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Linear–Cyclic Polymer Structural Transformation and Its Reversible Control using a Rational Rotaxane Strategy

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Linear-cyclic polymer structural transformation and its reversibility are demonstrated by a simple but rational strategy using the structural characteristics of crown ether-based rotaxane. The polymer containing a [1]rotaxane unit at one end was controlled its structure by conventional protection-deprotection reactions, giving rise to a reversible linear-cyclic polymer structural transformation.

Cyclic polymers exhibit characteristic properties distinct from their linear or branch counterparts because of their topological dissimilarities, prompting growing research interest over the last decade.^{1,2} Recent progress in cyclic polymer synthesis has disclosed that cyclic polymers show unique properties attributed to their topology,^{3–6} and these findings have further enhanced the applicability of cyclic polymers. Novel stimuli-responsive materials may also be created by exploiting reversible polymer structural changes between cyclic and linear polymers. These materials may incorporate polymers that exist in linear and cyclic states, depending on an external stimulus. A few synthetic strategies have been developed to generate cyclic polymers and address the entropic and enthalpic barriers to cyclization. The ring-expansion polymerization of cyclic monomers has proven useful but generates cyclic polymers with restricted chemical structures.⁷ On the other hand, most approaches involving the cyclization of linear polymer precursors under high-dilution conditions tend to present poor yields and competing reactions requiring tedious purification steps.⁸ Therefore, versatile synthetic methods are highly desirable to advance the science and the scope of cyclic polymers. Here, a simple and rational synthetic protocol leading to cyclic polymer from a linear polymer is proposed using the structural transformation of a crown ether-based macromolecular [1]rotaxane (Figure 1). This protocol rests on (i) the confirmed switching behavior of crown ether–*sec*-ammonium type [2]rotaxane,⁹ (ii) the self-entangled macromolecular pseudo[1]rotaxane,¹⁰ and (iii) the synthesis of a well-defined macromolecular [2]rotaxane.¹¹ Furthermore, this [1]rotaxane system enables reversible structural transformation between linear and cyclic ones.

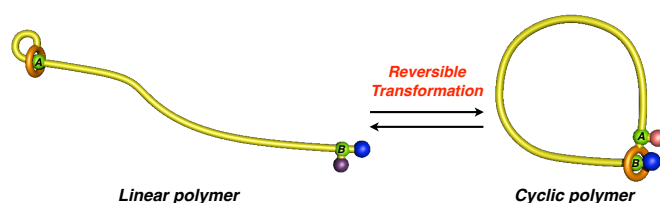


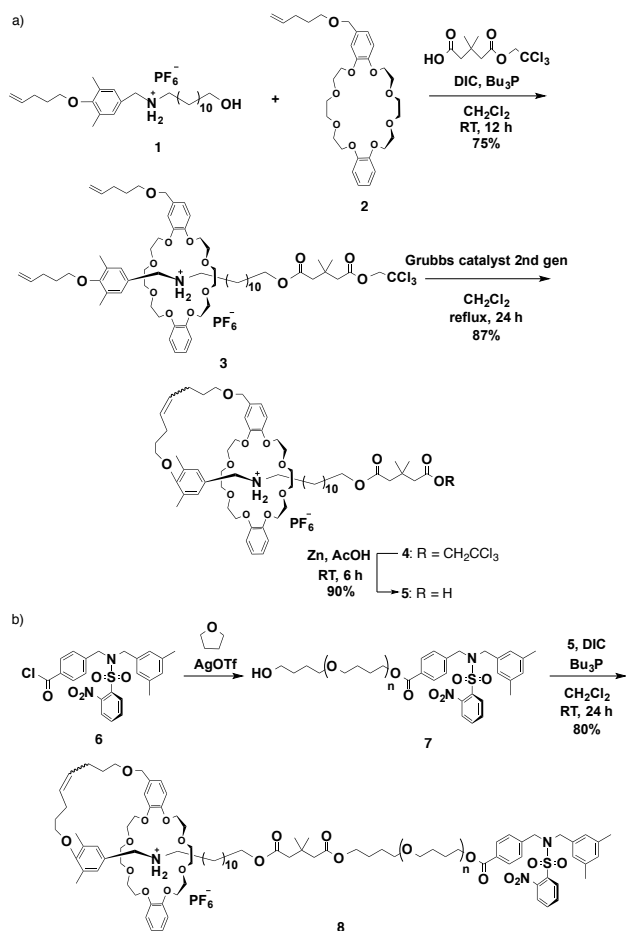
Fig. 1. Reversible linear–cyclic polymer structural transformation.

As shown in Figure 1, the small cyclic part of linear polymer is gradually expanded by the movement of the wheel component to be formed the large cyclic structure. The cyclic polymer is formed when the wheel component moves from one end (station A) of the polymer axle of the macromolecular [1]rotaxane to the other end (station B). Unlike previously reported methods, this protocol promises a quantitative cyclization of linear polymers without any side reaction regardless of concentration. In this cyclization, protecting the *sec*-ammonium end group (station A) allowed the crown ether wheel component to move along the polymer chain from A and allowed successive activation of station B to catch the wheel component at B. Consequently, reversible processes can lead to a reversible transformation.

The basis of this study is the efficient synthesis of macromolecular [1]rotaxane, and more specifically, the successful introduction of the [1]rotaxane moiety at the linear polymer end. Therefore, a self-entangled [1]rotaxane unit was designed according to a conventional rotaxane synthesis involving a dibenzo-24-crown-8-ether (DB24C8) wheel and *sec*-ammonium salt axle (Scheme 1). Such a crown ether–*sec*-ammonium type [1]rotaxane have been reported by several groups.^{12,13} According to their reports, there are two synthetic approaches, one is self-entangled method from wheel-axle conjugated precursor¹² and the other is cyclization method from [2]rotaxane precursor.¹³ Since the structural selectivity, without unentangled one or mutually entangled oligomers, and scalability we employed the latter approach.

The inclusion complex formation of axle **1** and wheel **2**, followed by end-capping using a protected bulky carboxylic acid group and size-complementary neopentyl group, gave [2]rotaxane **3** bearing terminal olefins on each component.¹⁴ The ring-closing metathesis of the two

olefinic groups afforded [1]rotaxane **4** in a good yield (2 steps 65%) and the subsequent ester deprotection produced the chain end modifier **5** (Scheme 1a). Compound **5** was fully characterized by various spectroscopic analyses (Supporting Information (SI)). ^1H NMR and MALDI-TOF-MS clearly indicated that **5** adopted a self-entangled pseudo[1]rotaxane structure.

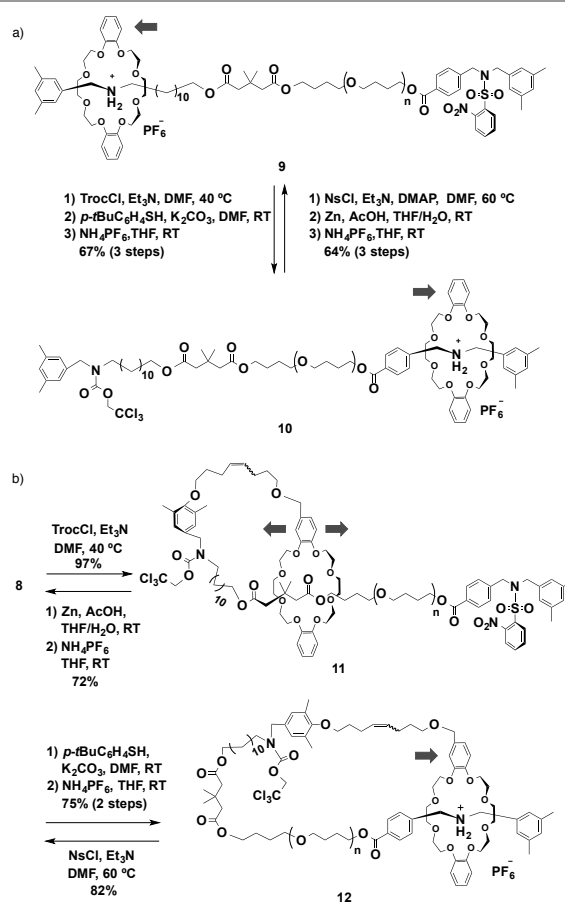


Scheme 1. Synthesis of a chain-end modified linear polymer containing a PTHF main chain (**8**). (a) Synthesis of [1]rotaxane-type chain end modifier **5**. (b) Synthesis of [1]rotaxane-terminated PTHF **8** using **5**. DIC: *N,N'*-diisopropylcarbodiimide.

The [1]rotaxane-terminated linear polymer **8** was obtained by introducing compound **5** into the polymer chain end. Living cationic ring-opening polymerization of tetrahydrofuran (THF) using a bulky benzoyl chloride initiator bearing an *o*-nitrobenzenesulfonylamino (Ns-amino) group **6** gave OH-terminated poly(THF) (PTHF) **7** (Scheme 1b). Next, the condensation of **7** and **5** in the presence of *N,N'*-diisopropylcarbodiimide (DIC) to produce **8** in 80% yield. The calculated $M_{n,\text{NMR}}$ of **7** was 22 kD ($n = 25$) while $M_{n,\text{SEC}}$ and M_w/M_n were 35 kD and 1.13, respectively. [2]Rotaxane-type model polymer (macromolecular [2]rotaxane) **9** (Scheme 2a) was also synthesized similarly to **8** (Schemes S8).

To confirm that the wheel movement along the polymer axle played a central role in structural changes, the long-distance transport of the wheel was first evaluated using model polymer **9**. Polymer **9** was treated with trichloroethylcarbonyl (*N*-Troc) chloride and triethylamine to break the hydrogen bonding between the wheel and axle components and protect the

ammonium group (Scheme 2a).^{15a} The neopentyl group incorporated in **3** is a unique size-complementary group to the crown ether cavity.^{15a} Consequently, the crown ether wheel only moved toward PTHF when hydrogen bonding was suppressed.¹⁵ To displace the wheel further along PTHF, the *N*-Ns group at the opposite polymer end of **9** was deprotected using basic thiophenol to generate the *sec*-ammonium group (station B), providing a new station capable of catching the wheel. Positional changes of the wheel component along the polymer chain coincided ^1H NMR spectral changes (Figure S31). In particular, signals for the complex between the dibenzylammonium group and the wheel appeared as a characteristic multiplet assignable to *N*-benzyl protons at 4.78 ppm.^{15a} Spectral analyses clearly demonstrated the complete transport of the wheel from one polymer end (**9**) to the other (**10**). The reverse transport of the wheel, *i.e.*, the conversion from **10** to **9**, was achieved by a protection–deprotection sequence, in which the ammonium group of **10** was protected with NsCl before *N*-Troc group removal in the presence of zinc in acetic acid. These results suggest that the wheel moves reversibly along the entire axle in this macromolecular [2]rotaxane.



Scheme 2. a) Transposition of the wheel component in model polymer **9**. b) Structural transformation of [1]rotaxane polymer **8**. TrocCl = 2,2,2-trichloroethoxycarbonyl chloride, NsCl = 2-nitrobenzenesulfonyl chloride.

Next, the protection–deprotection protocol was applied to the linear–cyclic structural transformation of macromolecular [1]rotaxane **8** (Scheme 2b). Protection of linear PTHF **8** into station free PTHF **11** and the subsequent deprotection of **11** into cyclic PTHF **12** according to a similar treatment to those of **9** and **10** proceeded with a very high efficiency, implying the effectiveness of the protection–deprotection protocol for cyclic

polymer synthesis. Experimental MALDI-TOF-MS peaks matched the calculated values within experimental error, providing a powerful and concrete evidence for this transformation (Figure 2a). The MS signals of **11** and **12** became broadened owing to the presence of the isotopomers due to the *N*-Troc group. In addition, a comparison between the ^1H NMR spectra of **8** and **12** unambiguously indicated that the local positions of the wheel components corresponded to these polymers (see SI).

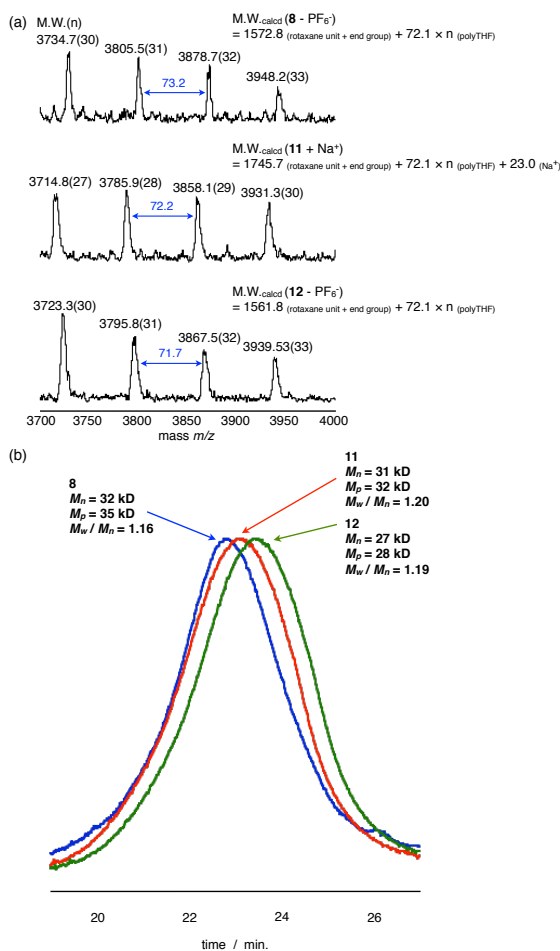


Fig. 2. Linear and cyclic polymer characterization. a) MALDI-TOF-MS spectra and b) SEC profiles (eluent: DMF) of **8**, **11**, and **12**.

As illustrated in Scheme 2b, the reverse transformation of **12** to **8** was successfully achieved by the same approach (see SI). Thus, this “rotaxane protocol” enabled reversible linear–cyclic polymer structural changes, paving the way for new dynamic polymer structure changing systems along with a new cyclization method for linear polymers.

Property variations caused by structural changes further strengthened the polymer structures. The SEC results of polymers **8**, **11**, and **12** in DMF showed that the hydrodynamic volume decreased with increased degree of cyclization (Figure 2b),^{8,9,10b,16} in agreement with the structural changes observed from **8** to **12**. Cyclic polymer **12** showed apparent lower molecular weight than linear polymer **8** by SEC despite their quasi-similar compositions. The calculated molecular weight ratio of **12** to **8** equaled ca. 0.80; by comparing their peak SEC top values (M_p), we found that the values are in good agreement with the previously reported value 0.81.³ This suggests that the structure changed from linear **8** to cyclic **12**. Similarly, the intrinsic

viscosity ratio η_{12}/η_8 amounted to 0.70 using the SEC universal calibration theories, closely matching the theoretical value of 0.66¹⁷ (see SI). Furthermore, the retention time of **11** was between those of **8** and **12**, consistent with the “free structure” like lasso-shaped of **11** because the lacking an attractive station for the wheel on the axle polymer (Scheme 2b). In our preliminary investigation to estimate the mobility of the wheel of the macromolecular [2]rotaxane, we have confirmed the complete deslippage of the wheel component from the axle polymer of *macromolecular pseudo[2]rotaxane* in solution state.^{11b,d} In addition to it, we have also reported on the shuttling behavior of a few low molecular weight rotaxanes.^{15b,18} Thus, if there is no attractive interaction between the components of the macromolecular [2]rotaxane, the wheel must freely move along the axle polymer. The spectral and SEC data reflect the averaged structure among the structures that **11** can take, and therefore, the components of **11** should move sufficiently fast in these measurements.

The diffusion coefficient D of the structurally different polymers **8** and **12** were measured by NMR to obtain additional evidence for the polymer structural transformation. According to previously reported theoretical and experimental data on cyclic polymers, linear polymers present smaller D values than their cyclic counterparts to be 0.85 in their D value ratio (D_{linear}/D_{cyclic}).^{16a} The D values obtained for **8** and **12** were 2.93×10^{-10} and 3.59×10^{-10} m²/s, respectively, and the ratio D_8/D_{12} equaled 0.82. Although this ratio is somewhat smaller than the reported D ratios, it appears appropriate to prove the cyclic topology, regardless of the very small difference in chemical structure between **8** and **12**. The polymer structural change clearly corresponded to solution property change in addition to spectroscopic changes.

Although a low molecular weight PTHF was used in this study to contrast the spectral difference in characterization, the structural difference is sufficiently clear while the volume ratio of the rotaxane part seems small, even a 25-mer PTHF, as shown in the simulated structures of **8** and **12** (Figure 3). Therefore, these significant property differences between **8**, **11**, and **12** should be due to polymer structural differences. This dynamic polymer structural changing system using supramolecular architecture of rotaxane has a potential to be applied for a high molecular weight polymer, if the interaction enough to overcome the entropic and enthalpic barriers to cyclization exist between the wheel and the axle end.

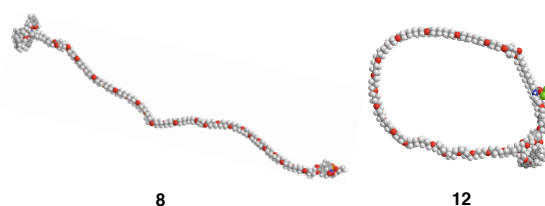


Fig. 3. Simulated structures of **8** and **12** (degree of polymerization of THF = 25, calculated by MM2).

In conclusion, the efficient linear-to-cyclic polymer structural transformation was demonstrated based on the simple but rational protocol using the structural characteristics of crown ether-based rotaxane in addition to a simple protection–deprotection technique. From a synthetic perspective, the cyclization paves the way for the large-scale synthesis of cyclic polymers, regardless of concentration and side reactions such as macrocyclization and polymer–polymer

reactions. In fact, a large-scale experiment has readily produced these polymers in high yield and at the gram scale. In principle, this synthetic protocol can be applied to versatile linear polymers displaying modifiable chain ends that react with [1]rotaxanes, such as **5**, as well as sophisticated molecular architectures. The protocol also enabled a reversible transformation, generating a novel dynamic polymer system that may lead to new stimuli responsive polymers.

Notes and references

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† Electronic Supplementary Information (ESI) available: [Experimental procedures, spectra, SEC profiles]. See DOI: 10.1039/c000000x/

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Graphical Abstract

Linear–Cyclic Polymer Structural Transformation and Its Reversible Control using a Rational Rotaxane Strategy

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A new strategy for “polymer structural transformation” was developed. One [1]rotaxane unit was introduced at the chain end of a linear polymer and the wheel component position was defined by controlling the attractive interaction between the polymer ends. Thus, the reversible linear–cyclic structural transformation was demonstrated.

