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Universal Cyclic Polymer Templates

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Supporting Information

ABSTRACT: Two unique molecular templates for generating polymeric materials with a cyclic molecular architecture were developed by combining ring-expansion metathesis polymerization and click chemistry. These two universal cyclic polymers were used in three examples to demonstrate the wide range of potential materials enabled. They include functional cyclic polymers, cyclic polymer brushes, and cyclic gels.

Cyclic polymers have a fascinating macromolecular architecture and have been pursued by material scientists in recent years due to their unique properties that differentiate them from their linear counterparts, such as a smaller hydrodynamic volume and lower melt viscosity at a given molecular weight (MW), as well as higher thermostability.[1] To date, known synthetic strategies for cyclic polymers can be generalized into two main categories: ring-closure methods and ring-expansion techniques. In the ring-closure methods, cyclic polymers were prepared by applying highly efficient coupling chemistry to end-functionalized linear telechelic polymers. This approach has successfully cyclized homodifunctional polymers,[2] heterodifunctional polymers,[3] and triblock copolymers.[4] However, disadvantages in this method still persist, such as the necessity for highly dilute reaction conditions and the difficulty of separating cyclic polymers from linear polymer impurities.

Conversely, ring-expansion techniques, which are based on the insertion of monomer units into an activated cyclic chain, do not require highly dilute conditions. Several ring-expansion polymerization systems have been explored, including cyclic oligoethylenes by insertion of methylene units into the carbon−boron bond of cyclic boraalkanes,[5] cyclic polyesters from cyclic tin[6] and N-heterocyclic carbene initiators,[7] reversible addition−fragmentation chain-transfer polymerization with cyclic dithioester agents,[8] and ring-expansion metathesis polymerization (REMP) with cyclic ruthenium−alkylidene catalysts.[9] Although the improvements are remarkable when compared to ring-closure methods, disadvantages are still present in ring-expansion techniques. These methods greatly reduce, but may not completely eliminate, linear byproducts. The main challenges include severe polymerization conditions, limited types of suitable monomers, and time-consuming processes for synthesizing cyclic initiators along with their sensitivity to functional chemical groups. These limitations have prevented the ring-expansion techniques from being widely used to prepare functionalized cyclic polymers by direct polymerization. As a result, despite great success constructing polymer chains with a cyclic topology, simple, efficient, and universal methods for preparing cyclic polymers with varied functionalities are still lacking.

Since the concept was introduced by Sharpless in 2001,[10] click chemistry has gained considerable attention in the fields of organic synthesis,[10] polymer chemistry,[11] materials science,[12] and biology,[13] due to the excellent selectivity, near-perfect reliability, high yields, and exceptional tolerance toward a wide range of functional groups and reaction conditions. Several so-called click reactions have been developed over the years, such as copper(I)-catalyzed azide−alkyne cycloaddition,[14] thiol−ene coupling,[15] nucleophilic substitution of activated esters with amines,[16] and Diels−Alder reactions.[17] Based on these click reactions, various polymer architectures, including block copolymers,[18] star polymers,[19] polymer brushes,[20] hyperbranched polymers,[21] dendrimers,[22] and cyclic polymers,[3,23] have been prepared.

Herein, a new approach to functional polymeric materials with cyclic molecular topologies was envisaged, combining the merits of both ring-expansion techniques and click chemistry. By incorporating clickable chemical groups into the perfect cyclic polymer main chains formed by ring-expansion techniques, functional materials based on cyclic polymers could be prepared by post-functionalizing the cyclic main chain. Among the existing ring-expansion techniques, the elegant REMP is the most appropriate candidate for this design strategy because it not only produces cyclic polymers with the highest reported MW, but also has good functional group tolerance due to the Ru-based metathesis catalyst and mild polymerization conditions that ensure the stability of the clickable functionalities during the polymerization process. This approach specifically overcomes the limited availability of suitable monomers by using a universal strategy to generate cyclic polymers, which are then easily modified via highly efficient post-polymerization chemistry.

Two cyclic polymer templates, one bearing pentafluorophenol activated ester side groups and the other containing alkyne clickable side groups, were prepared as demonstrations of the above design strategy. By combining REMP with activated ester and copper(I)-catalyzed azide−alkyne click chemistry, the versatility of these universal cyclic polymer templates was demonstrated not only through the synthesis of cyclic functional polymers and cyclic polymer brushes but also through the preparation of novel network materials containing cyclic molecular architectures.

The cyclic ruthenium−alkylidene catalyst **UC-6** was synthesized according to the literature,[9b] and the related ^{1}H NMR characterizations are shown in the Supporting Information, Figures S1 and S2. Clickable monomer *exo*-5-norbornenecarboxylic acid pentafluorophenol ester (**M1**) was prepared by

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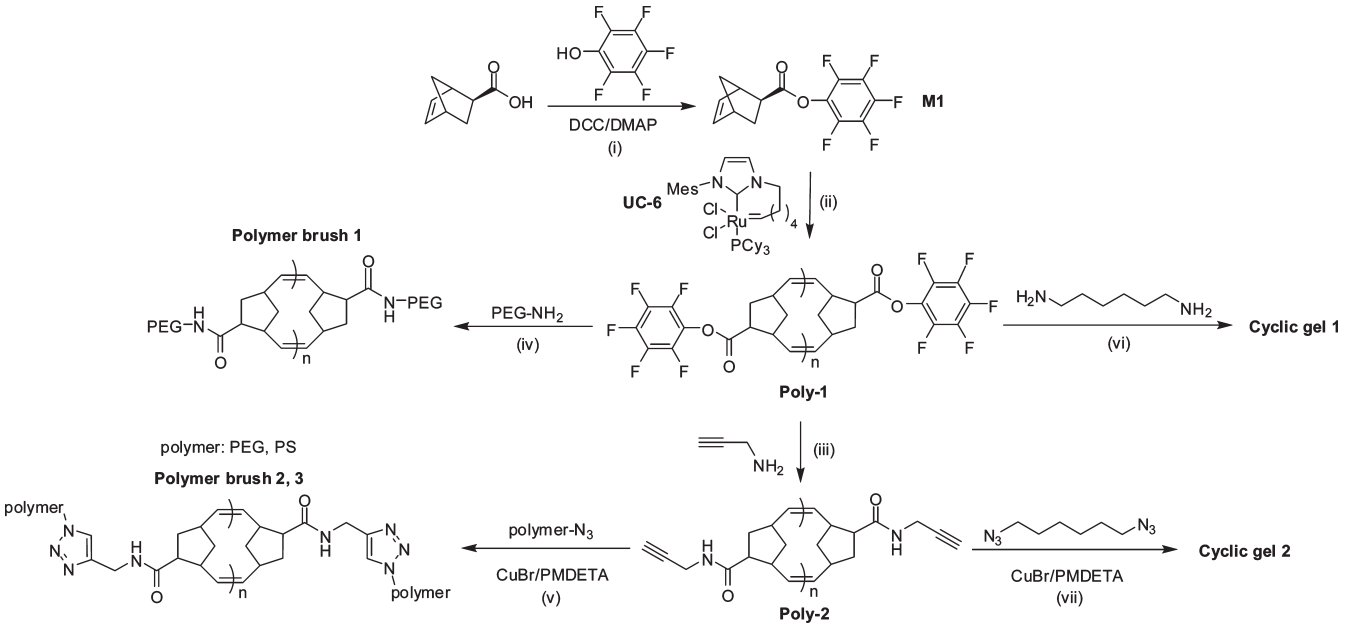
Scheme 1. Syntheses of Cyclic Polymers, Cyclic Polymer Brushes, and Cyclic Gels



esterification of *exo*-5-norbornenecarboxylic acid with pentafluorophenol (Scheme 1(i)). The corresponding ^{1}H NMR spectrum and peak assignments are shown in Figure S4A. Using **UC-6** as the catalyst, cyclic **Poly-1** was then obtained by REMP in less than 30 min (Scheme 1(ii)). The ^{1}H NMR spectrum of cyclic **Poly-1** (Figure S4B) showed the complete disappearance of the peak at 6.2 ppm (peak a,b in Figure S4A) ascribed to -C*H*═C*H*- in **M1**, and a new broad peak at 5.5 ppm (peak a,b in Figure S4B) was observed, belonging to -C*H*═C*H*- in cyclic **Poly-1**. This indicated that the polymerization was carried out successfully, with quantitative **M1** conversion. Figure S5A shows the gel permeation chromatography (GPC) curve with a monomodal peak that corresponds to $M_{n,apparent}$ = 446 700 g/mol and M_w/M_n = 1.7. The broad polydispersity index is typical for REMP and is one potential disadvantage if a narrow MW distribution is required.

To confirm the cyclic topology of **Poly-1** formed from **UC-6**, its linear analogue was synthesized using the linear ruthenium−alkylidene catalyst for comparison (see experimental details in Supporting Information). As shown in Figure 1A, both polymers have similar apparent MWs, as shown by the overlapped GPC curves from the refractive index (RI) detector. While these two polymers have similar apparent MWs, the dashed lines in Figure 1A show that in fact the cyclic polymer has a much higher absolute MW ($M_{n,absolute}$ ~926 700 vs ~466, 800), demonstrating that **Poly-1** from **UC-6** has a significantly smaller hydrodynamic volume compared to its linear analogue, consistent with a cyclic polymer topology. Further, by comparing slices across the entire peak area, it was determined that the absolute MW of cyclic **Poly-1** was always larger than that of its linear analogue at the same elution time. The ratio of absolute MWs between the cyclic and linear **Poly-1** slices was nearly constant (ca. 1.8) across the entire peak area. The two absolute MW curves are parallel across the entire peak, indicating that the absolute MW of cyclic **Poly-1** is homogeneous. This

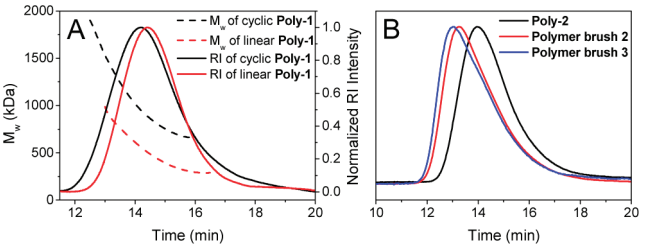


Figure 1. (A) GPC data for cyclic **Poly-1** (black) and its linear analogue (red): absolute M_w values (dashed lines) and normalized RI detector intensities (solid lines) vs elution time. THF was used as eluent. (B) GPC traces (normalized RI intensities vs elution time) of cyclic **Poly-2** (black), cyclic PEG (**Polymer brush 2**) (red), and PS (**Polymer brush 3**) (blue) polymer brushes from copper(I)-catalyzed click chemistry, where DMF with 0.01 M LiBr was the eluent and poly(methyl methacrylate) standards were used for the calibration.

supports the topological purity of cyclic **Poly-1** and indicates the possiblity of contamination from linear analogues is remote.

Cyclic **Poly-1** was designed to bear activated pentafluorophenol ester side groups so that, by virtue of the highly efficient nucleophilic substitution of activated esters with amines,[16] it could be used as a general template to prepare a variety of materials with an inherent cyclic molecular topology. By reacting cyclic **Poly-1** with small amine-functionalized chemicals, a library of novel cyclic functionalized polymers could be easily obtained. To demonstrate this concept, propargylamine was chosen as a model (Scheme 1(iii)), as it not only shows the ease of functionalizing cyclic **Poly-1** but also provides the opportunity for further modifications through the clickable alkyne group. To ensure a quantitative reaction, a 3 times molar excess of propargylamine to pentafluorophenol ester side groups in cyclic **Poly-1** was used. Figure 2A shows the ^{1}H NMR spectrum of the resultant **Poly-2** and the peak assignments. The area ratio of 1 between peak a,b (-C*H*═C*H*-) at 5.6−5.1 ppm and peak i

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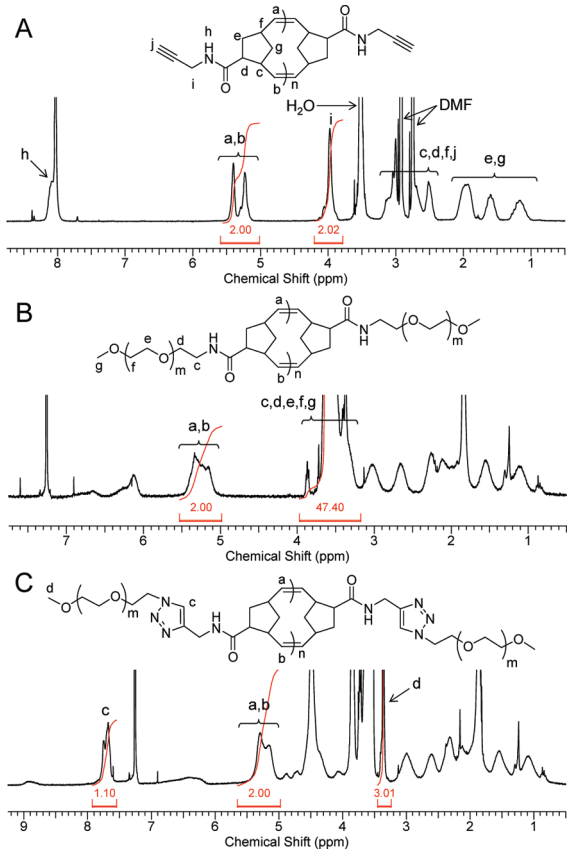

Figure 2. ^{1}H NMR spectrum of cyclic **Poly-2** (in DMF-d_7) (A) and cyclic PEG **Polymer brush 1** (in $CDCl_3$) from activated ester chemistry (B), and cyclic PEG **Polymer brush 2** (in $CDCl_3$) from copper(I)-catalyzed azide−alkyne click chemistry (C).

(-CH_2-N-) at 3.9 ppm confirmed the quantitative reaction conversion. The GPC curve of **Poly-2** in DMF is shown in Figure 1B (black). The M_n and M_w/M_n were measured to be 378 600 g/mol and 1.6, respectively, and the monomodal peak shape of the precursor, cyclic **Poly-1** (Figure S5A), was preserved. As a result, by post-functionalizing cyclic **Poly-1** with propargylamine, the clickable alkyne side groups were successfully introduced. This produced the second universal cyclic polymer template, **Poly-2**, which can be conveniently modified with azide groups using copper(I)-catalyzed azide−alkyne click chemistry.

In addition to simple functionalized cyclic polymers, various cyclic polymer brushes, which remain a challenge for today's polymer chemistry, can also be efficiently synthesized by post-functionalizing the two universal cyclic templates described above. For cyclic **Poly-1**, monofunctional poly(ethylene glycol) (PEG) with an amine end group and a MW of 550 (PEG-NH_2 550) was chosen to demonstrate the concept (Scheme 1(iv)). To ensure a high grafting density of the PEG side chains, PEG-NH_2 550 was used in a 1.5 times molar excess over the pentafluorophenol ester side groups. The resultant **Polymer brush 1** was purified by dialysis to remove excess PEG-NH_2 550 (Figure S5B). Figure 2B shows its ^{1}H NMR spectrum. The area ratio between peaks a,b (-C*H*═C*H*- in the main chain) at 5.5−5.0 ppm and peaks c−g (all *H* from the PEG side chains) at 4.0−3.2 ppm was used to calculate the reaction conversion. The efficient activated ester chemistry resulted in a high grafting density of >95%. While the MWs of the cyclic PEG **Polymer brush 1** and its precursor, cyclic **Poly-1**, could not be compared directly by GPC due to the lack of a peak signal for **Polymer brush 1** with the RI detector in THF, the corresponding GPC curve in DMF is shown in Figure S5B, where M_n = 490 600 g/mol and M_w/M_n = 1.7. Compared to Figure S5A (**Poly-1**), the monomodal peak shape was maintained. The conformation of cyclic PEG **Polymer brush 1** was studied by AFM, and, as seen in Figures 3A−C and S6, a circular morphology with an outer diameter of ∼30 nm was observed.

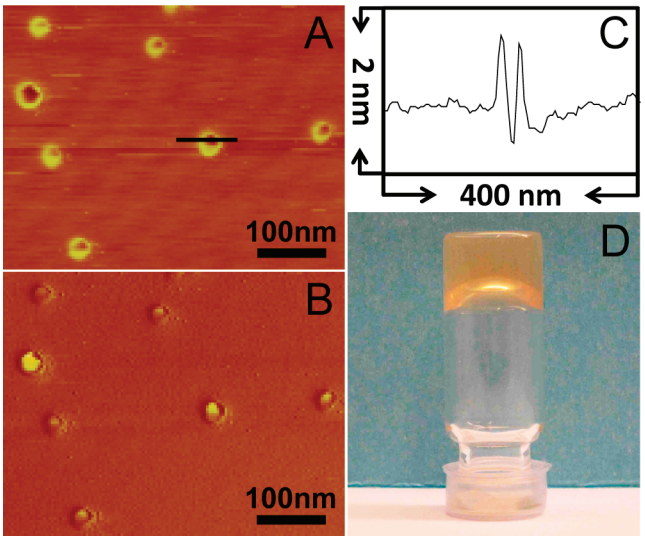

Figure 3. AFM height (A) and phase (B) images of cyclic PEG **Polymer brush 1**. (C) Profile analysis of the cyclic brush indicated by the black line in (A). (D) Picture of **Cyclic gel 1** from activated ester chemistry.

The second template, cyclic **Poly-2**, was used, along with the commercially available azide end-functionalized PEG with a MW of 550 (PEG-N_3 550), to prepare cyclic PEG **Polymer brush 2** (Scheme 1(v)). A 1.5 times molar excess of PEG-N_3 550 to alkyne side groups in **Poly-2** was used to ensure a high grafting density. Functionalization via azide−alkyne click chemistry was carried out in the presence of CuBr and PMDETA as the catalyst and ligand, respectively. The resultant **Polymer brush 2** was purified by dialysis to remove excess PEG-N_3 550 (Figure S7). The ^{1}H NMR spectrum is shown in Figure 2C. An area ratio of approximately 1:2:3 among peaks c (-N-C*H*═), a,b (-C*H*═C*H*-), and d (CH_3-O-) was evidence of a high grafting density. The corresponding GPC curve is shown in Figure 1B (red), where M_n = 499400 g/mol and M_w/M_n = 1.7. Compared to the precursor, **Poly-2** (Figure 1B), the monomodal peak shape was preserved and a clear peak shift to higher MW was observed. Further, the conformation of cyclic PEG **Polymer brush 2** was studied by AFM, and, as seen in Figure S8, circular-shaped molecules with an outer diameter of ∼30 nm were observed.

Since azide end-functionalized polymers can be conveniently obtained by atom-transfer radical polymerization (ATRP), it is possible to use **Poly-2** as a template for synthesizing cyclic polymer brushes with a variety of side polymer chains. The preparation of a cyclic polymer brush with polystyrene (PS) side chains was used to illustrate this concept (Scheme 1(v)). After preparing PS-Br by ATRP, the terminal bromine atom was substituted with an azide moiety in the presence of sodium azide. Figure S9 shows the IR spectrum of the PS-N_3, in which

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the peak at 2100 cm^{-1}, ascribed to the azide group, was clearly present, and Figure S10 shows its GPC curve, which is well defined, monomodal, and symmetrical. The M_n and M_w/M_n were measured as 1000 g/mol and 1.1, respectively. PS **Polymer brush 3** was produced under the same synthesis conditions as cyclic PEG **Polymer brush 2**. From the GPC shown in Figure 1B (blue), it can be seen that the monomodal peak shape of the precursor, **Poly-2**, was preserved, and a complete peak shift to the higher MW was observed. This confirms that, by combining the **Poly-2** template with ATRP, a wide range of cyclic polymer brushes can be prepared.

Additionally, by introducing a chemical agent with two or more reactive groups as a cross-linker, novel network materials with cyclic molecular structures can be prepared by cross-linking the cyclic templates. To demonstrate this concept, 1,6-hexanediamine was used as a model cross-linker for **Poly-1** (Scheme 1(vi)) and 1,6-hexanediazide was used for **Poly-2** (Scheme 1(vii)). By using a molar ratio of 1:5 between reactive groups in the cross-linkers and clickable side groups in the templates, both **Cyclic gel 1** and **Cyclic gel 2** were obtained in less than 5 min at room temperature. Figures 3D and S11 show representative photos of the resulting gels in inverted vials. Compared to conventional gels that are formed by cross-linking linear polymer chains, the novel cyclic gels should possess unique properties, as the cyclic polymer chains serve as a form of secondary topological cross-links.[24] Rather than the uncontrolled free radical coupling reaction developed in our recent publication,[24] the click chemistries described here will enable more freedom to manipulate the internal structure of these novel cyclic gels and should lead to an even wider array of network properties.

In conclusion, the synthesis and application of two universal cyclic polymer templates were demonstrated, combining REMP and click chemistry. Using activated ester chemistry, cyclic **Poly-1**, bearing pentafluorophenol ester side groups, was post-functionalized by amine functional agents. By virtue of copper(I)-catalyzed click chemistry, cyclic **Poly-2**, with alkyne side groups, was modified by azide functional agents. Based on these clickable cyclic polymer templates, several diverse novel materials with cyclic molecular topologies were developed, including functional cyclic polymers, microscopic cyclic polymer brushes, and macroscopic cyclic gels. Theoretically, the use of these universal cyclic polymer templates could be expanded to incorporate other types of click chemistry, such as thiol−ene coupling and Diels−Alder click reactions, following the same concept. Further, due to the high selectivity of click chemistry and orthogonal reaction mechanisms, these individual templates could be combined. This provides practical methods to explore novel materials not only bearing cyclic main-chain topologies but also having an advanced hierarchy, such as new double-network materials containing two independent cyclic macromolecules. Current investigations of these and other possibilities are ongoing.

■ ASSOCIATED CONTENT

Supporting Information. Experimental details and Figures S1−S11. This material is available free of charge via the Internet at http://pubs.acs.org.

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