

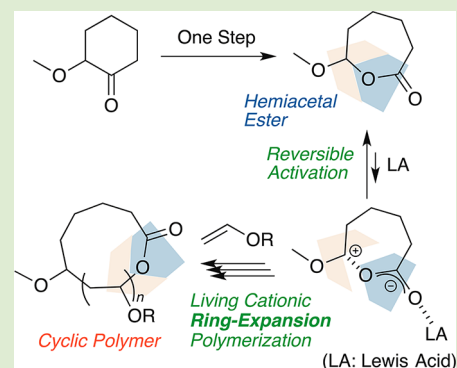
Ring-Expansion Living Cationic Polymerization via Reversible Activation of a Hemiacetal Ester Bond

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Supporting Information

ABSTRACT: In this paper, we provide an effective route to cyclopolymers via the Lewis acid-assisted “ring-expansion” living cationic polymerization of vinyl ethers, directly from a simple “cyclic initiator” designed with a hemiacetal ester for dynamic and reversible initiation and propagation. The built-in hemiacetal ester, or a carboxylic acid–vinyl ether adduct, is a key to control the polymerization: as the leaving group, the activated carboxylate is well-suited for designing the ring structure, differing from monovalent halogens often employed in carbocationic initiation. The choice of a Lewis acid catalyst (SnBr_4) is equally crucial to retain the cyclic structure via the reversibly dissociable but relatively strong ester bond not only during propagation but also even after quenching. The formation of cyclic polymers was proved by irreversibly cleaving the hemiacetal ester linkage of the product via acidic hydrolysis into an open-chain structure, i.e., an increase in size exclusion chromatography (SEC) molecular weight (hydrodynamic radius), along with the clean transformation of the endocyclic hemiacetal ester into an α -carboxylic acid and ω -aldehyde terminals (by NMR). The polymerization was really “living” polymerization via ring-expansion, as demonstrated by successful monomer-addition experiments and a linear increase in molecular weight with conversion. This ring-expansion living polymerization would open a door to well-defined cyclic polymers free from terminus (end groups) and to hybrid macromolecules with combinations of cyclic and linear architectures.



Linear polymers are so common that most polymer chemists would picture linear chains in their mind when discussing polymer design. In contrast, “cyclic” polymers belong to an atypical category in terms of topology¹ since they carry no end groups, by which they are accordingly expected to hold the promise of specific functions and physical properties. For example, polymer physicists have been interested in properties or functions derived from the cyclic structures in solution, in bulk, or on surface, most typically lower viscosity than linear counterparts, though still poorly understood. The paucity of detailed knowledge about cyclic polymers is primarily due to the limited availability of synthetic methods for cyclic polymers,^{2,3} in sharp contrast to that a wide variety of well-defined linear polymers have been constructed by living and controlled polymerizations. Obviously, precision synthesis of cyclic polymers will open the door toward new polymer design and functions.⁴

A possible way to cyclic polymers is to connect both end groups of a linear chain, i.e., by intramolecular chain-end coupling.^{5–7} In this case, diluted conditions are often required to prevent intermolecular coupling or chain extension, and quantitative single-chain cyclization is not so easy, which would have hindered extensive research and application of cyclic polymers.

Another methodology is a “ring-expansion” polymerization^{8–18} from a cyclic initiator, which is in principle independent of the concentration and possibly quantitative in cyclization. Though rather limited in scope, successful examples

include ring-opening metathesis polymerization (ROMP)⁸ and nitroxide-mediated radical polymerization (NMP).^{16,17} The leaving or capping group in these cyclic initiators should be endocyclic, a carbene in ROMP or a nitroxide in NMP as designed for a “reversibly activatable” bond to which monomers successively insert to expand a cyclic architecture. However, the reported syntheses are apparently not so straightforward, and polymerization control is less perfect than with the corresponding linear initiator. Indeed, there have been little examples of well-defined ring-expansion block copolymerization.

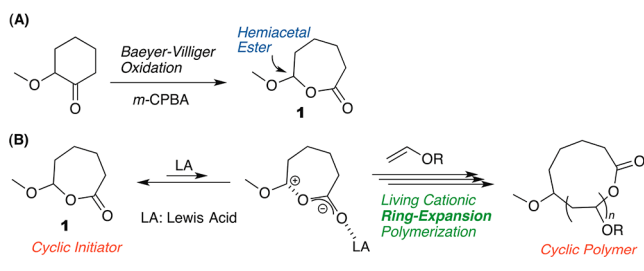
In this research, we provide an effective system for “ring-expansion living cationic polymerization”, a precisely controlled ring-expansion via a carbocationic growing species (Scheme 1). Crucial is the use of a cyclic hemiacetal ester, or a carboxylic acid–vinyl ether adduct,¹⁹ as an initiator where, upon coupling with a Lewis acid, the endocyclic activated carboxylate reversibly generates a growing carbocation associated with a nucleophilic ester anion within a single molecule. The initiator can readily be synthesized in one step from a common compound, and the polymerization is really “living” polymerization, as demonstrated by a monomer addition experiment.

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Scheme 1. (A) Synthesis of Cyclic Initiator (1) and (B) Ring-Expansion Living Cationic Polymerization of Vinyl Ethers with 1 (*m*-CPBA: *m*-Chloroperoxybenzoic Acid)



The cyclic hemiacetal initiator (1) was synthesized by Baeyer–Villiger oxidation from a cyclohexanone with a vicinal methoxy group (Scheme 1, A);²⁰ note that, with the six-membered precursor, 1 was designed to have a weakly strained seven-membered ring to facilitate initiation via transient ring-opening. As demonstrated in living cationic propagation of vinyl ethers,^{21,22} the hemiacetal ester can be “reversibly” activated and dissociates into a carbocation with a Lewis acid (LA) as a catalyst, and proper choice of LA would allow retention of the intramolecular (endocyclic) hemiacetal ester bond not only in initiation/propagation but also even upon quenching the polymerization with methanol.²³ In this regard, we found that tin tetrabromide (SnBr₄) is suitable as the LA catalyst for this purpose, as we have already achieved, with this particular LA, precise syntheses of “cleavable” block copolymers in which two segments are connected by a hemiacetal ester connection.^{24,25}

Given these initiator/catalyst design criteria, isobutyl vinyl ether (IBVE) was polymerized with 1 and SnBr₄ in the presence of dioxane and 2,6-di-*tert*-butyl-4-methylpyridine (DTBMP) in CH₂Cl₂ at 0 °C (Figure 1); the cyclic ether is a mild Lewis base for reaction control,²⁶ and the pyridine for sequestration of a proton is possibly generated from

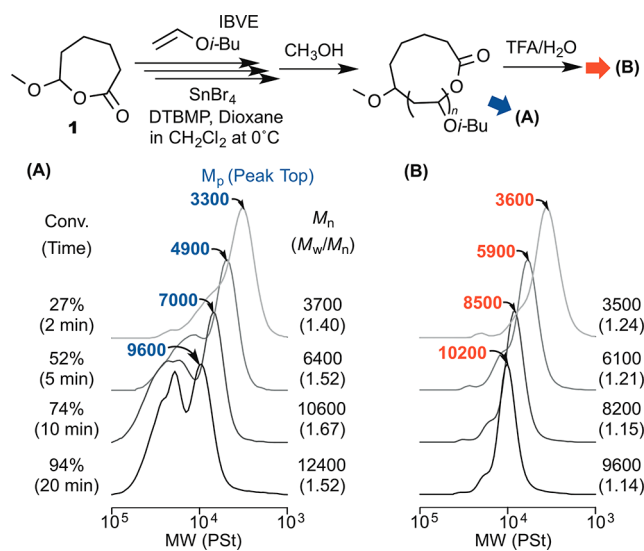


Figure 1. SEC curves of polymers in the polymerization of IBVE with 1 (A) and after hydrolysis of the products with aqueous trifluoroacetic acid (TFA) (B). Polymerization: [IBVE]₀/[1]₀/[SnBr₄]₀/[DTBMP]₀ = 380/5.0/0.50/0.15 mM in CH₂Cl₂ with 2.5 vol % dioxane at 0 °C. Hydrolysis: TFA (1.40 mL) and H₂O (0.20 mL) for polymer (0.157 g) in THF (4.0 mL) at rt for 12 h.

adventitious protogen and/or β-proton elimination (chain transfer) from the growing vinyl ether cation.²⁷ The polymerization was quenched by an addition of methanol in predetermined time. The monomer was smoothly consumed, and the conversion reached 94% in 20 min. Size exclusion chromatography (SEC) curves of the obtained polymers turned out multimodal, but the main population was very sharp and shifted to higher molecular weight with increasing conversion without any tailing (Figure 1A). From these results, any irreversible chain transfer reaction (typically β-hydrogen elimination) did not occur during the polymerization.

The obtained polymers were mixed with aqueous CF₃COOH (TFA) to convert the expected cyclic form into a linear open-chain form via the hydrolysis of the hemiacetal ester linkage. As shown in Figure 1B, the SEC curve turned almost unimodal and narrower, and most importantly, the peak top shifted to higher molecular weight, as typical in the transformation of a cyclic polymer into a linear counterpart due to an increase in hydrodynamic volume.⁶

The product structures were further analyzed in detail by ¹H NMR spectroscopy before and after the hydrolysis. For the as-obtained polymer before hydrolysis (Figure 2A), a peak (*i*)

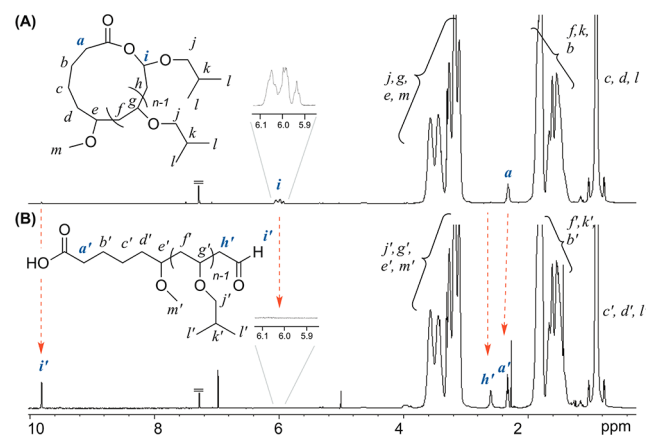


Figure 2. ¹H NMR spectra of the obtained poly(IBVE)s before (A) and after (B) hydrolytic cleavage of hemiacetal ester.

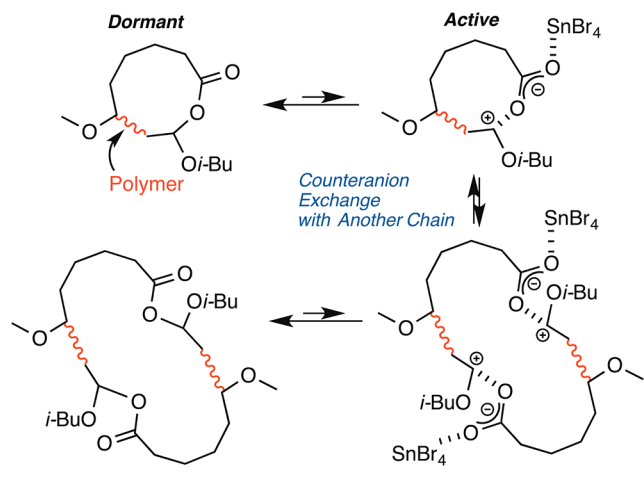
characteristic of the methine in the hemiacetal ester was clearly observed around 6.0 ppm, in addition to another distinct signal (*a*) at 2.4 ppm from the neighboring methylene. Note that virtually no peak was detected for the methine of a methoxy-capped terminal [$\sim\sim\text{CH}(\text{O}i\text{-Bu})\text{OCH}_3$; around 4.6 ppm], though the polymerization was quenched with methanol.²¹ The apparent number-average molecular weight ($M_{n,\text{NMR}}$) was 5300, as calculated from the integrated intensity of signal *a* relative to the main-chain peaks (0.7–1.1 ppm), which was much lower than $M_{n,\text{SEC}}$ (8600) by SEC but agreed well with $M_{n,\text{conv}}$ (4900) by conversion (at 63%). All these observations indicate the expected cyclic structure. The cyclic structure was also supported by MALDI-TOF-MS analysis (see Supporting Information).

After the hydrolysis, the methine peak from the hemiacetal ester disappeared, and instead a new peak (*i'*) assignable to an aldehyde was observed at 9.8 ppm. The aldehyde/main chain signal ratio gave $M_{n,\text{NMR}} = 4600$, reasonably close to $M_{n,\text{conv}} = 4900$. From these results, the ring-expansion polymerization of IBVE was well controlled to give cyclic polymers.

The multimodal SEC profile of the pristine polymers (before cleavage), with a minor fraction of higher molecular weights,

suggests that a larger ring consisting of several segments (and thus of multiple hemiacetal linkages) was generated by occasional “fusion” of two or more cyclic living polymers via counteranion exchange, particularly at higher conversion (Scheme 2).^{18,28} The near disappearance of these minor

Scheme 2. Proposed Mechanism for Generation of Larger Cyclic Polymers



products upon hydrolytic cleavage supports this proposition, where the multiple hemiacetal linkages have all been cleaved to give a set of linear chains of similar molecular weights.

The living or precision-controlled nature of the polymerization was further demonstrated by sequential monomer-addition (chain-extension) experiments (Figure 3): When the polymerization was almost completed (conversion = 95%), a fresh feed of IBVE monomer was added to the reaction mixture. The added monomer was smoothly consumed up to a high conversion above 90% (Figure 3A), to give second-stage products with SEC distributions overall shifting to higher molecular weight along with conversion, though somewhat multimodal (Figure 3C, left).

After hemiacetal cleavage, much narrower and virtually monomodal SEC curves emerged (Figure 3C, right), with a clear molecular weight increase. The conversion– M_n plots (Figure 3B) are linear and passing through the origin, both before and after the ring cleavage (squares and triangles, respectively), and the slope was reduced into half upon the cycle-to-linear transformation, all consistent with living nature of the polymers as well as the cyclic structures maintained throughout the two-stage polymerization processes. In addition, as also seen in Figure 3B, $M_{n,SEC}$ (triangles) after the cleavage agreed well with the calculated values ($M_{n,conv}$) for linear polymers (the straight line in red).

From these results, the system is essentially “living” polymerization via the proposed ring-expansion mechanism. This feature further implies the possibility of ring-expansion “block” copolymerization by sequential addition of different monomers, and this will be presented in our forthcoming publication.

In conclusion, we have achieved a ring-expansion living cationic polymerization with a hemiacetal ester-based cyclic initiator **1** and an LA catalyst SnBr_4 . The polymerization was well controlled without any unfavorable reactions to the ring-expansion event, such as β -hydrogen elimination and a bromide capping of the cationic intermediate with SnBr_4 [e.g.,

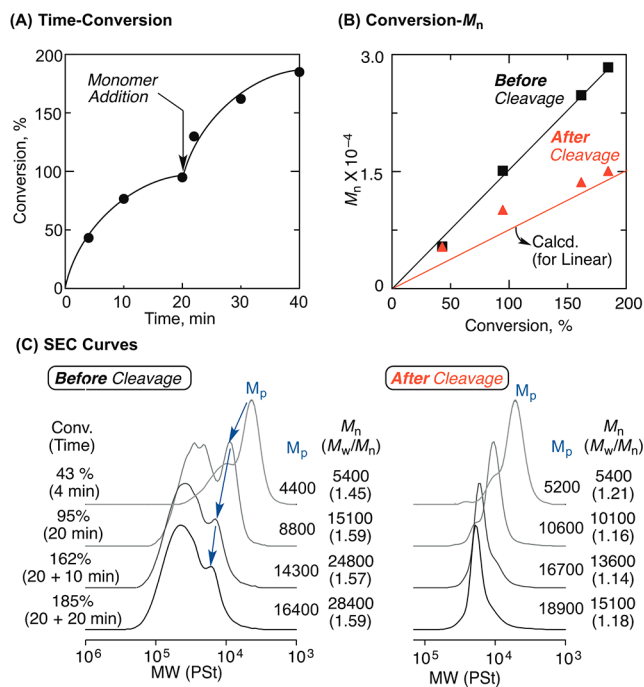


Figure 3. Sequential monomer-addition experiment in the ring-expansion living cationic polymerization of IBVE and hydrolysis (ring-cleavage) of the polymers with aqueous TFA: (A) Time–conversion curve; (B) conversion– M_n plots before and after hydrolysis; and (C) SEC curves of the products. Polymerization: $[\text{IBVE}]_0/[\mathbf{1}]_0/[\text{SnBr}_4]_0/[\text{dioxane}]_0/[\text{DTBMP}] = 380/5.0/0.50/0.15$ mM in CH_2Cl_2 with 2.5 vol % dioxane at 0 °C; $[\text{IBVE}]_{\text{add}} = 380$ mM. Hydrolysis: see Figure 1 (caption).

$\sim\sim\text{C}(\text{OR})\text{—OCO}\sim\sim + \text{SnBr}_4 \rightarrow \sim\sim\text{C}(\text{OR})\text{—Br} + (\text{SnBr}_3\text{—OCO}\sim\sim)$. The polymerization control even after the fresh monomer would involve the potential of ring-expansion block copolymerizations. Block copolymers of cyclic structures would interest us for material applications of the ring-oriented self-assembly.²⁹ Larger cycles were in fact generated apparently via counteranion exchange between two hemiacetal linkages, but in our viewpoint, contriving polymerization conditions (solvent, temperature, and reagent concentrations) would suppress this process. In another extreme, the promotion of this cyclic fusion via counteranion exchange would in turn be interesting in that it would lead to another synthetic possibility of cyclic “multiblock copolymers”, which is also among our future research targets.

■ ASSOCIATED CONTENT

Supporting Information

Experimental details for synthesis of **1**, polymerizations, and structural characterization of obtained polymers. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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