with hexane, the desired polymer (**poly-1a**) was obtained in 66% yield (M_w = 10,400, M_w/M_n = 1.26).[51] The polymerization of **1b** was attempted under the conditions of entry 1 to give the desired polymer (**poly-1b**) in 66% yield after

TABLE 1 Polymerization of Monomer 1 Using μ-Ethynediyl Pt-Pd Dinuclear Complex[a]

Entry	1	Solvent	Conv.[b] (%)	Yield (%)	M_w[c]	M_w/M_n[c]
1	**1a**	THF	92	66	10,400	1.26
2	**1b**	THF	80	66	6900	1.18

[a] I (3.0 μmol), 1 (0.30 mmol) in THF, [1] = 0.15 M, [1]/[I] = 100.
[b] Estimated by the peak area ratio of SEC.
[c] Estimated by SEC analysis using polystyrene standard.

purification (entry 2). Both polymers were soluble in water and in common organic solvents, such as toluene, dichloromethane, THF, acetonitrile, and methanol.



UV and CD Spectra

To determine the architecture of the obtained polymers, UV absorption and circular dichroism (CD) measurements were carried out. As shown in Figure 1, the CD spectrum of **poly-1a** in $CHCl_3$ at 25 °C exhibited a negative Cotton effect at 365 nm ($\Delta\varepsilon_{365} = -13.6$), which is characteristic of helical chiral poly(aryl isocyanide)s and is assignable to the n-π^* transition of the imino chromophore. A similar Cotton effect was also observed for **poly-1b** ($CHCl_3$, 25 °C). The helical senses of these poly(arylisocyanide)s were determined based on the exciton-coupled CD of the porphyrin chromophores;[40] therefore, this negative Cotton effect at 365 nm confirms that the poly(aryl isocyanide)s adopted a left-handed helical structure. Previously, Yashima and coworkers reported the polymerization of phenyl isocyanide bearing an L-alanine pendant with a long *n*-decyl chain using a Pt–Pd catalyst to produce almost completely right- and left-handed helical polyisocyanides with different molecular weights, where each single-handed helical polymer was separated by facial solvent fractionation.[52] Based on their studies, helical-sense excess (ee_h)[53,54] value were estimated to be 66% ee_h and 70% ee_h for **poly-1a** and **poly-1b**, respectively, which indicated that these polymers contain both right- and left-handed helices with different molecular weights. Indeed, **poly-1a** and **poly-1b** gave relatively higher molecular weight distributions, similar to that of Yashima's polymer, immediately after polymerization. However, it was not possible to separate **poly-1** into its two individual helical structures. Subsequent experiments were therefore conducted using **poly-1** without further purification.

Temperature and Solvent Dependence of CD Spectra

The temperature dependence of the CD spectra of **poly-1a** was examined to investigate the stability of the polymer. The UV and CD spectra of **poly-1a** at 0–75 °C are shown in Figure 2(A). The intensity of the Cotton effect at 365 nm was slightly decreased (ca. 10%) at higher temperature (50 and 75 °C), and the UV spectra were not changed. Additionally, these transitions are completely reversible. Probably, the phenomena was showed the conformational fluctuations of flexible terminal moiety of the **poly-1a** and mainly adopted the proposed helix conformation. Additionally, we also investigated the solvent effect of **poly-1a**. As shown in Figure 2(B), the CD spectra of **poly-1a** exhibited a noticeable solvent effect, although UV spectra was not changed. The intensity of the Cotton effect on 365 nm in the presence of different solvents, it was apparent that the helical structure of the poly(aryl isocyanide)s was altered to varying extent (i.e., toluene < $CHCl_3$ ≈ THF < acetonitrile < DMF < methanol) based on the value of Hildebrand solubility parameters of the solvents examined [Fig. 2(C)].[55] This indicates that the solubility of solvents with the crown ethers present on the side chains influences the helical conformation. As crown ethers are relatively flexible in solution, their bulkiness can be altered based on their affinity to any specific solvent. Such transformations likely influence the helical structure through changes in the main chain configuration (syn-anti isomerization of the imino groups (Chart 1).[26]

Effect of a Cationic Guest on the Helical Conformation

To investigate the effect of cationic guest on the helical conformation of **poly-1**, the addition of various metal cations was examined. Following the addition of sodium tetraphenylborate ($NaBPh_4$) to an acetonitrile solution of **poly-1a** ([$NaBPh_4$]/[crown ether of **poly-1**] = 10, [$NaBPh_4$] = 1.4×10^{-2} M), CD measurements were recorded. As shown in Figure 3(A), the initial CD spectrum was comparable intensity to that of the original spectrum of **poly-1a**. However, upon warming the solution to 50 °C, the CD spectrum slowly changed, and the CD intensity (θ_t) of the Cotton effect around 365 nm decreased with time, despite the negligible

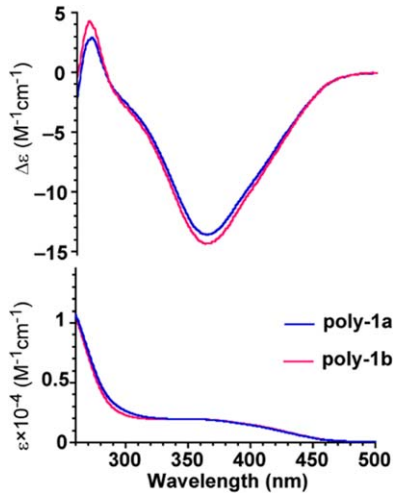


FIGURE 1 CD and UV spectra of **poly-1a** (0.10 mM) and **poly-1b** (0.10 mM) in $CHCl_3$ at 25 °C. [Color figure can be viewed at wileyonlinelibrary.com]

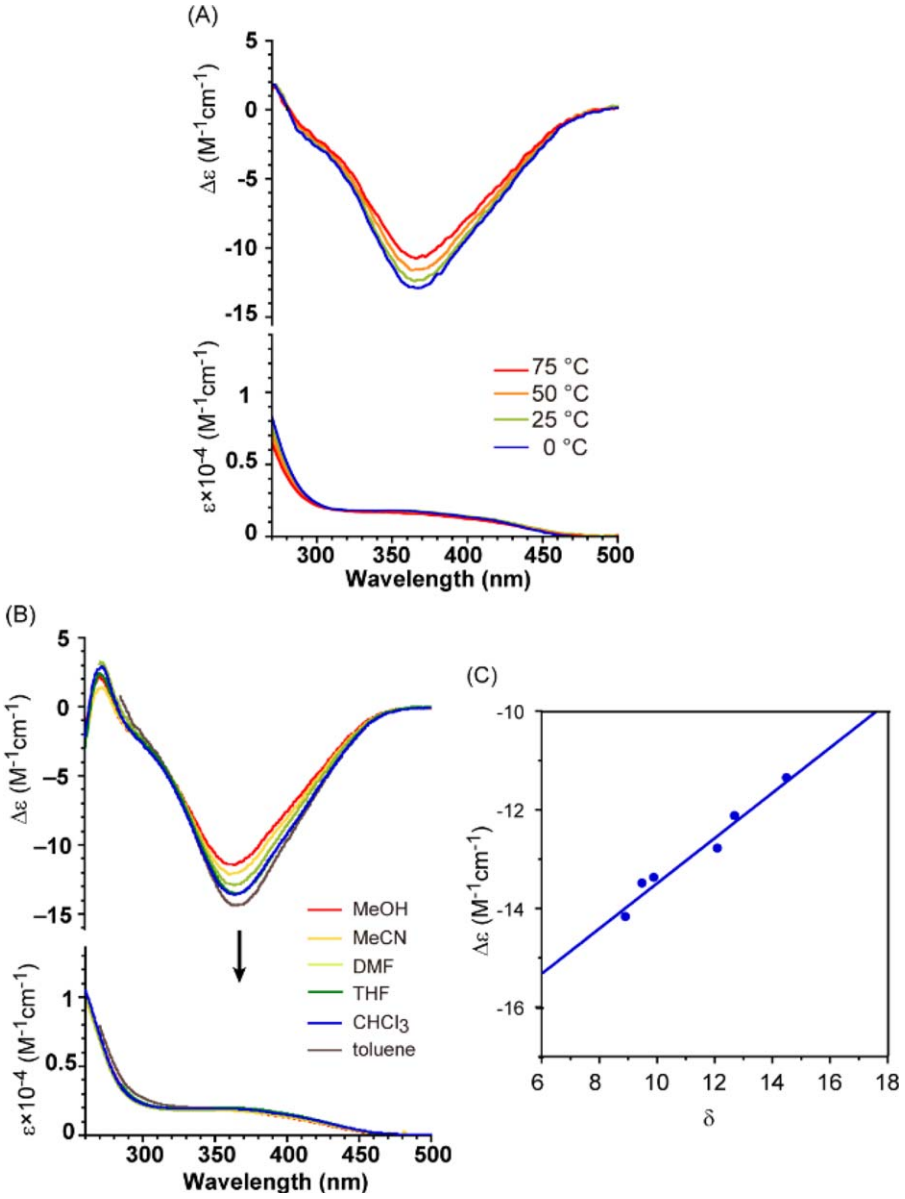


FIGURE 2 CD and UV spectra of (A) temperature dependence of **poly-1a** (0.10 M) in $CHCl_3$ and (B) effect of the solvent of **poly-1a** (0.10 M) at 25 °C, and (C) plots of Hidebrand solubility parameter (δ) dependence change of the CD intensity at 365 nm. [Color figure can be viewed at wileyonlinelibrary.com]

changes in absorption [Fig. 3(A)]. After 360 h, θ_{360} reached 67% ($\theta_{360}/\theta_0 \times 100$) of the initial value ($\theta_0$). In contrast, in the absence of the metal salt, the change was less significant ($\theta_{360}/\theta_0 \times 100 = 91\%$). In addition, this phenomenon was found to depend on the type of the cation employees [Fig. 3(B)]. More specifically, when $KBPh_4$ or $CsBPh_4$ were employed, the CD intensities decreased, but to a lesser extent than for $NaBPh_4$ [Fig. 3(B,C)]. These results indicate that the aza-15-crown ether groups of **poly-1a** can selectively complex with sodium cations to induce dramatic changes in the CD spectra. In addition, it appears that the helical structure of **poly-1a** partially collapses due to electrostatic repulsions between the side chains bearing the cation-aza-15-crown ether complexes (Fig. 4). Indeed, Yashima and coworkers reported interconversion of the helical structures of poly(aryl isocyanide)s via syn-anti configuration isomerization around the C═N bonds (Chart 1). In this case, the initial helical structure of **poly-1a** was in its kinetically controlled conformation following the polymerization, and this conformation changed to the more thermodynamically controlled structure[56,57] due to

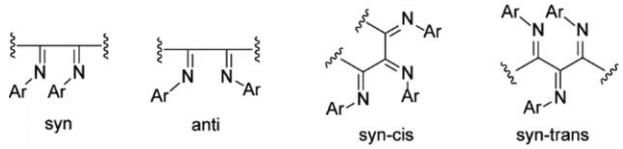


CHART 1 Stereoregularity in polyisocyanide.

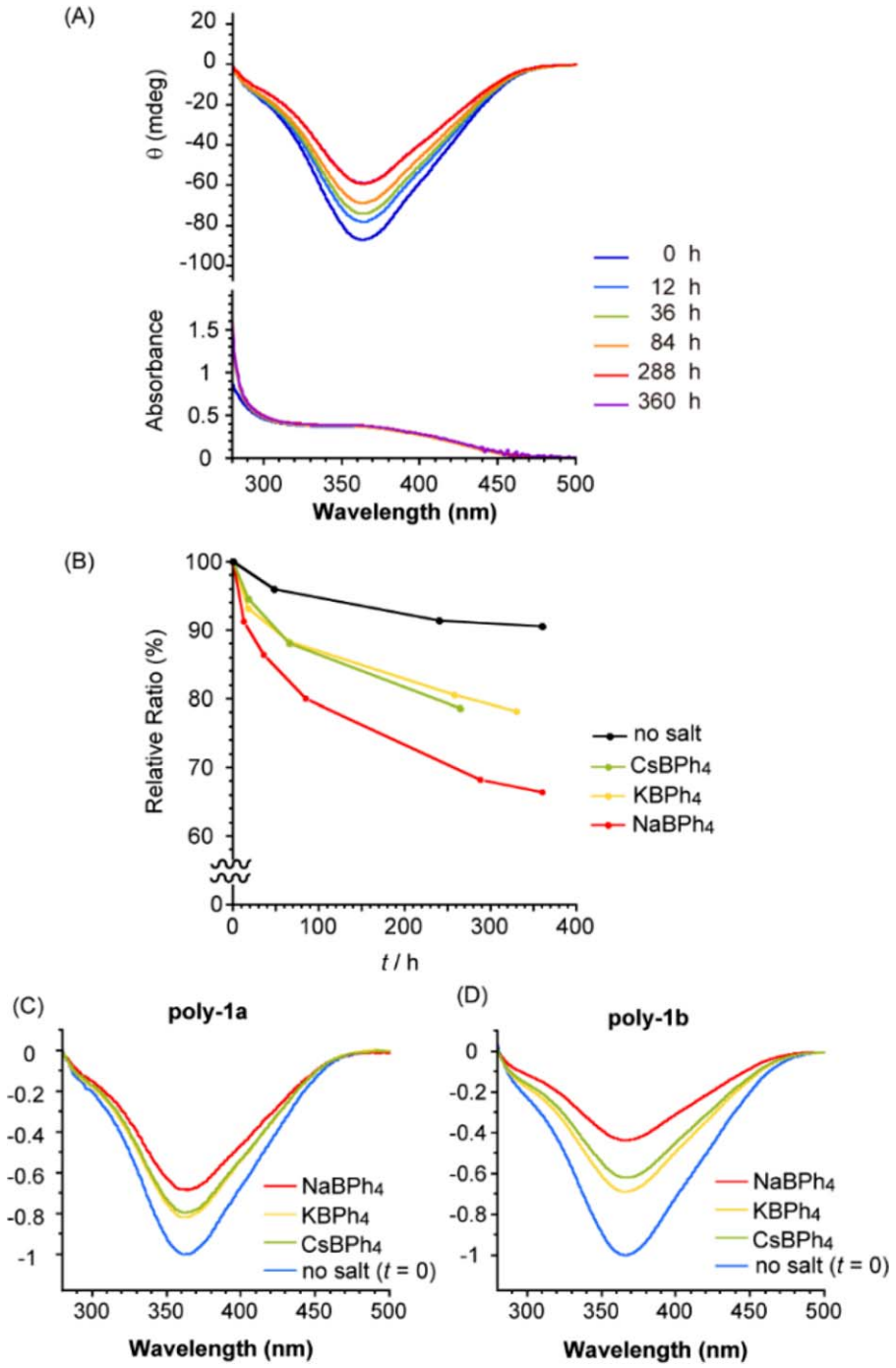


FIGURE 3 (A) Change in the CD spectra of the **poly-1a** (0.10 mM) with $NaBPh_4$ in acetonitrile at 25 °C. (B) Change in the CD intensity ($\theta_t/\theta_0 \times 100$) of **poly-1a** with $NaBPh_4$, $KBPh_4$, and $CsBPh_4$ in acetonitrile at 365 nm. (C) Change in the CD spectra of **poly-1a** with $NaBPh_4$, $KBPh_4$, and $CsBPh_4$ after 10 days, and initial polymer ($t = 0$) in acetonitrile at 25 °C. (D) Change in the CD spectra of **poly-1b** with $NaBPh_4$, $KBPh_4$, and $CsBPh_4$ after 10 days, and initial polymer ($t = 0$) in acetonitrile at 25 °C. The spectra of (C) and (D) are normalized on the basis of the CD intensity on 365 nm of initial polymer. [Color figure can be viewed at wileyonlinelibrary.com]

the both electrostatic repulsions between the metal cationic complexes of the crown ethers and to syn-anti isomerization at high temperatures. As the interconversion of **poly-1a** is slow in the absence of cationic salts even when heat is applied [Fig. 3(B)], it is apparent that electrostatic repulsions of the side chains is necessary to meet the required activation energy for the conformational change.[26] Similar experiments were also conducted using **poly-1b**, which has a larger aza-crown ether ring size, that is, aza-18-crown. In this case, a decrease in the CD intensities compared to that of the initial polymer was also observed for all cations, with the largest change being observed for the sodium cation. These results differ from the

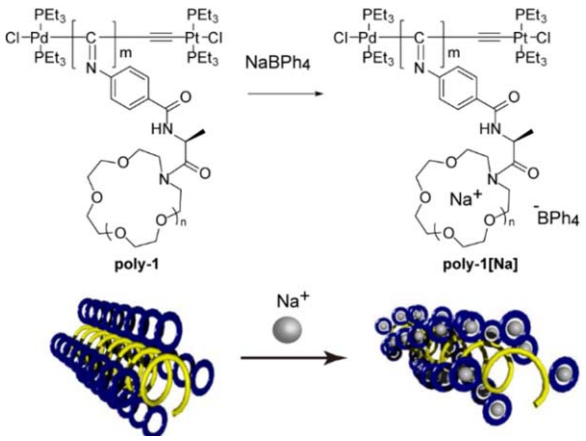


FIGURE 4 Chemical structures of **poly-1** and **poly-1[Na]** and a schematic illustration of the helical structure of **poly-1** and its partial collapse due to electrostatic repulsions between the sodium cations and the aza-15-crown ether moiety upon complex formation. [Color figure can be viewed at wileyonlinelibrary.com]

normal complex formation tendencies of 18-crown-6 macrocycles ($K > Na \approx Cs$).[58] However, such tendencies are known to change when the aza-crown ether bears a bulky substituent on the nitrogen atom. In the case of *N*-9-anthrylaza-18-crown ethers, a considerably higher affinity is displayed for the sodium cation compared to the potassium cation.[59] As the metal cation is situated one side of the macrocyclic cavity remote from the nitrogen atom due to conformational constraints, it is coordinated only to the oxygen atoms of the crown ether moiety. As such, the binding properties of **poly-1b** are affected by steric hindrance on the nitrogen atom of aza-crown ether.

CONCLUSIONS

In conclusions, we successfully designed and synthesized new type of responsive helical poly(aryl isocyanide)s bearing aza-crown ether pendants using a Pd-Pt μ-ethynediyl complex. Following the efficient preparation of the chiral isocyanide monomer using the benzyloxycarbonyl-L-alanine as the chiral source, polymerization of the chiral isocyanide bearing aza-crown ether groups proceeded smoothly despite the presence of this bulky aza-crown ether moiety. Examination of the circular dichroism spectra of the resulting polymers showed negative Cotton effect assignable to the n-π^* transition of the imino chromophore, which suggested these polymers adopted a left-handed helical conformation in solution. In addition, the resulting polymers were soluble in a range of solvents. Furthermore, the addition of suitable alkali metal ions to the crown ether moiety of the helical polyisocyanide side chain to form host-gest complexes resulted in deformation of the helix due to electrostatic repulsion. These results indicate that the stable positioning of crown ethers on chiral helical structure for the preparation of novel polymer materials is possible, and we expected that such systems could be applied in chiral catalysts and molecular recognition materials. Further study of this approach is now in progress.

ACKNOWLEDGMENTS

This work was supported by a grant-in-aid for JSPS KAKENHI Grant number JP16K21154 (N.K) and JP21350065 (K.O), and the Kyoto Technoscience Center. The authors thank the group of Takahiro Sato (Osaka University) for CD measurement.

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