# Concise *Click*/ESA-CF Synthesis of Periodically-Positioned Trifunctional *kyklo*-Telechelic Poly(THF)s

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Ⓢ *Supporting Information*

ABSTRACT: A concise two-step *click*/ESA-CF process has been developed to prepare a *kyklo*-telechelic poly-(tetrahydrofuran), poly(THF), having three functional groups at the constant intervals. Thus, a key linear precursor (**I**), having *N*-phenylpyrrolidinium salt groups at the chain ends and having two hydroxyl groups at the prescribed inner positions, has been prepared through the alkyne−azide addition (*click*) reaction using one unit of a linear telechelic poly(THF) having a pair of an alkyne and a hydroxyl groups (**1**) and two units of a linear asymmetric telechelic poly(THF) having an azide and an *N*-phenylpyrrolidinium salt group (**2**). The subsequent polymer cyclization by means of an *electrostatic self-assembly and covalent fixation* (ESA-CF) process, by employing a dicarboxylate counteranion having an additional alkyne group (**3**) to **I**, could produce a trifunctional *kyklo*-telechelic poly(THF) (**II**), having two hydroxyl and one alkyne groups positioned at the constant intervals along the ring polymer backbone. The subsequent esterification of the hydroxyl groups in **II** was performed to give a *kyklo*-telechelic poly(THF) having three alkyne groups at the constant intervals (**III**), and a further *click* reaction of **III** with **2** was conducted to produce a ring polymer product having three emanating graft segments at the constant intervals along the ring unit (**IV**), i.e., a three-tail tadpole topology.
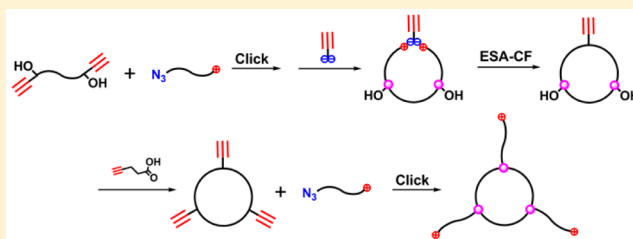
INTRODUCTION

Cyclic polymers are unique in their architectures by their elimination of chain termini in contrast to their linear and branched counterparts.[1−4] A remarkable progress has been witnessed in a recent decade to afford a wide range of *single* cyclic polymers, relied on innovated end-to-end intramolecular linking processes,[5−8] as well as on alternative new ring-expansion polymerizations.[9−13] And with the use of newly synthesized cyclic polymers having diverse chemical compositions, unprecedented properties and functions by cyclic polymer topologies have now been revealed.[1,4,14]

A current synthetic challenge in this growing area has focused on the precision design of cyclic/linear and cyclic/branched as well as multiple cyclic polymer architectures.[1,15] A class of tailored *cyclic and multicyclic* polymer precursors having prescribed reactive groups at designated location (positions), i.e., *kyklo*-telechelics, are crucially important to achieve any ambitious synthetic goals.[1,16,17] We have so far reported a wide variety of *kyklo*-telechelics having either hydroxyl, alkenyl, alkynyl, or azide groups based upon an *electrostatic self-assembly and covalent fixation* (ESA-CF) protocol,[1,18] where linear or branched prepolymers possessing prescribed cyclic ammonium salt end groups, accompanying plurifunctional carboxylate counteranions having additional functional groups, have been employed as key intermediates.

Notably, moreover, the precise positional control of not only single but also plural functional groups in the *kyklo*-telehelics is a critical prerequisite for the step toward tailored construction of complex polymer topologies. A simple ring polymer having

ONE functional group at the prescribed position, as well as those having TWO identical or different functional groups at the opposite positions of the ring structure, are readily accessible by the ESA-CF protocol, by using a center-fuctional linear polymer precursor (*kentro*-telechelics) obtained with a bifunctional initiator having an additional functional group.[19] A class of a *spiro*-dicyclic (8-shaped) and a *spiro*-tricyclic (trefoil-shaped) polymer precursors, having ONE functional group specifically at the core position, has also been introduced and used to produce a double-eight and a double-trefoil polymers.[16]

Furthermore, a series of tandem *spiro*-dicyclic (8-shaped), *spiro*-tricyclic and *spiro*-tetracyclic polymer precursors having TWO functional (alkenyl) groups at the opposite positions of the multiply linked ring units have been designed upon the ESA-CF protocol, and employed for the construction of tri-, tetra, and even pentacyclic multiply-*fused* polymer topologies.[20−22] Also, a new *kyklo*-telechelics having THREE functional (azide) groups positioned at the constant intervals in the ring backbone segment was recently introduced by an iterative alkyne−azide *click* addition reaction.[23] This trifunctional *kyklo*-telechelics was employed for the subsequent construction of *spiro*-type tetra- and heptacyclic polymer topologies, where a set of end-group transformation processes, i.e., the azidation of bromoalkyl group and the deprotection of alkyne group on the linear polymer precursors, was applied
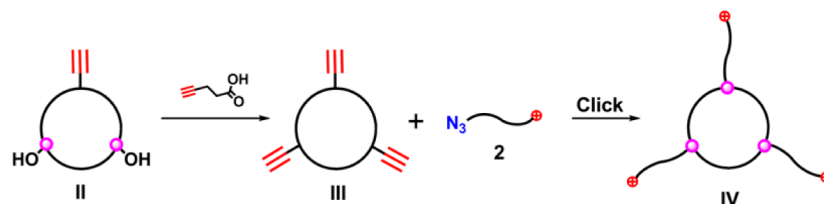
Scheme 1. Synthesis of a Periodically-Positioned Trifunctional *kyklo*-Telechelic Poly(THF) by an Orthogonal Click/ESA-CF Process
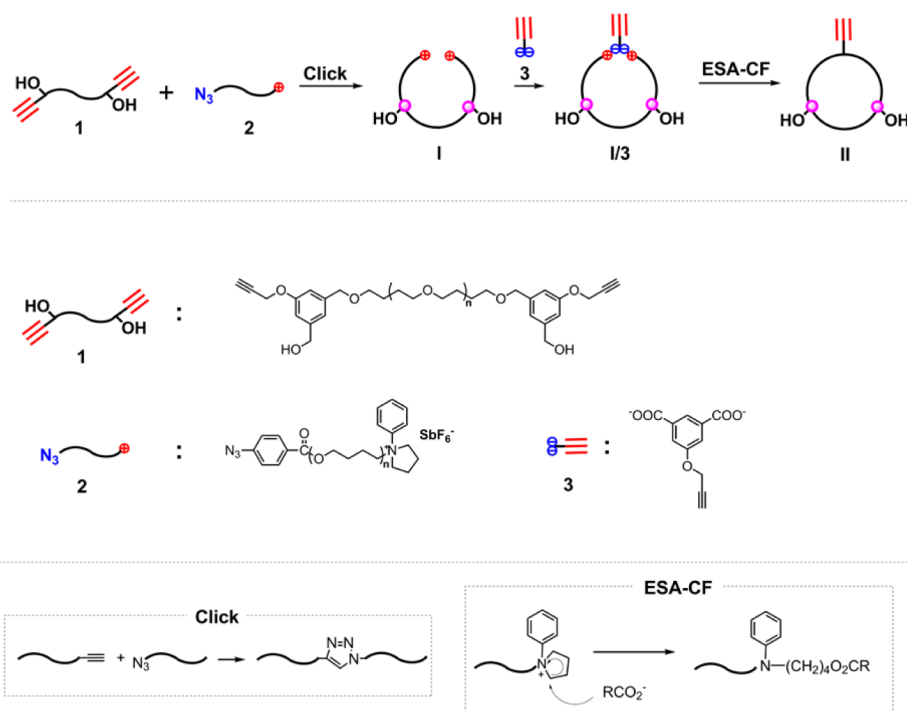
Scheme 2. Reactions of a Periodically-Positioned Trifunctional *kyklo*-Telechelic Poly(THF)

repeatedly to undergo the *click* chain extension as well as the final *click* polymer cyclization.[23]

We report herein an alternative and concise synthetic means to give the *kyklo*-telechelics having THREE functional groups at the constant intervals, which will be used for the precision synthesis of a variety of complex multicyclic polymers. Thus, we have employed an orthogonal *click*/ESA-CF process,[17] by utilizing a key linear precursor (I) having an *N*-phenyl-pyrrolidinium salt groups at the chain ends and two hydroxyl groups at the prescribed inner positions. (Scheme 1) The alkyne−azide *click* reaction was applied to obtain I by using a pair of complementary precursors, namely one unit of a linear telechelic poly(THF) precursor having a set of an alkyne and a hydroxyl groups (1) and two units of a linear asymmetric telechelic poly(THF) precursor having an azide and a cyclic ammonium salt groups (2). The subsequent polymer cyclization of I with the ESA-CF process, by introducing a dicarboxylate counteranion having an additional alkyne group (3) by the ion-exchange reaction, could afford a trifunctional *kyklo*-telechelic poly(THF) (II) having two hydroxyl and one alkyne groups positioned at the constant intervals along the ring polymer backbone.

The synthetic potential of II has subsequently been demonstrated first by the esterification of the hydroxyl groups in II by 4-pentynoic acid to give a *kyklo*-telechelic poly(THF),

III, having three alkyne groups at the constant intervals, and further by the *click* reaction of III with 2 to give a ring polymer product having three emanating segment along the ring unit, IV, i.e., a three-tail tadpole topology. (Scheme 2)

■ **RESULTS AND DISCUSSION**

1. Synthesis of a Periodically-Positioned Trifunctional *kyklo*-Telechelic Poly(THF). A pair of complementary reactive telechelic poly(THF) precursors, 1 and 2, have been introduced in this study for the subsequent use in a *click*/ESA-CF protocol. The prepolymer 1, having a set of alkyne/hydroxyl groups at the both chain ends, was obtained by the end-capping reaction of a living bifunctional poly(THF) with an excess of sodium alcolate of 1-proprgyloxy-3,5-bis-(hydroxymethyl)benzene. (Scheme S1) The prepolymer 2, having an azide and an *N*-phenylpyrrolidinium group at each chain end, was prepared by the end-capping of a monofunc-tionally living poly(THF), initiated with a 4-azidobenzoyl chloride/AgSbF₆ system, with *N*-phenylpyrrolidine. (Scheme S1)

The ¹H NMR analysis of 1 and 2 (Figure 1, top and bottom, respectively) showed the alkyne end group signal at 2.53 ppm for the former and the azidophenyl and *N*-phenylpyrrolidinium signals at 7.07/8.03 and at around 2.1−2.5 ppm for the latter, respectively. The MALDI−TOF mass spectra of 1 and 2, after
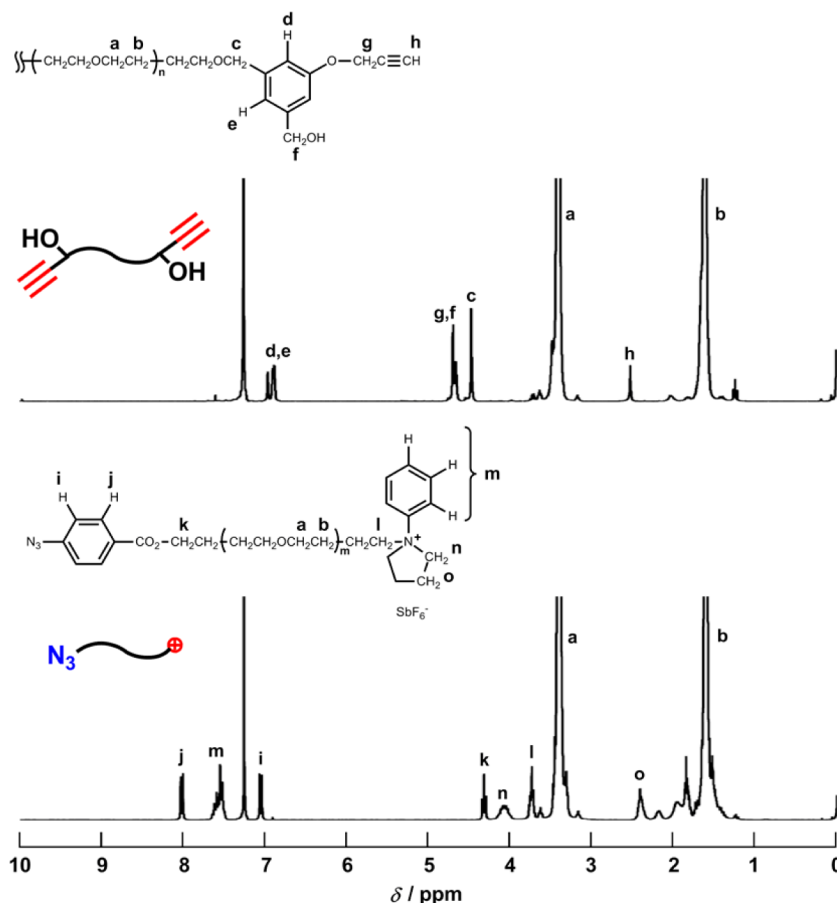
Figure 1. ^{1}H NMR spectra of (top) a poly(THF) having a pair of an alkyne and an hydroxyl end groups, **1**, and (bottom) a poly(THF) having an *N*-phenylpyrrolidinium salt and an azide end groups, **2** (300 MHz, CDCl$_3$, 40 °C).

the covalent conversion of pyrrolidinium group with benzoate anions, (Figure 2, top and bottom, respectively) showed a uniform series of peaks with an interval of 72 mass units corresponding to repeating THF units. Moreover, each peak exactly matched the total molar mass of the expected products having the corresponding end groups. Thus, the peak at m/z = 2553.6 corresponds to the expected chemical structure of **1** as the Na$^+$ adduct with a DP$_n$ of 30; (C$_4$H$_8$O) × 30 + C$_{22}$H$_{22}$O$_5$ plus Na$^+$ = 2552.62. Also, the peak at m/z = 2599.2, again assumed to be the adduct with Na$^+$, corresponds to the expected chemical structure of the covalent conversion derivative of **2** with a DP$_n$ of 30; (C$_4$H$_8$O) × 30 + C$_{24}$H$_{22}$N$_4$O$_3$ plus Na$^+$ = 2600.67.

We managed to obtain the listed MALDI−TOF mass spectrum of **2**, in particular, and those in Figure 5 shown later, which exhibited sufficient resolution to determine accurately the peak mass values for their characterization, after several attempts to optimize the MALDI−TOF measurement conditions. We could presume that the presence of a trace amount of contamination including SbF$_6$ anions, initially introduced as counteranions of cyclic ammonium salt end groups of telechelic precursors (the product **2**, Figure 2, bottom), might cause adverse effects on the ionization process in MALDI−TOF condition, as the relevant counterparts derived from CF$_3$SO$_3$ anions (the product **1**, Figure 2, top) gave comparatively well-resolved MALDI−TOF spectra.

The SEC examination indicated that the prepolymer, **1**, recovered just after the reaction, contained a noticeable portion of the higher MW fraction (the broken line in Figure 3A), and

was subjected to the preparative SEC fractionation technique for the purification (the solid line in Figure 3A, M_p = 2700 and PDI = 1.25). The SEC analysis of **2**, performed after the covalent conversion of pyrrolidinium group with benzoate anions, confirmed the comparable MW (M_p = 3200 (PDI = 1.17) against the prepolymer **1**. (Figure 3, B)

A pair of the complementary reactive prepolymers **1** and **2** were then subjected to the alkyne−azide *click* reaction in the presence of CuSO$_4$ and sodium ascorbate in THF/water, where 20 % molar excess of **2** was charged relative to **1** to complete the reaction. Notably, *N*-phenylpyrrolidinium salt groups in **2** were retained intact in the course of the reaction. After the column chromatography purification with silica gel, a linear polymer product, **I**, having two hydroxyl groups at the constant intervals in the interior positions and having two *N*-phenyl-pyrrolidinium salts end groups, was recovered. (Scheme 1)

The ^{1}H NMR analysis of **I** (Figure 4, top) confirmed the selective *click* addition reaction between the alkyne groups in **1** and the azide group in **2**. Thus, the signals assigned to the ethynyl proton (2.53 ppm) and to the propynyl methylene protons (4.70 ppm) in **1** were removed and the new signal was emerged at 5.31 ppm assignable to the methylene protons on the triazole ring unit. The IR analysis (Figure S1) showed that the azide absorption at 2094 cm^{-1} observed in the precursor **2** became scarcely visible in the product, **I**, indicating that the *click* reaction proceeded effectively.

In order to complete the MALDI−TOF mass and SEC characterization of the product **I**, the covalently converted derivative was prepared by the ring-opening reaction of the *N*-
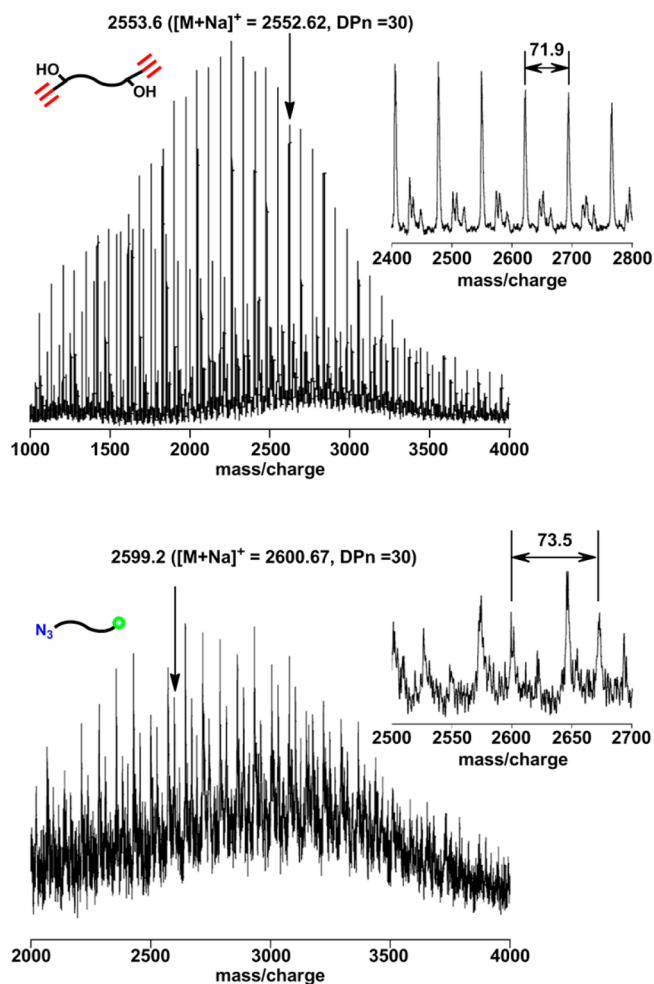
Figure 2. MALDI–TOF mass spectra of (top) a poly(THF) having a pair of an alkyne and an hydroxyl end groups, **1**, and (bottom) a poly(THF) having an *N*-phenylpyrrolidinium salt and an azide end groups, **2**, measured after the ring-opening reaction of the *N*-phenylpyrrolidinium salt group by a benzoate anion (linear mode, dithranol with sodium trifluoroacetate as a matrix. DP_n denotes the number of monomer units in the products).

phenylpyrrolidinium salt groups with a benzoate anion. The ^{1}H NMR analysis (Figure S2) confirmed the effective covalent conversion of the end groups in **I**, with the signal of ester methylene protons visible at 4.25 ppm, together with the signals of *N*-phenyl protons on the dialkyl amine unit at around 6.6 and 7.2 ppm, instead of the *N*-phenyl protons on the pyrrolidinium group at around 7.6 ppm observed before the reaction.

The MALDI–TOF mass spectra of **I** after the covalent conversion the pyrrolidinium end groups (Figure 5, top) showed uniformly separated peaks with an interval of 72 mass units corresponding to repeating THF monomer units. Moreover, each peak corresponded exactly to the total molar mass of the expected products having the respective end/interior groups. Thus, the observed peak at m/z = 7707.6 corresponds to the covalently converted derivative of **I** as the Na$^+$ adduct with a DP_n of 90; $(C_4H_8O) \times 90 + C_{70}H_{66}N_8O_{11}$ plus Na$^+$ = 7707.99.

The subsequent SEC comparison of the covalent conversion product from **I** with the starting precursors, i.e., **1** and the covalent conversion product from **2**, (Figure 3, chart C against
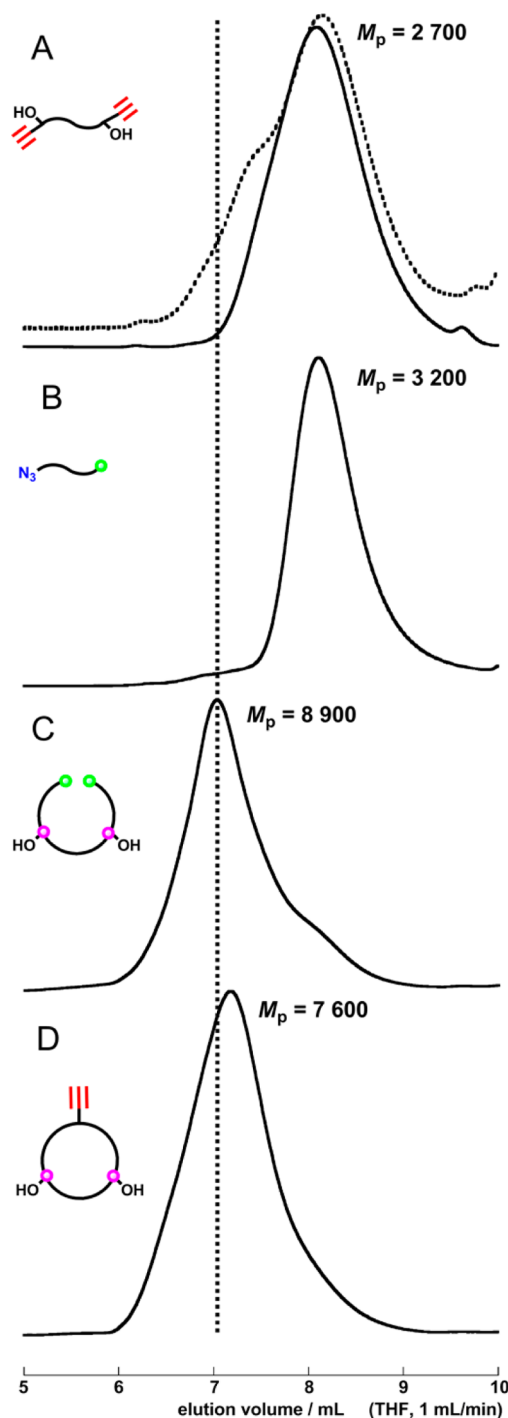

Figure 3. SEC traces of [A] a poly(THF) having a pair of an alkyne and an hydroxyl end groups, **1**, (Broken and sold lines show those obtained before and after SEC fractionation, respectively.) [B] a poly(THF) having an *N*-phenylpyrrolidinium salt and an azide end groups, **2**, measured after the ring-opening reaction of the *N*-phenylpyrrolidinium salt group by a benzoate anion, [C] an alkyne–azide click reaction product, **I**, from **1** and **2**, measured after the ring-opening reaction of the *N*-phenylpyrrolidinium salt groups by a benzoate anion, and [D] a trifunctional *kyklo*-telechelic polymer having two hydroxyl and one alkyne groups positioned periodically along the ring polymer backbone, **II**, obtained by the ESA-CF process with **I**, after introducing a dicarboxylate counteranion having an additional alkyne group, **3** (THF as an eluent with the flow rate of 1.0 mL/min, using a column of TSK G4000HXL).
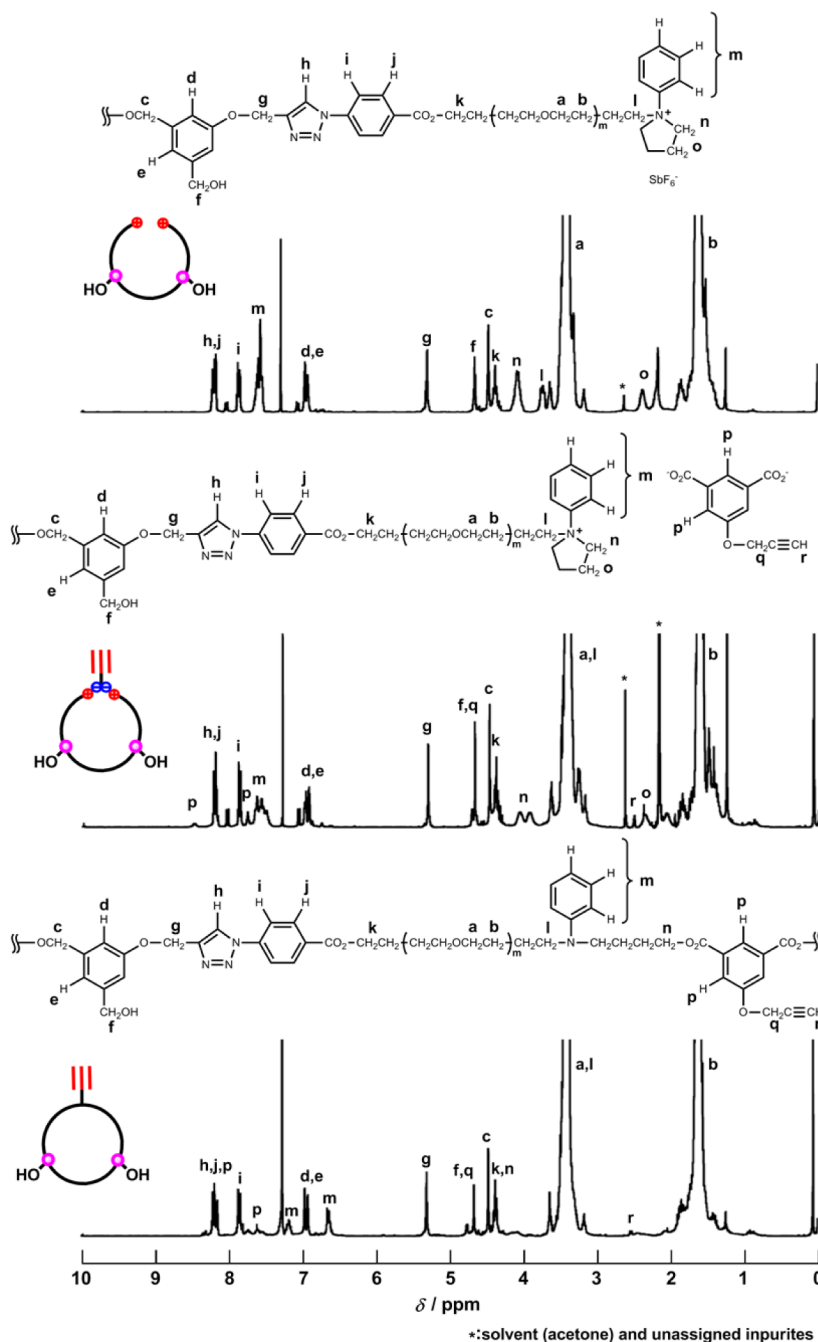
Figure 4. ^{1}H NMR spectra of (top) a poly(THF) having an *N*-phenylpyrrolidinium salt group at the chain ends and having two hydroxyl groups at the interior positions, **I**, (middle) a telechelic precursor having a dicarboxylate counteranion with an additional alkyne group, **I/3**, and (bottom) a trifunctional *kyklo*-telechelic polymer having two hydroxyl and one alkyne groups positioned periodically along the ring polymer backbone, **II** (300 MHz, CDCl$_3$, 40 °C).

charts A and B) showed a noticeable peak shift toward the higher molecular weight region to indicate the effective *click* linking reaction between **1** and **2**. Thus, the peak molecular weight for the covalent conversion product from **I** (M_p = 8900, PDI = 1.36) was close to the total sum (9100) of the corresponding M_p of **1** (M_p = 2700) and twice that of **2** (M_p = 3200).

The linear telechelic precursor, **I**, initially accompanying SbF$_6$ counteranions on two *N*-phenylpyrrolidinium salt end groups, was subsequently employed for the ESA-CF procedure after the introduction of a dicarboxylate counteranion having an additional alkyne group, **3**. (Scheme 1) In this ion-exchange

reaction, we employed a stepwise rather than a direct process first from the SbF$_6$ anion to chloride anion by the treatment with brine, to facilitate the subsequent introduction of a dicarboxylate counteranion.[1] Thus, the precipitation of the acetone solution of the pretreated **I** was conducted into an ice-cooled aqueous solution containing an excess of **3** as a sodium salt form to result in the high ion-exchange yield (87%).

The ^{1}H NMR analysis of the ion-exchanged product, **I/3**, (Figure 4, middle) showed the signals assignable to the dicarboxylate counteranion, **3**, at 7.75/8.47 as well as 2.54 ppm and the high ion-exchange yield was confirmed from the signal intensity ratio. The obtained ionic product **I/3** was then heated
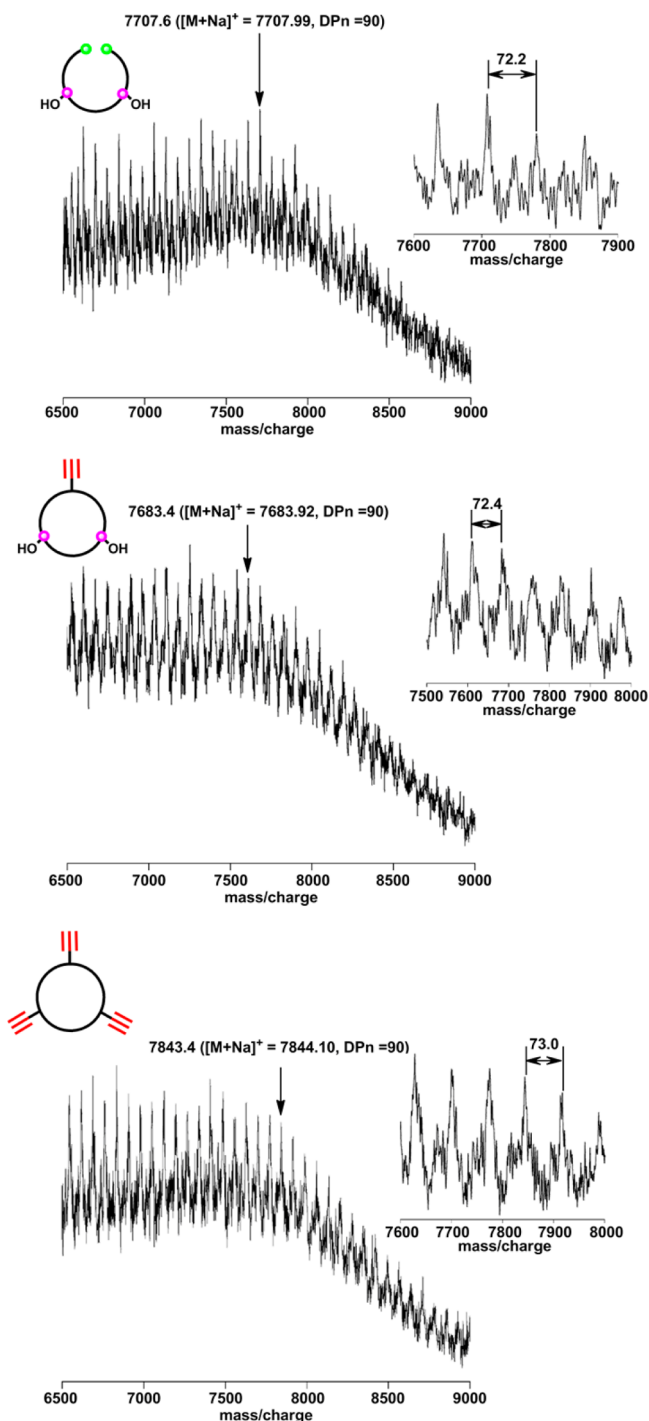
Figure 5. MALDI−TOF mass spectra of (top) a poly(THF) having an N-phenylpyrrolidinium salt group at the chain ends and two hydroxyl groups at the prescribed inner positions, **I**, measured after the ring-opening reaction of the N-phenylpyrrolidinium salt group by a benzoate anion, (middle) a trifunctional *kyklo*-telechelic polymer having two hydroxyl and one alkyne groups positioned periodically along the ring polymer backbone, **II**, and (bottom) a trifunctional *kyklo*-telechelic polymer having three alkyne groups positioned periodically along the ring polymer backbone, **III** (linear mode, matrix, dithranol with sodium trifluoroacetate; DP_n denotes the number of monomer units in the products).

to reflux under dilution (0.2 g/L) in THF for 14 h, to cause the nucleophilic attack of the carboxylate anion on the

pyrrolidinium salt units. The covalent product, **II**, was isolated after the silica gel column chromatography in 58% yield.

The ^{1}H NMR comparison of **II** against **I/3** (Figure 4, bottom and middle, respectively) confirmed the ESA-CF polymer cyclization to proceed effectively. Thus, the broad methylene proton signal due to the pyrrolidinium ring unit in **I/3** observed at around 3.8−4.2 ppm was removed after the reaction, and an alternative triplet signal due to the ester methylene protons became visible at 4.25 ppm, though with overlapping by other ester methylene proton signals. In addition, the N-phenyl proton signal on the pyrrolidinium unit in **I/3** observed at around 7.4−7.7 ppm was replaced by the two-set of signals at around 6.6−6.7 and 7.2 ppm in **II** after the ESA-CF process. The signal of ethynyl proton remained visible at 2.53 ppm.

Moreover, the MALDI−TOF mass analysis of **II** (Figure 5, middle) showed the peak at m/z = 7683.4, corresponding to the expected chemical structure of **II** as the Na$^+$ adduct with a DP_n of 90; $(C_4H_8O) \times 90 + C_{67}H_{62}N_8O_{12}$ plus Na$^+$ = 7683.92.

Finally, the SEC of the cyclized product **II** in comparison with the linear precursor **I** (Figure 3, charts D and C, respectively) indicated that the apparent peak MW, M_p, of the former (7600) was reduced to 0.85 of the latter (8900), to support the polymer cyclization.

2. Reactions of a Periodically-Positioned Trifunctional *kyklo*-Telechelic Poly(THF). The synthetic potential of the periodically positioned trifunctional *kyklo*-telechelic precursor **II** has subsequently been demonstrated by the selective transformation of functional groups (Scheme 2) Thus, first, the *kyklo*-telechelics **II** was subjected to the esterification reaction with 4-pentynoic acid, to give the product **III** having THREE alkyne groups at the constant intervals along the cyclic backbone chain.

The ^{1}H NMR spectrum of **III** (Figure 6, top) showed the pentynoyl methyn group signal at around 2.5 ppm, together with the ester methylene group signal at 5.05 ppm, by replacing the hydroxymethylene signal visible at 4.67 ppm in **II**. (Figure 4, bottom)

The MALDI−TOF mass analysis of **III** (Figure 5, bottom) showed the peak at m/z = 7843.4, corresponding to the expected chemical structure of **III** as the Na$^+$ adduct with a DP_n of 90; $(C_4H_8O) \times 90 + C_{77}H_{70}N_8O_{14}$ plus Na$^+$ = 7844.10. The observed mass increase of 161.0 from the precursor **II**, the peak at m/z = 7683.4 (Figure 5, middle), coincides with the two pentynoyl units introduced to **II** by the esterification. Moreover, the SEC comparison of **III** against **II** (Figure 7, top and middle, respectively) confirmed that the respective two profiles were intact during the course of the esterification, to indicate the absence of the chain decomposition under the applied condition.

Finally, the *click* reaction of the trifunctional *kyklo*-telechelic precursor **III** with a linear prepolymer having azide end groups, **2**, was conducted to produce a topologically unique polymer **IV** having a three-tail tadpole form. (Scheme 2) Thus, the precursor **III** was allowed to react with an excess molar amount of **2** in the presence of a catalyst system of CuSO$_4$ and sodium ascorbate. The product of **IV** was recovered as a crude form through the column chromatography with silica gel, and was subsequently isolated by the preparative SEC fractionation technique.

The ^{1}H NMR inspection of the product **IV** itself together with its covalently converted derivative (Figure 6, middle and bottom, respectively) showed commonly signals due to the
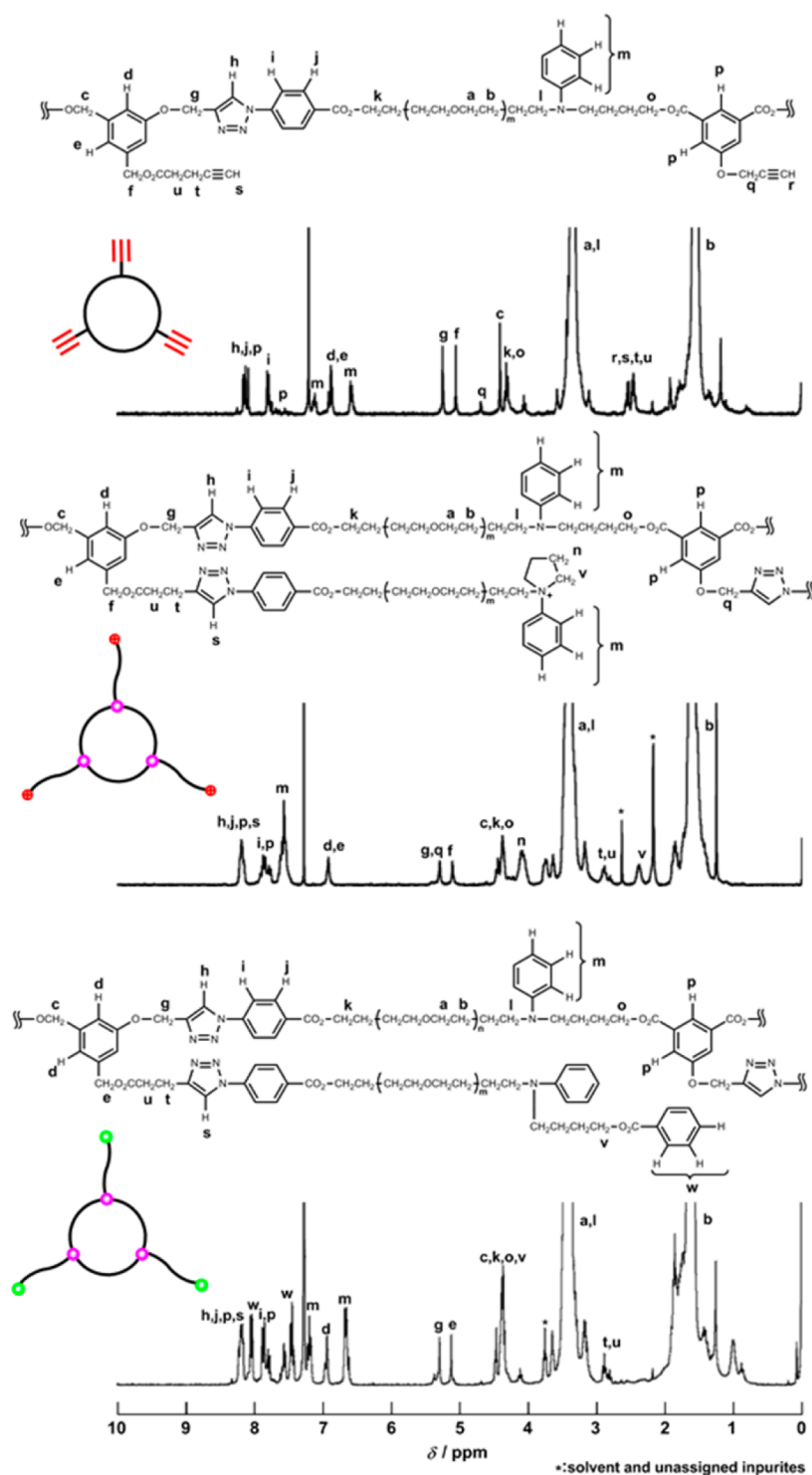
Figure 6. ^{1}H NMR spectra of (top) a trifunctional *kyklo*-telechelic polymer having three alkyne groups positioned periodically along the ring polymer backbone, **III**, (middle) the product **IV**, obtained through an alkyne−azide click reaction product of **III** with **2**, and (bottom) the covalent conversion product from **IV** after the ring-opening reaction of the *N*-phenylpyrrolidinium salt groups by a benzoate anion. (300 MHz, CDCl$_3$, 40 °C).

triazole proton at around 8.2 ppm, by replacing the ethynyl proton signal at around 2.5 ppm observed in **III** (Figure 6, top), to indicate the selective *click* linking reaction of **III**, having three alkyne units, with the linear precursor **2**, having an azide end group.

The SEC the covalently converted derivative of **IV** in comparison with **III** (Figure 7, bottom and middle, respectively) showed the distinct peak shift toward the higher molecular weight region ($M_p = 13600$, PDI = 1.11), while the value is comparatively smaller than the sum (17200) by one unit of **II** ($M_p = 7600$) and three units of **2** ($M_p = 3200$). This might correspond to the combined contraction effect by the branch and cyclic structures.
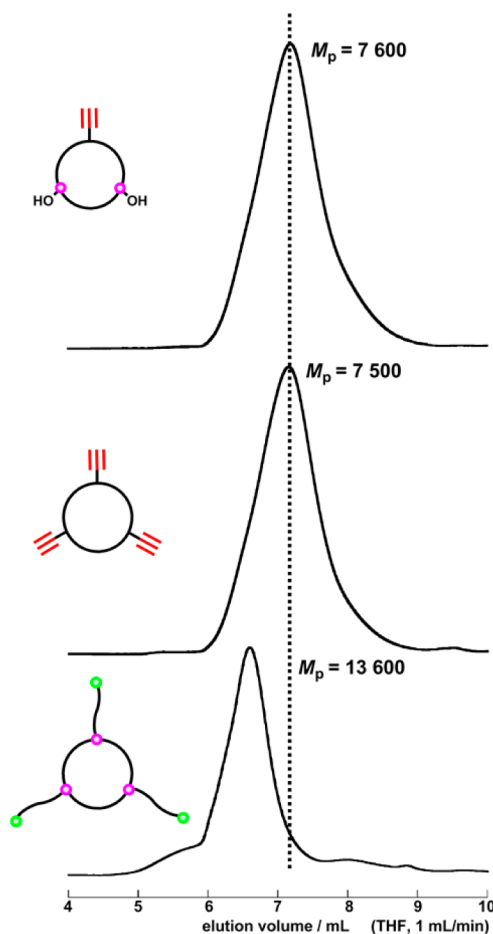
Figure 7. SEC traces of (top) a trifunctional *kyklo*-telechelic polymer having two hydroxyl and one alkyne groups positioned periodically along the ring polymer backbone, **II**, (middle) a trifunctional *kyklo*-telechelic polymer having three alkyne groups positioned periodically along the ring polymer backbone, **III**, and (bottom) the product **IV**, obtained through an alkyne–azide *click* reaction product of **III** with **2**, measured after the ring-opening reaction of the *N*-phenylpyrrolidinium salt group by a benzoate anion (THF as an eluent at the flow rate of 1.0 mL/min, a column of TSK G4000HXL.).

■ **CONCLUSION**

We have demonstrated herein a concise synthetic process of a *kyklo*-telechelics having THREE functional groups at the constant intervals. Thus, we have introduced a key linear polymer precursor having an *N*-phenylpyrrolidinium salt groups at the chain ends and two hydroxyl groups at the prescribed inner positions, which was obtained though the alkyne–azide *click* reaction by using a pair of complementary precursors, namely one unit of a linear telechelic precursor having a set of an alkyne and a hydroxyl groups and two units of a linear asymmetric telechelic precursor having an azide and a pyrrolidinium salt groups. The ESA-CF polymer cyclization technique was then applied by the subsequent introduction of a dicarboxylate counteranion having an additional alkyne group, to produce a trifunctional *kyklo*-telechelics having two hydroxyl and one alkyne groups positioned at the constant intervals along the ring polymer backbone. The synthetic potential of this new type of *kyklo*-telechelics was subsequently been demonstrated first by the synthesis of another *kyklo*-telechelic derivative having three alkyne groups at the constant intervals, and further by the *click* synthesis of a novel ring polymer

product with a three-tail tadpole topology. A new class of *kyklo*-telechelics will be accessible by the concise synthetic protocol shown by this work, and they will be utilized in the future to construct a broader range of complex polymer topologies in order to put forward the current frontier of synthetic polymer chemistry.

■ **EXPERIMENTAL SECTION**

Materials. 1-Propargyloxy-3,5-bis(hydroxymethyl)benzene,[19] 4-azidobenzoyl chloride,[24] *N*-phenylpyrrolidine,[18] and 5-propargyloxyisophthalate,[25] as well as its sodium salt **3**,[26] were synthesized by the method reported before. THF (Kanto Chemical Co., Inc.) was distilled over Na wire. Trifluoromethanesulfonic anhydride (triflic anhydride) (98%, Nacalai Tesque, Inc.) was distilled from P_2O_5 just before use. Sodium hydride (60% oil dispersion, Nacalai Tesque, Inc.) was used after washing by hexane twice and by THF once. Silver hexafluoroantimonate(V) (98%, Aldrich), sodium ascorbate (98.0+%, Wako pure Chemical Industries, Ltd.), $CuSO_4 \cdot 5H_2O$ (99.5+%, Wako pure Chemical Industries, Ltd.), 1-ethyl-3-(3-(dimethylamino)propyl)-carbodiimide hydrochloride (EDAC, > 98.0%, Tokyo Chemical Industry Co., Ltd.), 4-dimethylaminopyridine (DMAP, > 99.0%, Tokyo Chemical Industry Co., Ltd.), 4-pentynoic acid (98%, Acros Organics) were used as received. Wakosil C-300 (Wako Pure Chemical Industries, Ltd.) was used for flash chromatography.

Synthesis of a Linear Poly(THF) Having a Pair of Hydroxyl and Alkyne Groups at Both Ends (1). Into a flame-dried flask, THF (50 mL) was introduced to maintain the temperature at 25 °C. Thereupon, trifluoromethanesulfonic anhydride (50 μL, 0.30 mmol) was added, and the mixture was stirred for 4 min. The terminating reagent, prepared separately by the treatment of 1-propargyloxy-3,5-bis(hydroxymethyl)benzene (1.14 g, 5.94 mmol) with sodium hydride (238 mg, 5.94 mmol) in THF solution (50 mL), was then added into the polymerization solution, and the mixture was stirred for further 30 min. After removing the unreacted THF by evaporation, the residue was washed by a 3 M aqueous HCl and brine. The product was extracted with CH_2Cl_2, and the solution was placed in a dry ice/acetone bath to remove the precipitates by the filtration. After removing CH_2Cl_2 by evaporation, the product was subjected to a preparative SEC fractionation (Japan Analytical Industry Co., Ltd. LC-908 equipped with JAIGEL-3H and JAIGEL-2H as columns, and $CHCl_3$ as an eluent at 3.5 mL/min), in order to remove the higher molecular weight side products. The product **1** was isolated in a yield of 347 mg. (M_n(NMR) = 2.7 kDa, M_p(SEC) = 2.7 kDa)

^{1}H NMR of **1** ($CDCl_3$), δ: 1.47–1.78 (m, CH_2CH_2O), 2.53 (s, 2H, J = 2.3 Hz, CH_2CCH), 3.22–3.59 (m, CH_2CH_2O), 4.49 (s, 4H, ArCH_2OCH_2), (m, 6H), 4.59–4.80 (m, CH_2CCH, ArCH_2OH), 6.89 (d, 4H, J = 5.3 Hz, Ar–H ortho to OCH_2), 6.97 (s, 2H, Ar–H para to OCH_2).

Synthesis of a Linear Poly(THF) Having an Azide and an N-Phenylpyrrolidinium Salt End Group (2). Into a flame-dried flask was prepared a THF solution (30 mL) containing a weighed amount of 4-azidobenzoyl chloride (91 mg, 0.50 mmol) at 0 °C, and a THF solution (5 mL) containing silver hexafluoroantimonate (155 mg, 450 μmol) was added. The polymerization of THF was allowed to proceed under stirring for 8 min. Thereafter, a measured amount of *N*-phenylpyrrolidine (0.50 mL, 3.38 mmol) was added, and the mixture was stirred for further 2 h. After removing AgCl by the filtration, and removing the unreacted THF by evaporation, the residual product was reprecipitated twice from acetone into hexane placed in a dry ice/acetone bath. The product **2** was isolated in a yield of 800 mg. The M_p of the product **2** was determined by the SEC measurement after the ring-opening reaction of the *N*-phenylpyrrolidinium salt end group of **2** with a benzoate anion (M_n(NMR) = 2.3 kDa, M_p(SEC) = 3.2 kDa, PDI = 1.17).

^{1}H NMR of **2** ($CDCl_3$), δ: 1.35–1.78 (m, CH_2CH_2O), 2.08–2.30 (m, 4H, *exo*-NCH_2CH_2), 2.30–2.52 (m, 4H, *endo*-NCH_2CH_2), 3.22–3.59 (m, CH_2CH_2O), 3.68–3.82 (m, 2H, *exo*-CH_2N), 3.95–4.23 (m, 4H, *endo*-CH_2N), 4.33 (t, 2H, J = 6.3 Hz, $COOCH_2$), 7.07 (d, 2H, J =

8.6 Hz, Ar−*H* ortho to N_3), 7.46−7.71 (m, 5H, NAr−*H*), 8.03 (d, 2H, *J* = 8.7 Hz, Ar−*H* ortho to $COOCH_2$).

Synthesis of a Linear Poly(THF) Having N-Phenylpyrrolidinium Salt End Groups and Two Hydroxyl Groups at the Interior Position with Constant Intervals (I). A THF/water (4.0/1.0 in mL/mL) solution containing a weighed amount of **1** (50 mg, 19 μmol) and **2** (123 mg, 46 μmol) was charged in a flask, together with $CuSO_4 \cdot 5H_2O$ (73 mg, 292 μmol) and sodium ascorbate (107 mg, 541 μmol). The resulted suspension solution was subjected to three cycles of the freeze−pump−thaw treatment, and the reaction was allowed to proceed under stirring at ambient temperature for 36 h. Acetone was then added to the reaction mixture to remove the precipitates by filtration. After the evaporation to remove the solvents, the residual product was subjected to silica gel column chromatography first with acetone/hexane (1/2 v/v), and with acetone. The product **I** was isolated in a yield of 114 mg. The M_p of the product **I** was determined by the SEC measurement after the ring-opening reaction of the *N*-phenylpyrrolidinium salt end group with a benzoate anion (M_n(NMR) = 8.6 kDa, M_p(SEC) = 8.9 kDa, PDI = 1.36).

^{1}H NMR of **I** ($CDCl_3$), δ: 1.33−1.78 (m, CH_2CH_2O), 2.11−2.27 (m, 4H, exo-NCH_2CH_2), 2.29−2.49 (m, 4H, endo-NCH_2CH_2), 3.24−3.58 (m, CH_2CH_2O), 3.74 (t, 4H, *J* = 8.9 Hz, exo−CH_2N), 3.96−4.18 (m, 8H, endo-CH_2N), 4.27 (t, 4H, $COOCH_2$), 4.48 (s, 4H, $ArCH_2$), 4.65 (s, 4H, $ArCH_2OH$), 5.31 (s, 4H, OCH_2-triazole), 6.87−7.02 (m, 6H, Ar−*H* ortho and para to OCH_2−triazole), 7.49−7.72 (m, 10H, CH_2NAr−*H*), 7.87 (d, 4H, *J* = 8.6 Hz, Ar−*H* ortho to triazole), 8.12−8.31 (m, 6H, Ar−*H* ortho to COO, triazole-*H*).

Synthesis of a Cyclic Poly(THF) Having Periodically Positioned Alkyne and Hydroxyl Groups (II). A $CHCl_3$ solution of **I** (114 mg, 13 μmol) was treated first with brine in order to replace the couteranions in **I** from SbF_6^- to Cl^-, to facilitate the subsequent introduction of dicarboxylate counteranion. An acetone solution of the modified product of **I** was then added dropwise into an ice-cooled (<5 °C) aqueous solution (13 mL) containing sodium salt of dicarboxylate **3** (50 mg, 189 μmol) under vigorous stirring for 30 min, to proceed the ion-exchange reaction. The precipitated product was then collected by filtration and dried in vacuo to give the product (**I/3**, 107 mg) with 87% ion-exchange yield, in which a trace amount of water was purposely retained to avoid uncontrolled ring-opening reaction.

^{1}H NMR of **I/3** ($CDCl_3$)m δ: 1.31−1.93 (m, CH_2CH_2O), 1.95−2.24 (m, 4H, exo-NCH_2CH_2), 2.26−2.47 (m, 4H, endo-NCH_2CH_2), 2.54 (s, 1H, OCH_2CCH), 3.20−3.58 (m, CH_2CH_2O), 3.82−4.17 (m, 8H, exo-NCH_2) 4.25 (t, 4H, $COOCH_2$), 4.48 (s, 4H, $ArCH_2$), 4.62−4.81 (m, 6H, $ArCH_2OH$, OCH_2CCH), 5.31 (s, 4H, OCH_2-triazole), 6.84−7.02 (m, 6H, Ar−*H* ortho and para to OCH_2−triazole), 7.38−7.72 (m, 10H, CH_2NAr−*H*), 7.75 (s, 2H, Ar−*H* ortho to OCH_2CCH), 7.87 (d, 4H, *J* = 8.7 Hz, Ar−*H* ortho to triazole), 8.12−8.30 (m, 6H, triazole-*H*, Ar−*H* ortho to COO), 8.47 (s, 1H, Ar−*H* para to OCH_2CCH).

The ionic product **I/3** (107 mg) was then dissolved in THF (500 mL), at the concentration of 0.2 g/L, and was heated to reflux for 14 h. Thereafter, the solvent was removed by evaporation, and the residue was reprecipitated from acetone into water placed in an ice-cooled bath. The product **II** was isolated in a yield of 62 mg, after a plug of silica gel with hexane/acetone (1/1 v/v). (M_n(NMR) = 8.9 kDa, M_p(SEC) = 7.6 kDa, PDI = 1.30).

^{1}H NMR of **II** ($CDCl_3$), δ: 1.37−1.72 (m, CH_2CH_2O), 2.55 (s, 1H, OCH_2CCH), 3.23−3.59 (m, CH_2CH_2O, $ArNCH_2CH_2$), 4.25 (t, 8H, $COOCH_2$), 4.50 (s, 4H, $ArCH_2$), 4.58−4.74 (m, $ArCH_2OH$, OCH_2CCH), 5.32 (s, 4H, OCH_2−triazole), 6.52−6.73 (m, 6H, Ar−*H* ortho and para to NCH_2), 6.87−7.08 (m, 6H, Ar−*H* ortho and para to OCH_2−triazole), 7.10−7.25 (m, 4H, Ar−*H* meta to NCH_2), 7.46−7.67 (m, 4H, Ar−*H* ortho to OCH_2CCH), 7.86 (d, 4H, *J* = 8.7 Hz, Ar−*H* ortho to triazole), 8.11−8.40 (m, 7H, triazole-*H*, Ar−*H* meta to triazole, Ar−*H* para to OCH_2CCH).

Synthesis of a Cyclic Poly(THF) Having Periodically Positioned Three Alkyne Groups (III). In a flame-dried flask were added a THF (10 mL) solution containing a weighed amount of the product **II** (62 mg, 7.0 μmol) and 4-pentynoic acid (24 mg, 245 μmol), EDAC (47 mg, 246 μmol), and DMAP (10 mg, 82 μmol) , and the reaction was

allowed to proceed at reflux for 21 h. The reaction product was extracted with CH_2Cl_2 and treated with a 3 M aqueous HCl, with a saturated aqueous $NaHCO_3$ solution, and finally with brine. After the collected organic phase was concentrated under reduced pressure, the product **III** was isolated in a yield of 34 mg by means of the fractionation with a preparative SEC apparatus (Japan Analytical Industry Co., Ltd. LC-908 equipped with two columns, JAIGEL-3H and JAIGEL-2H, and $CHCl_3$ as an eluent at 3.5 mL/min) (M_n(NMR) = 8.9 kDa, M_p(SEC) = 7.5 kDa, PDI = 1.26).

^{1}H NMR of **III** ($CDCl_3$) δ: 1.26−1.86 (m, CH_2CH_2O), 2.34−2.64 (m, 11H, OCH_2CCH, $ArCH_2OCOCH_2$, $ArCH_2OCOCH_2CH_2$, $OCOCH_2CH_2CCH$), 3.15−3.52 (m, CH_2CH_2O, $ArNCH_2$), 4.18−4.37 (m, 8H, $ArCOOCH_2$), 4.44 (s, 4H, $ArCH_2O$), 4.68 (s, 4H, OCH_2CCH), 5.05 (s, 4H, $ArCH_2OCO$), 5.24 (s, 4H, OCH_2−triazole), 6.48−6.67 (m, 6H, Ar−*H* ortho and para to NCH_2), 6.79−7.04 (m, 6H, Ar−*H* ortho and para to OCH_2−triazole), 7.04−7.17 (m, 4H, Ar−*H* meta to NCH_2), 7.60−7.72 (m, 4H, Ar−*H* ortho to OCH_2CCH), 7.79 (d, 4H, *J* = 8.4 Hz, Ar−*H* ortho to triazole), 8.02−8.30 (m, 7H, triazole-*H*, Ar−*H* meta to triazole, Ar−*H* para to OCH_2CCH).

Synthesis of a Three-Tail Tadpole Polymer Product (IV). Into a THF/water (4.0/1.0 in mL/mL) solution in a flask containing a weighed amount of the product **III** (31 mg, 3.5 μmol) and **2** (43 mg, 19 μmol) were added $CuSO_4 \cdot 5H_2O$ (21 mg, 82 μmol) and sodium ascorbate (33 mg, 165 μmol). The resulted suspension solution was subjected to three cycles of the freeze−pump−thaw treatment, and the reaction was allowed to proceed under stirring at ambient temperature for 42 h. Acetone was then added to the reaction mixture to remove the precipitates by the filtration. After the evaporation to remove the solvents, the residual product was subjected to silica gel column chromatography first with acetone/hexane (1/2 v/v), and with acetone. The three-tail tadpole polymer product **IV** was isolated in a yield of 47 mg. The M_p of the product **IV** was determined by the SEC after the ring-opening reaction of the *N*-phenylpyrrolidinium salt end group with a benzoate anion (M_n(NMR) = 17.8 kDa, M_p(SEC) = 13.6 kDa, PDI = 1.11).

^{1}H NMR of **IV** ($CDCl_3$), δ: 1.32−1.79 (m, CH_2CH_2O), 2.08−2.28 (m, 6H, exo-NCH_2CH_2), 2.28−2.48 (m, 6H, endo-NCH_2CH_2), 2.75−3.00 (m, 4H, CH_2CH_2−triazole), 3.23−3.59 (m, CH_2CH_2O, $ArNCH_2$), 3.70−3.83 (m, 6H, exo-NCH_2), 4.19−4.52 (m, 18H, endo-NCH_2, CH_2OCH_2Ar, triazole-$ArCO_2CH_2$, Ar-$CO_2CH_2CH_2CH_2CH_2N$), 5.10 (s, 4H, CO_2CH_2Ar), 5.36 (s, 6H, $ArOCH_2$−triazole), 6.85−7.02 (m, 6H, Ar−*H* ortho and para to $CH_2OCOCH_2CH_2$), 7.43−7.71 (m, 25H, CH_2NAr−*H*), 7.71−7.98 (m, 12H, Ar−*H* ortho to triazole, Ar−*H* ortho to CO_2CH_2 and ortho to OCH_2−triazole), 8.10−8.28 (m, 16H, triazole-*H*, Ar−*H* meta to triazole, Ar−*H* ortho to CO_2CH_2 and CO_2CH_2).

Measurements. ^{1}H NMR spectra were obtained with a JEOL JNM-AL300 spectrometer at 300 MHz with $CDCl_3$ as a solvent. SEC measurements were conducted by a Tosoh model CCPS at 40 °C with a column of TSK G4000HXL and with a refractive index detector model RI 8020. An eluent was THF at the flow rate of 1.0 mL/min. The molecular weight, M_p(SEC), values were estimated by the calibration of polystyrene standard samples with the conversion factor of 0.556 for poly(THF)s.[27] MALDI−TOF mass measurements were conducted with a Shimadzu AXIMA Performance spectrometer by using a nitrogen laser (λ = 337 nm). In the spectrometer operation, an accelerating potential of 20 kV in a linear positive ion mode was employed with pulsed ion extraction. A sample solution was prepared by mixing a THF solution (10 μL, 10 mg/mL) of a polymer specimen, a THF solution (100 μL, 20 mg/mL) of dithranol, and a THF solution (100 μL, 10 mg/mL) of sodium trifluoroacetate, and a portion of the mixture solution was deposited onto a sample target plate. Mass values were calibrated by the four-point method using SpheriCal dendrimer calibrants (Polymer Factory, Sweden), at 3636.44, 4816.89, 5997.34, and 7263.87 Da (dendrimer plus Na^+).

■ ASSOCIATED CONTENT

S Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.macromol.5b01818.

Scheme showing the synthetic process of telechelic precursors for a *Click*/ESA-CF protocol, IR of **2**, **I**, **II** and **IV**, ^{1}H NMR of the covalently converted **I** (PDF)

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Notes

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